A SIMULATION MODEL FOR DRY MATTER PRODUCTION OF MAIZE BASED ON GAS EXCHANGE MEASUREMENTS OF THE WHOLE CANOPY

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INTRODUCTION

In the model BACROS (de Wit et al, 1978), the radiation regime in the canopy is calculated under different spatial positions and optical properties of individual leaves during different stages. Then, daily gross photpsynthesis can be calculated as a function of incident radiation, cloud abundance and geographical latitude.

The model MAIZE presented in this paper is constructed for the same purpose of predicting the dry matter production at Production Level 1 (F. W. Penning de Vries and H. H. van Laar et al, 1982), but the main difference is that in this model, the net CO2 assimilation is calculated on the basis of the response of the whole crop canopy to incident radiation during the process of plant growth.

A detailed discription of the model will be given in a later section. The simulation results are compared with observed field-data which are from periodic harvests of a maize crop.

1. MODEL AND SIMULATION

1.1. CO2 Assimilation

Attention is focused on the crop canopy system as a whole which interacts with weather factors, i.e., temperature and incident radiation. Differences among optical properties of differnet layers of leaves and the spatial patterns of plants are not taken into account.

In the model,light saturated assimilation rate (FM in kgCO2 ha-1 h-1), initial light use efficiency(EPS in kgCO2 s m2 ha-1 h-1 J-1) and dark respiration rate (RD in kgCO2 ha-1 h-1) are considered as crop properties (on a ground area basis) which may vary with the stages of development of the crop and with the weather conditions. Leaf area index(LAI in m2 m-2) and temperature are the factors which FM, EPS and RD dependent on. Then, net CO2 assimilation rate (FOT, in kgCO2 ha-1 h-1) can be aclculated directly from the photosynthesis-light response curve, expressed as

$$FOT = FM * (1.-EXP(-EPS*CRAD/FM))-RD \qquad (1)$$

where CRAD is global radiation in W m-2.

In two chambers situated in the experimental fields, photosynthesis and microclimatic condition were measured, so that the relationship between FOT and FM, EPS and RD could be found. In the simulation model equation (1) is applied for the local climatic conditions.

1.2. Model Input

Basic model input includes:

a. daily total radiation(DGRAD in J cm-2), from which the diurnal course of radiation is derived;

b. daily average air temperature(T in °C);

c. leaf area index LAI, which can ba either measured or simulated. LAI used in model MAIZE is measured.

These data are listed in Appendix(the program of the simulation model).

The simulation process is shown in Fig.1 in a Forrester diagram. For each day, the following steps are done:

a. intermediate variables FM, EPS and RD are estimated from LAI and temperature;

b. integrate daily total of net CO2 assimilation (DFN in kgCO2 ha-1 d-1) from FM, EPS, RD and the diurnal course of global radiation (CRAD). The diurnal net CO2 assimilation rate, expressed in kgCO2 ha-1 d-1, includes respiration of the shoot dark respiration of shoot, but not of the root. Root respiration was not measured and it is assumed to be 5% of the maximum net CO2 assimilation rate above ground (J. Goudriaan, 1985);

c. the diurnal net assimilation rate is converted to dry matter production by using the C content of dry matter which is 45%;

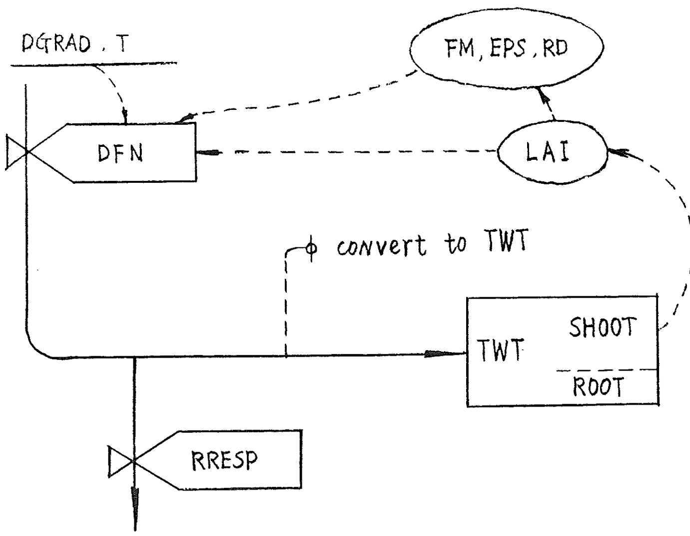


Fig.1. A relational diagram of this simulation model for dry matter production.

d. root dry matter production must also be subtracted. In this model root weight is estimated as 20% of the total vegetative biomass:

ROOT = 0.2 * (TWT - COLB) (2)

where COLB is the measured colb dry matter production and TWT is simulated total dry weight. So, above gound dry matter SHOOT (in kg ha-1) is:

SHOOT = TWT - ROOT

or SHOOT = 0.8 * TWTsimulated + 0.2 * COLBmeasured (3)

2. EXPERIMENT DESIGN AND FIELD DATA

The field experiments were done by W. Louwerse (CABO).

Data used for building the simulation model were originally from:

a. Measuring periodically gas exchange process of maize crop in two temperatural controlling chambers in the field situated in Wageningen, using mobile equipment (W. Louwerse and J. W. Eikhoudt, 1975), from the middle of June to the end of October, 1985. Items which were measured include photosynthesis and dark respiration of above-ground plants under 13°and 23°C temperatures. Global radiation was also measured at the same time.

b. Maize plants were harvested from the experimental field after every measurement. Leaf area index and biomass (wet and dry weights of the stems, leaves and colbs) were measured. In the two chambers (each covering 0.64 m2 and containing 7-8 plants of one row), the same procedure was taken as above.

c. Weather data concerning daily total radiation and daily average temperature were collected from weather station of Wageningen, the Netherlands.

3. PHOTOSYNTHESIS-LIGHT RESPONSE OF THE WHOLE CANOPY

3.1. Estimation of Parameters FM, EPS and RD With Equation (1) Using Measured Data

Two methods were applied. The first one is by using a nonliear regression method, the other is by visual estimation (estimate FM and EPS from the figuers drawn on graph papers). Fig.2 gives some examples from a set of graphs. The effect of temperature (13°and 23°C) on assimilation was estimated in three different periods. In the first period, average leaf area index in chambers (LAIC in m2 m-2) is from 0.84 to 2.44, censused from June 16-21, 23-28 and July 1-5), effect of temperature on photosynthesis is significant. Photosynthesis under 23°C are much higher than thoes under 13°C(Fig.2a,b). Respiration rate is also higher at higher temperature. During the second period (LAIC is from 3.55, reaching maximum value 4, to 3.16, censused from July 14-19, July 29 to August 2, August 11-15 and 26-30, and September 9-13) photosynthesis is almost the same under both 13°and 23°C, but maximum assimilation rate at 13°C decreases when crops are under high light intensity. RD is almost doubled in 23°C when compared to those in 13°C (Fig.2c,d). In the last period (LAIC is from 3.15 to 0.4, censused from September 23-27, October 7-11 and 21-25), only in high light intensity do photosynthesis show increasingly higher values at 23°C than those at 13°C.The behaviour patterns of RD in different temperatures are similar to those in the second period (Fig. 2e,f).

Light use efficiency EPS is independent of temperature during the measurements and it has a linear relation with leaf area index. FM, EPS and RD values increase and decrease due to the growth and development stages and leaf area index(as indicated by the curves Fig.3). Light compensation point rises during 1st and 3rd periods and remains the same (50 W m-2) in the 2nd period.

3.2. SELECTION OF THE PARATERS FM, EPS AND RD

The porcedure was as follows:

a. Select the optimal paraters by using an iterative calculation to modify the values of FM and EPS respectively.

b. The criterion is sum of squares of the deviation between calculated values of FOT and the observed.

c. By comparing the values of FOT obtained by both methods (repression and visual estimation) with the observed FOT values, these better fitting according to visual jungment are preferred.

The estimated and selected values of FM, EPS and RD are shown in Table 1.

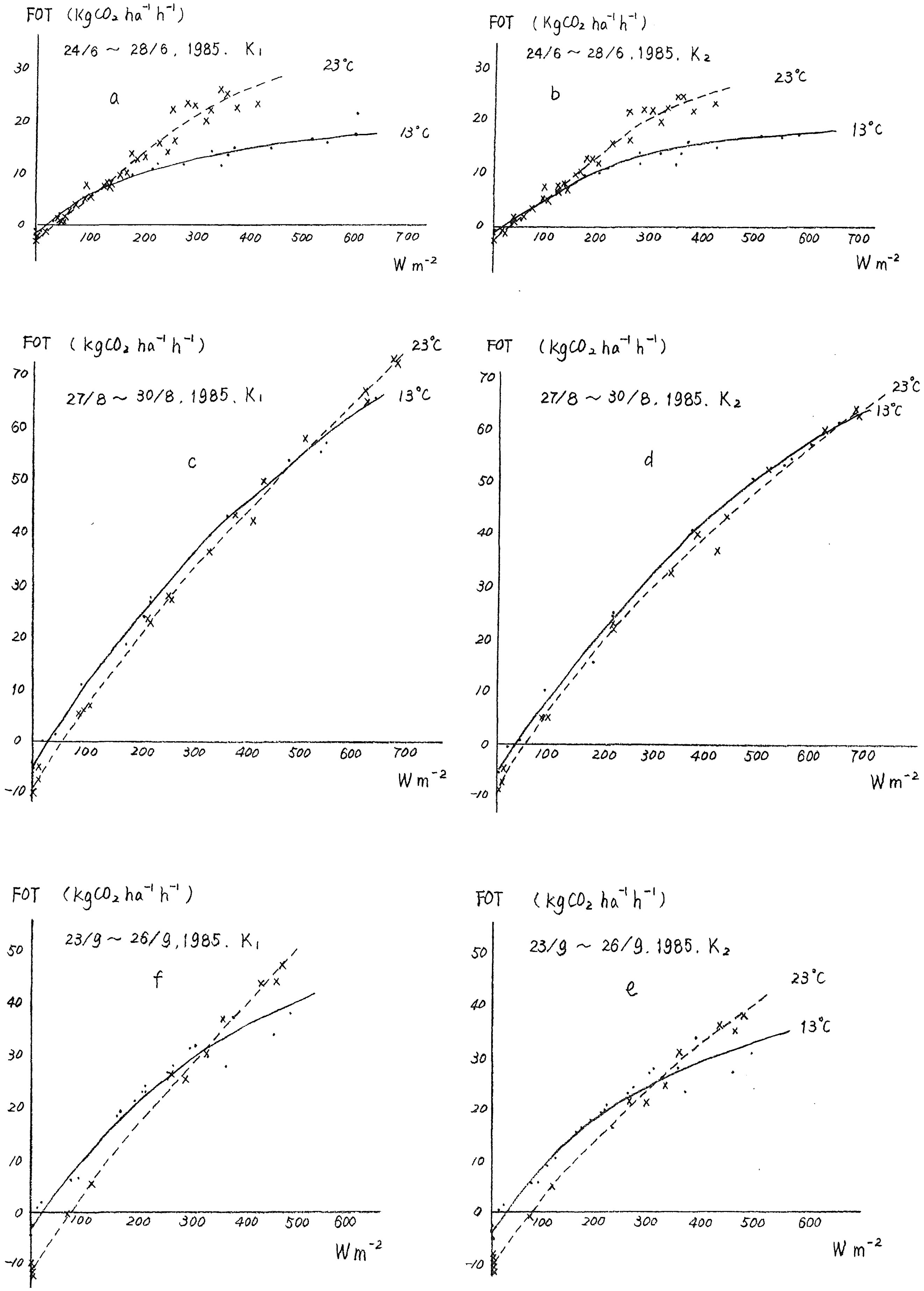
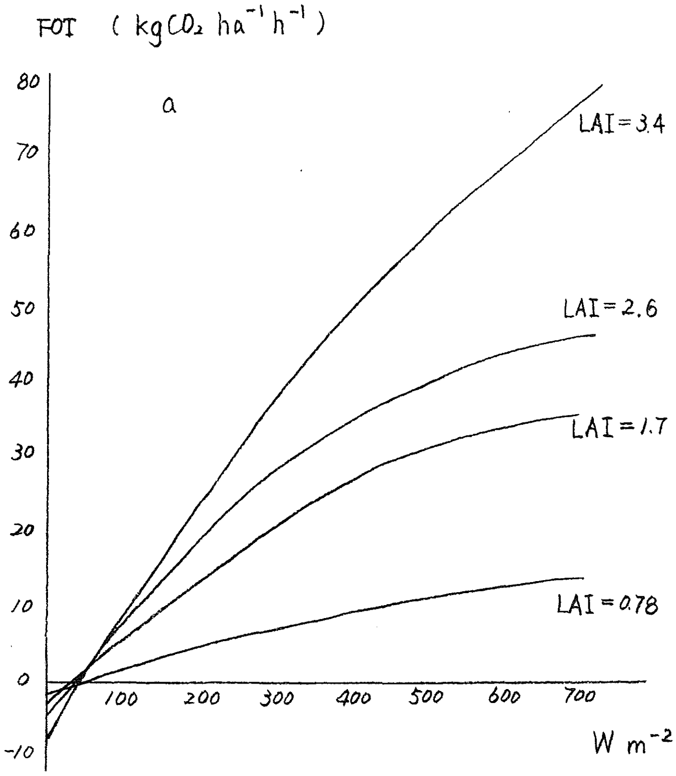
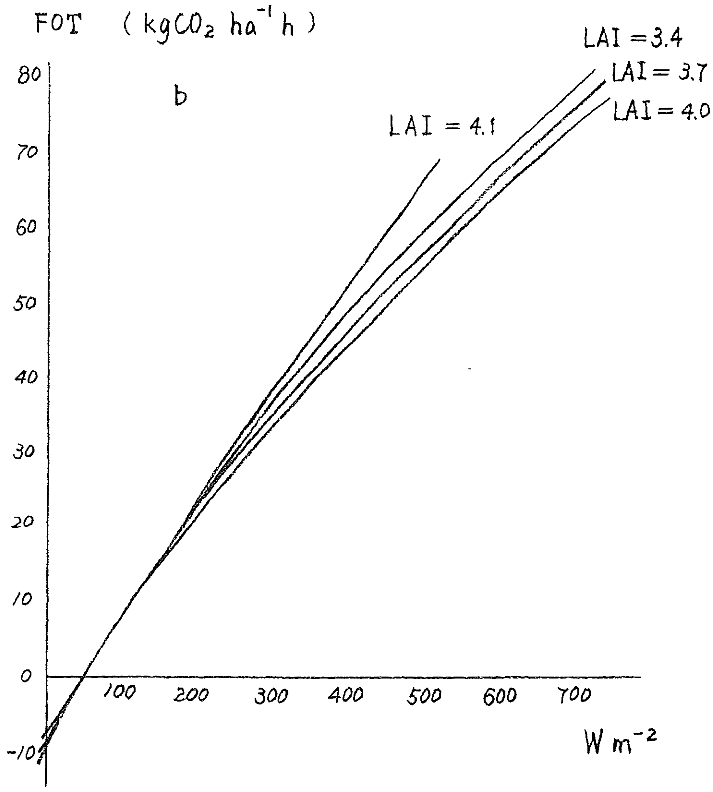


Fig.2a,b,c,d,e and f. Photosynthesis-light response curves of three different measurements which have two replicates in each time. ·——· and +----+ curves are in 13° and 23°C separately.





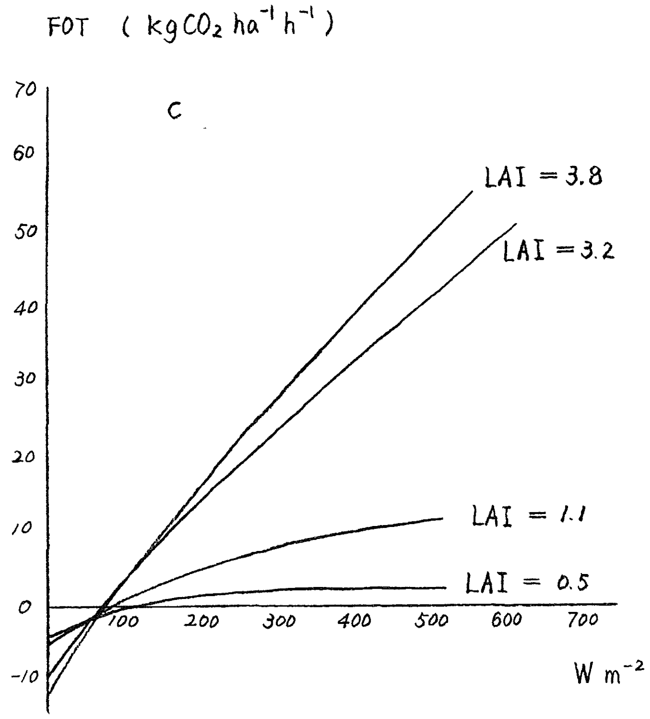


Fig.3a,b and c. Photpsynthesis-light response curve at different stages in the same temperature(23°C). a. 4 curves are from measurements of the 16-19th and the 24-28th of June, the 1-5th and the 15-19th of July; b.from the 15-19th and the 26-30th of July, the 10-14th and the 25-29th of August; c. from the 9-13th and the 21-25th of September, the 8-12th and the 21-25th of October. Leaf area index in each stage are labeled on the figures.

Table 1a. Parameters FM, EPS and RD in Temperature 13°C

DATE	17-06	26-06	03-07	17-07	29-07	12-08	27-08	11-09	23-09	10-10	23-10
FM1	8.67	17.77	39.5	97.54	109.9	99.04	109.9	80.44	46.36	12.77	1.64
fm1	9.41	19.89	40.21	119.1	130.0	80.3	95.0	77.0	60.0	17.0	3.1
FM2	7.64	18.94	35.79	101.7	85.41	138.9	113.3	86.49	36.79	22.62	----
fm2	8.59	20.24	36.71	130.5	121.1	99.0	90.0	82.0	40.0	28.0	----
FM	8.6	20.5	38.5	124.0	95.0	97.0	93.0	80.0	51.0	21.5	2.37
RD1	1.05	0.95	2.1	4.01	4.14	2.92	4.69	5.11	4.66	2.63	1.78
rd1	1.17	1.64	2.3	3.9	3.3	4.1	6.0	5.0	4.38	2.25	2.0
RD2	0.95	1.27	1.76	4.24	3.61	3.87	4.6	4.63	4.5	3.4	1.38
rd2	1.13	1.7	1.96	4.25	3.1	5.0	5.6	4.7	4.32	3.5	1.75
RD	1.15	1.67	2.13	4.08	3.2	4.6	4.8	4.9	4.35	2.9	1.68
EPS1	0.039	0.081	0.121	0.187	0.206	0.146	0.163	0.132	0.18	0.079	0.027
eps1	0.03	0.087	0.14	0.162	0.188	0.194	0.23	0.147	0.174	0.083	0.033
EPS2	0.034	0.085	0.099	0.178	0.172	0.124	0.149	0.112	0.165	0.156	----
eps2	0.03	0.08	0.102	0.167	0.157	0.167	0.19	0.123	0.171	0.151	----
EPS	0.03	0.082	0.12	0.165	0.172	0.181	0.183	0.135	0.173	0.11	0.015

Table 1b. Parameters FM, EPS and RD in Temperature 23°C

DATE	17-06	26-06	03-07	17-07	29-07	12-08	27-08	11-09	23-09	10-10	23-10
FM1	20.64	53.15	52.07	153.5	246.3	144.9	176.6	193.7	124.0	12.9	7.9
fm1	24.0	60.0	65.0	200.0	160.3	123.9	120.0	100.0	120.0	16.0	10.0
FM2	17.87	62.19	51.0	192.5	189.2	229.7	122.8-	253.6	76.53	37.48	----
fm2	15.3	80.0	58.0	160.0	140.0	116.2	100.0	240.0	75.0	41.0	----
FM	20.0	55.0	59.5	180.0	160.0	135.0	125.0	108.0	94.0	30.0	4.0
RD1	1.21	2.61	5.87	8.77	7.47	7.99	8.08	7.81	11.0	5.22	4.33
rd1	1.31	3.01	5.65	8.49	8.29	8.66	9.5	8.4	11.7	5.25	5.5
RD2	1.43	2.19	4.78	9.1	6.79	7.73	7.6	6.8	9.99	7.68	4.13
rd2	1.6	3.11	4.7	9.0	7.09	8.5	9.1	7.5	9.67	8.0	4.7
RD	1.46	3.06	5.18	8.75	7.69	8.58	9.3	8.0	10.78	6.63	4.38
EPS1	0.035	0.092	0.17	0.177	0.147	0.166	0.153	0.111	0.156	0.068	0.033
eps1	0.034	0.084	0.14	0.16	0.187	0.195	0.2	0.149	0.163	0.083	0.045
EPS2	0.035	0.087	0.117	0.156	0.145	0.137	0.15	0.078	0.143	0.135	0.005
eps2	0.035	0.083	0.11	0.17	0.15	0.166	0.19	0.1	0.158	0.154	----
EPS	0.035	0.084	0.12	0.165	0.169	0.181	0.19	0.13	0.161	0.111	0.02

Table 1a,b. Calculated and estimated values of maize maximum gross assimilation rate(FM and fm), dark respiration rate (RD and rd) and initial light use efficiency (EPS and eps) in chamber temperature 13°and 23°C during each measurement. FM, RD and EPS are the calculated values and fm, rd and eps are the estimated. Footmark 1 and 2 represents two chambers respectively. The values without footmark are those being used in Fig.4.

3.3. Relation of Photosynthesis Properties and Leaf Area Index(Fig.4)

The relation between FM (in 13°and 23°C) and LAI is expressed four epuaitons, RD (in 13°and 23°C) and LAI is expressed as two and EPS and LAI as one (see Appendix1). The effects of temperatures on FM and RD are treated with linear interpolation. The simulated FM and RD are shown in Fig.5, as a function of time.

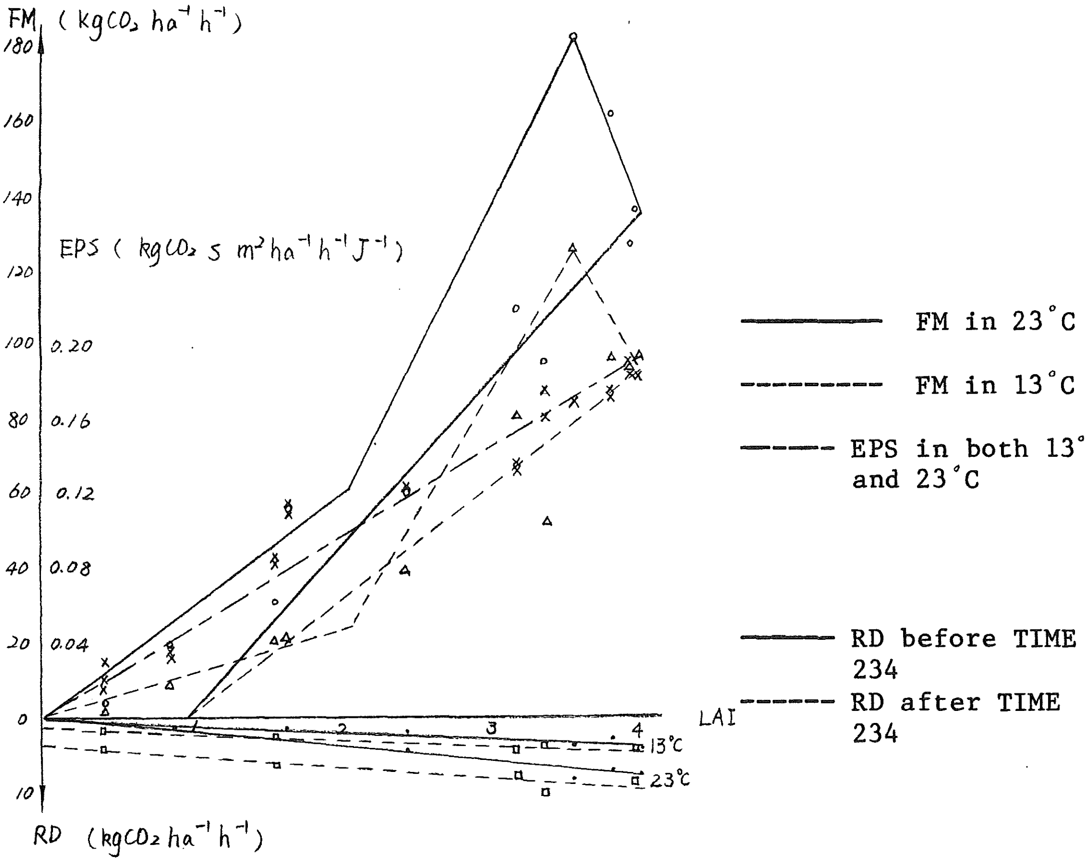


Fig.4. Change with LAI in maize(1985) maximum gross assimilation rate (FM) initial light use efficiency(EPS) and dark respiration rate(RD) as affected by two temperatures 13°and 23°C.

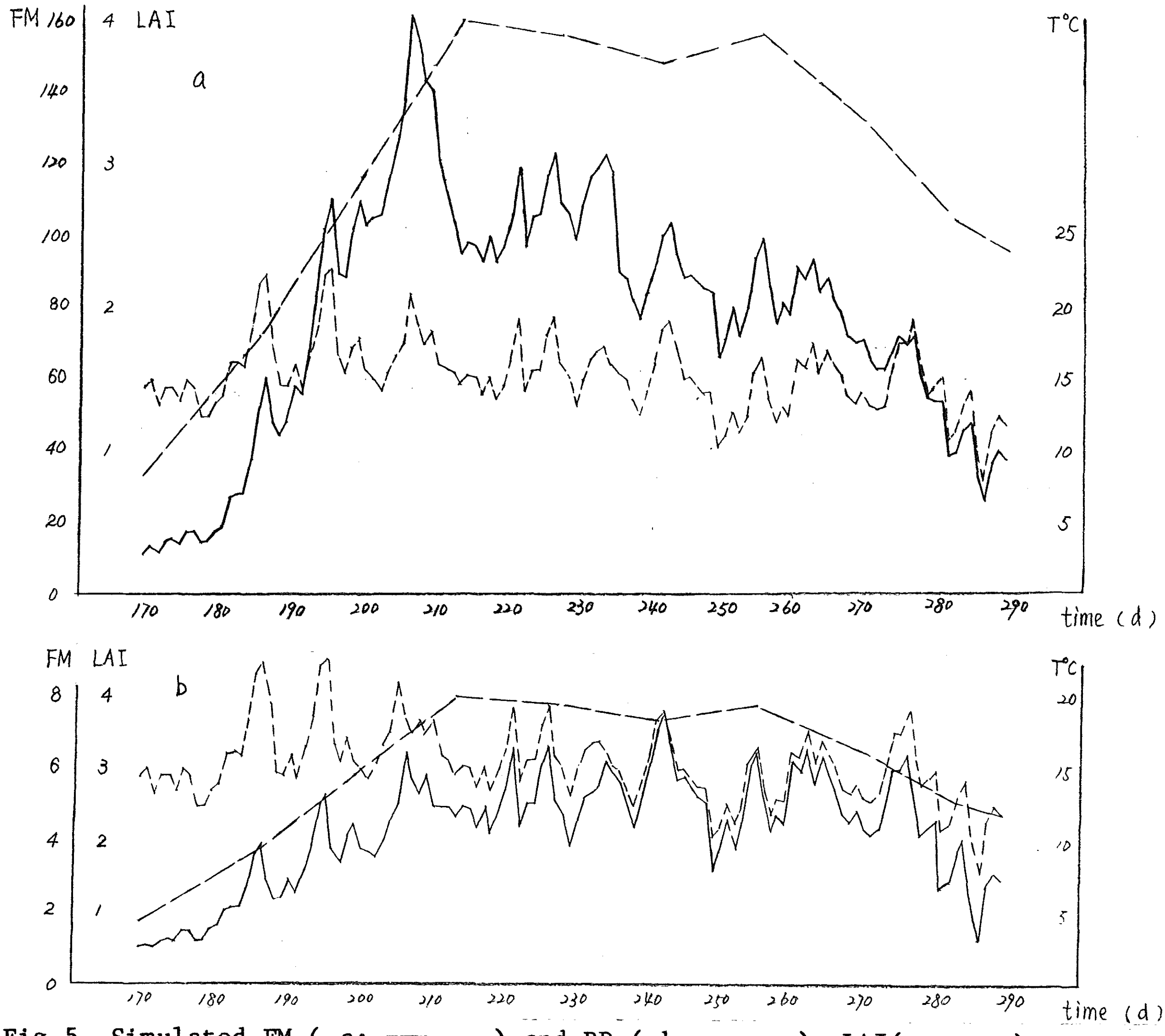


Fig.5. Simulated FM (a: ———) and RD (b: ———), LAI(———) obtained from the field and daily average temperatures (-----) of Wageningen (1985).

4. COMPARISONS OF THE SIMULATED RESULTS WITH THE FIELD DATA

For evaluation of this model, the output SHOOT of the model and corresponding field data have been compared (Fig.6). The mean error is 0.110 basis on the equation:

$$\text{Merror} = \text{SQRT}\{\sum_{i=1}^{n} ((\frac{\text{SHOOTsimul.}-\text{SHOOTmeas.}}{\text{SHOOTmeas.}})**2)/n\} \qquad (4)$$

where Merror is the average relative error. From Fig.6, it can be seen that the results have the trend of a relative precise fit at the early stage (TIME 169-187) and last stage (TIME 246-289) of the simulation process but an obvious unredestimation at the median stage (TIME 188-245). Perhaps the occurrence of this bias is due to that the values of LAI in the field are lower values at the begining (till TIME 210), similar from TIME 211 to 244, and higher after TIME 244 when compared to the LAI values measured from the chambers (Fig.7). This mean error of LAI is 0.261. The formulation of FM, EPS and RD are based on the chamber data, and LAI data obtained from the fields are utilized in the simulation process. This difference causes the underestimation of SHOOT at the early time and compensation during the last period, especially because FM is not only a function of LAI but also of plant development (Fig.4).

Simulated daily net CO2 assimilation (in temperature 13°C and 23°C separately) are compared with periodically measured data (in 13°C and 23°C). Fig.8 illustrates the comparison. The simulated values are slightly higher at the begining and much lower at the end, as a direct responsse to the differences between the LAI values measured in the chambers and in the fields.

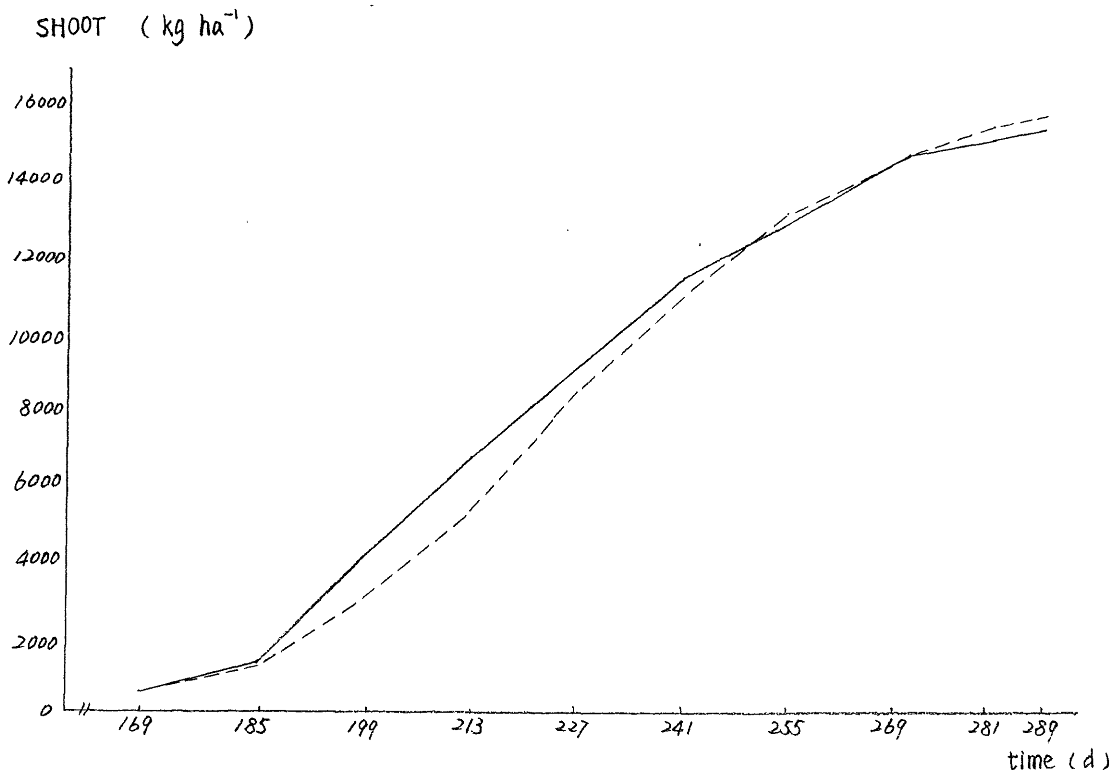


Fig.6. Simulated (----) and measured (——) above-ground dry matter production during whole season of maize crop(1985).

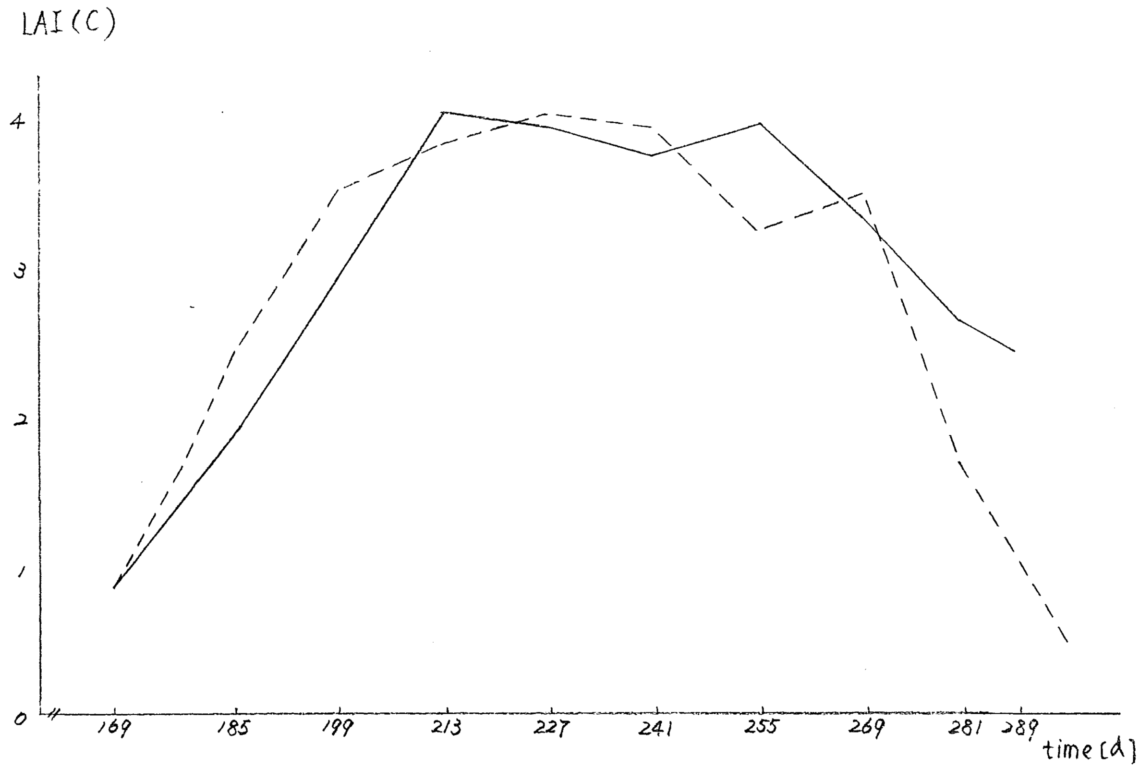


Fig.7. LAI (——) in the field are smaller during the begining time and larger in the later time than LAIC (----) in the plant chambers.

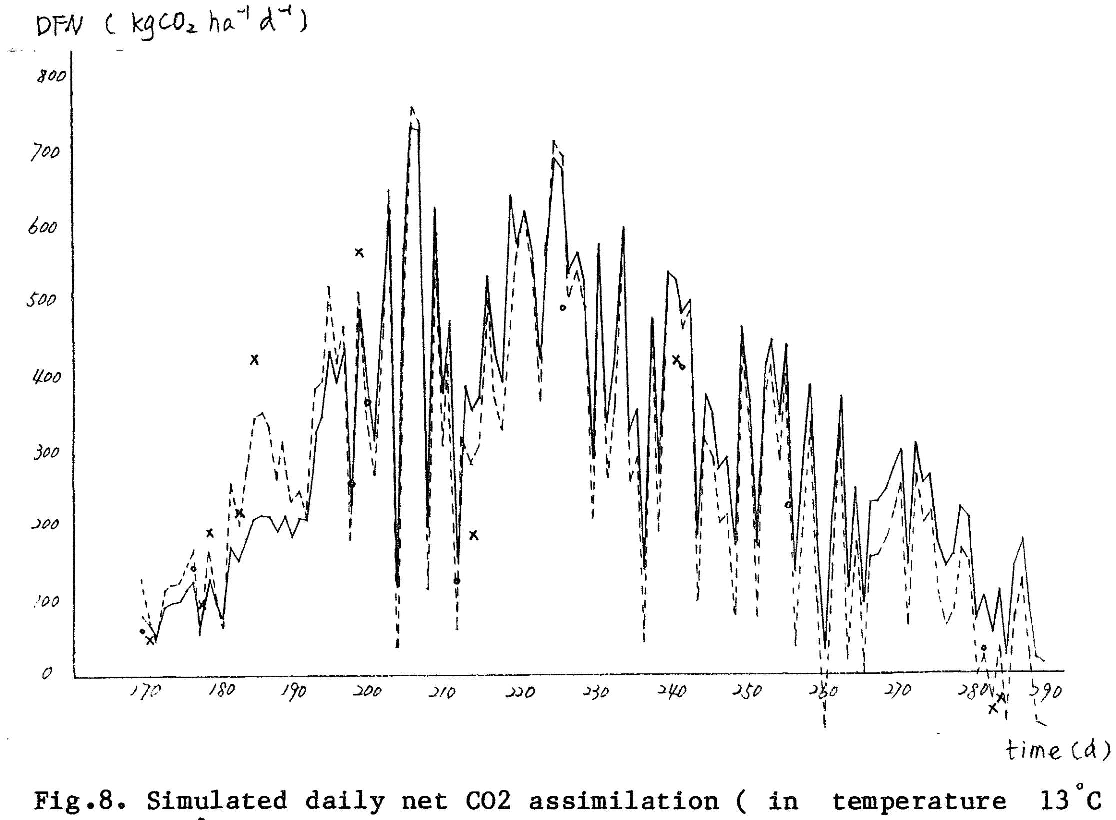


Fig.8. Simulated daily net CO2 assimilation (in temperature 13°C and 23°C) and periodically measured ones (◦ and +).

5. SENSITIVITY ANALYSIS OF THE MODEL

After construction of the model, one of the most important investment would be to perform the sensitivity analysis of the model. Its importance can be realized in three directions:

a. to validate the stability and feasibility of the model;

b. to explore the different contributions of the variables used in the model. Thus, more concentration could be focused on further research in improving the accuracies or the methodology in estimating the variables that are more sensitive;

c. the knowledge gained by performing this analysis may be useful in applied aspects and in explaining the characteristic of the model in application.

5.1. Definition of Sensitivity Analysis

The relative sensitivity of shoot weight to the variable λ may be defined as:

$$S(t,\lambda) = \frac{SHOOT(t,\lambda+\Delta\lambda)-SHOOT(t,\lambda)}{\Delta\lambda} \Big/ \frac{SHOOT(t,\lambda)}{\lambda} \qquad (5)$$

where t represents TIME.

From this definition, it is clear that the procedure of the analysis is to change each variable accordingly (while holding all the others unchanged), and see the relative change of the output of the model in the course of time. In this case, a perturbence of -10% of the variable was given.

There are altogether eight variables involved in the model: LAI, CRAD and T are original input data, from which the intermediate variables FM EPS and RD are derived. These variables are tested,and the model output SHOOT is used as the criterion for sensitivity.

5.2. Results from Sensitivity Analysis

The order of the importance (i.e. the sensitivity) of the variables is: CRAD, EPS, LAI, RRESP, RD, FM, T, and fially, COLB (Fig.9), according to their influences on the final output of the model.

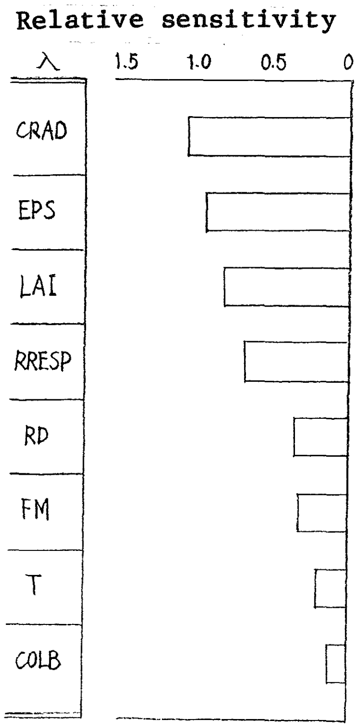


Fig.9. Relative sensitivity (in absolute values) to each variable with a disturbulance of -10%.

The most sensitive variable is CRAD, and its relative influence on the final output is less than 1.1. As for the other variables, the influences are less, 0.95 for EPS, 0.83 for LAI, 0.69 for RRESP, 0.36 for RD, 0.33 for FM, 0.20 for T and 0.12 for COLB.

CRAD is the only variable with an exclusively positive effect on FOT. The other five have both positive and negative contribution to the model output.

The changings of the relative sensitivity to T and LAI in the course of time are shown in Fig.10.

When temperature is raised, the subsequent effect on dry matter production is from positive to negative (Fig.10a). The reason is that, with the increase of temperature, both assimilation and respiration are changed. However, during the early stage the increase of assimilation is much larger than respiration, but after the peak stage of plant growth respiration has the largest increase. When temperature is given an increment of +10%, the changes of DFN,RD and RRESP are shown in Fig.11. This result is also consistent with the trends presented in Fig.2. Vice versa, the same phenomeno and reason hold true when temperature is decreased.

The effect of the changing LAI on net photosynthesis occured mainly before the crop canopy was closed. Therefore, LAI is most important before it reaches its maximum value (Fig.10b and Fig.3).

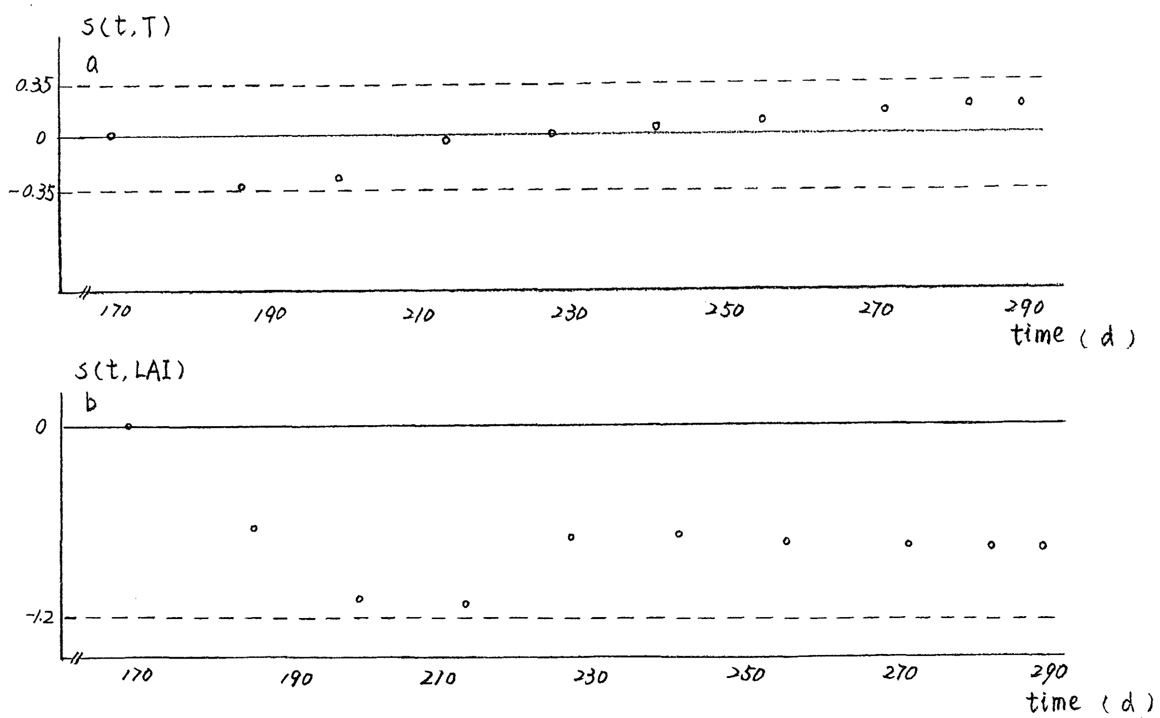


Fig.10 The dynamics of relative sensitivity S(t,λ) are caused by changing -10% of variables: T and LAI.

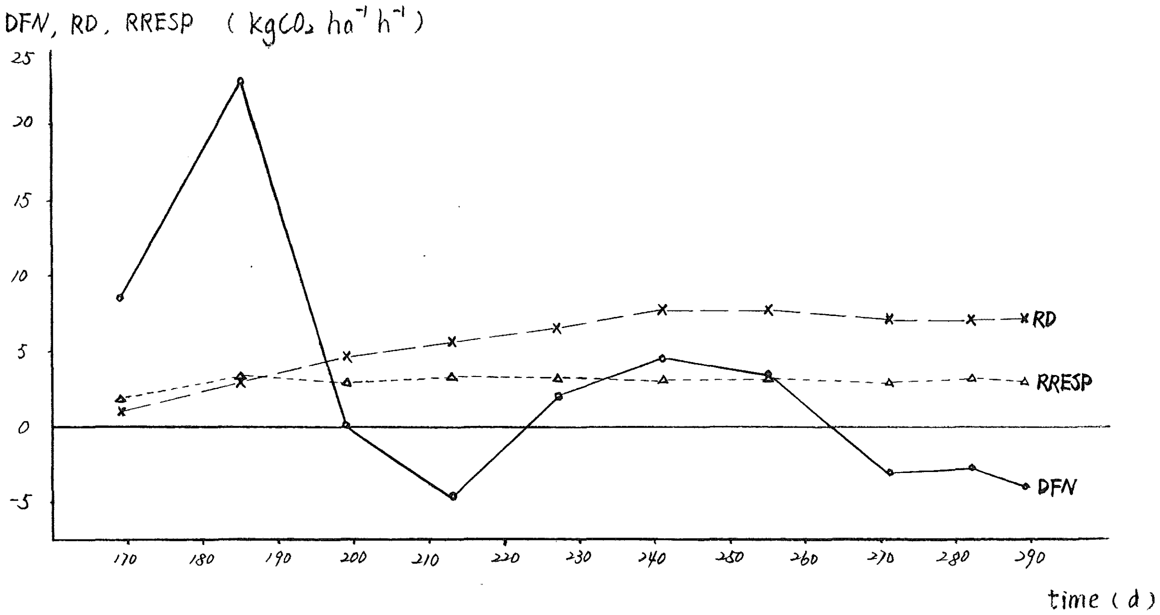


Fig.11. Changes of DFN, RD and RRESP when temperature is increased 10%.

6. COMPARISON WITH SUCROS MODEL

The model SUCROS was performed with the same input data (leaf area index from the experimental fields, actural daily total radiations and daily average temperatures). The above-ground dry matter production calculated by SUCROS is much higher than measured data and that simulated by MAIZE (Fig.12.).

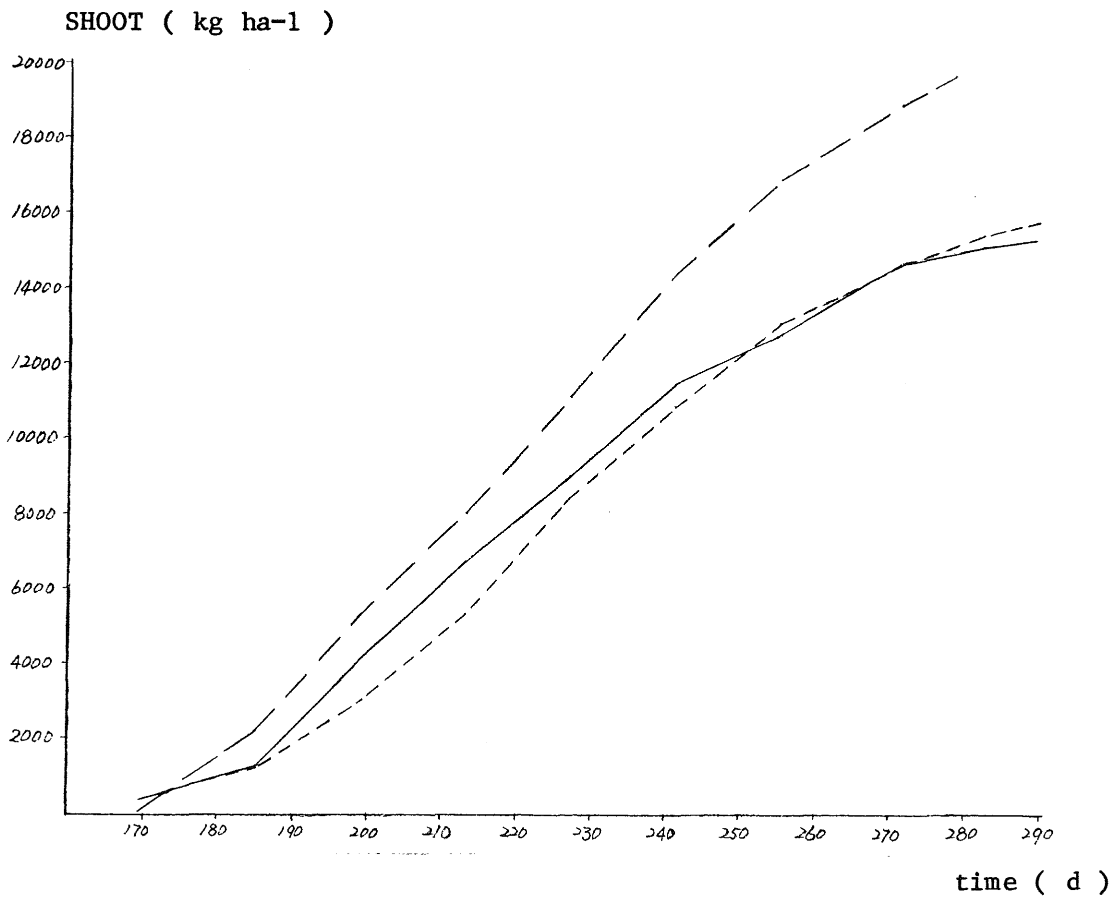


Fig.12. Simulated above-ground dry matter production of SUCROS (— —) and MAIZE (----) compared with the observed (——).

The reason is that in SUCROS, FM is considered as a photosynthetic property of individual leaves under optimal conditions, and is treated as a contant in whole period and is temperature independent.

We consider temperature as a main factor in influencing the values of FM, and FM is not a constant but a function of stages (othervise FM should have linear relationship with LAI in model MAIZE). As matter of fact, the estimated values of FM from equation (1) using measured data have great differences when temperature differs from 13°C and 23°C (see TABLE 1).Therefore, as illustrated in Fig.13, the calculated daily gross CO2 assimilation from SUCROS is much higher than that from MAIZE.

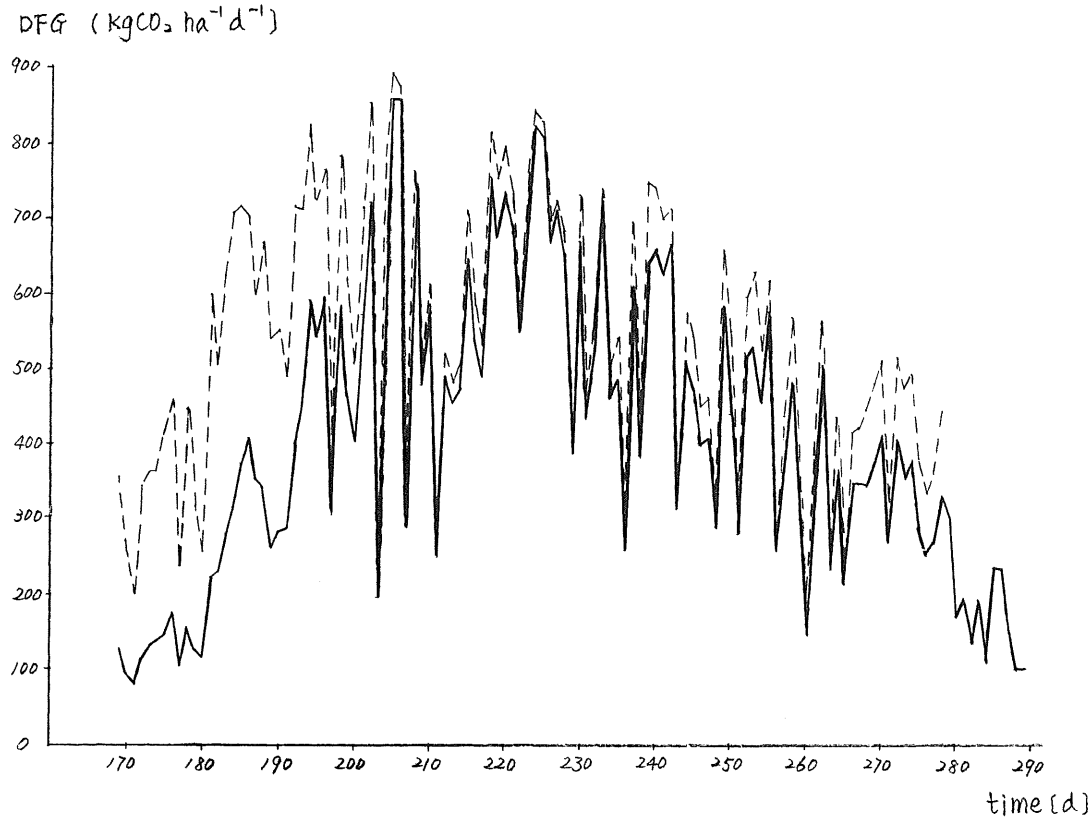


Fig.13. Daily gross CO2 assimilation simulated from model SUCROS (----) and MAIZE (——).

7. IMPROVED SUCROS MODEL

FM (see Table 1) is divided by leaf area index in the chamber, thus AMAX (maximum gross CO2 assimilation of per ha.leaf area) in 13°and 23°C is obtained. From Fig.14 it can be seen that AMAX is not only tempera-tural dependent but also a function of time. With the improved AMAX SUCROS (see Appendix2) was executed and its output SHOOT is showed in Fig.15 compared with the measured above-ground dry matter production.

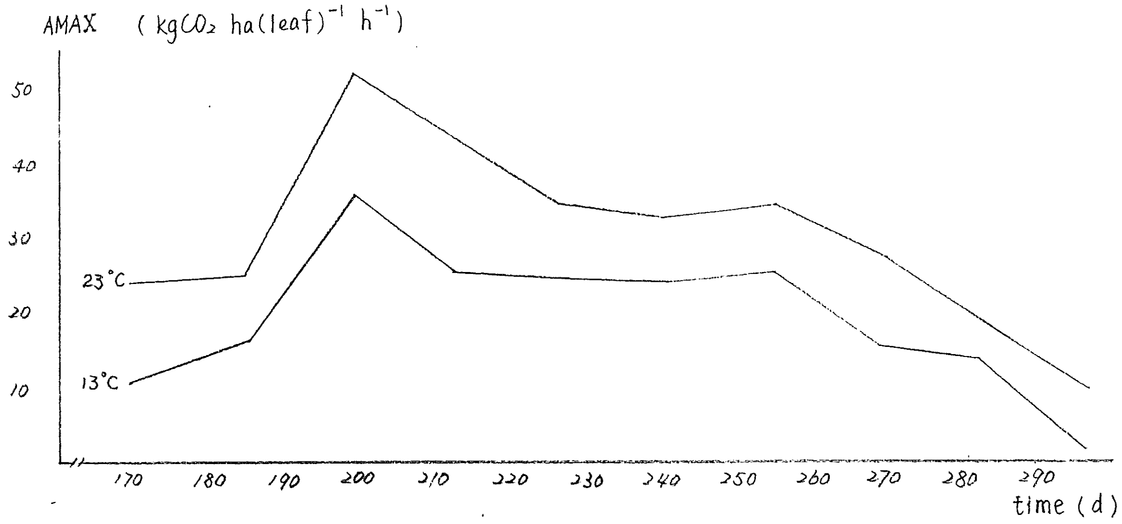


Fig.14. Maximum gross CO2 assimilation per ha. leaf area at both 13 and 23 C during the course of time.

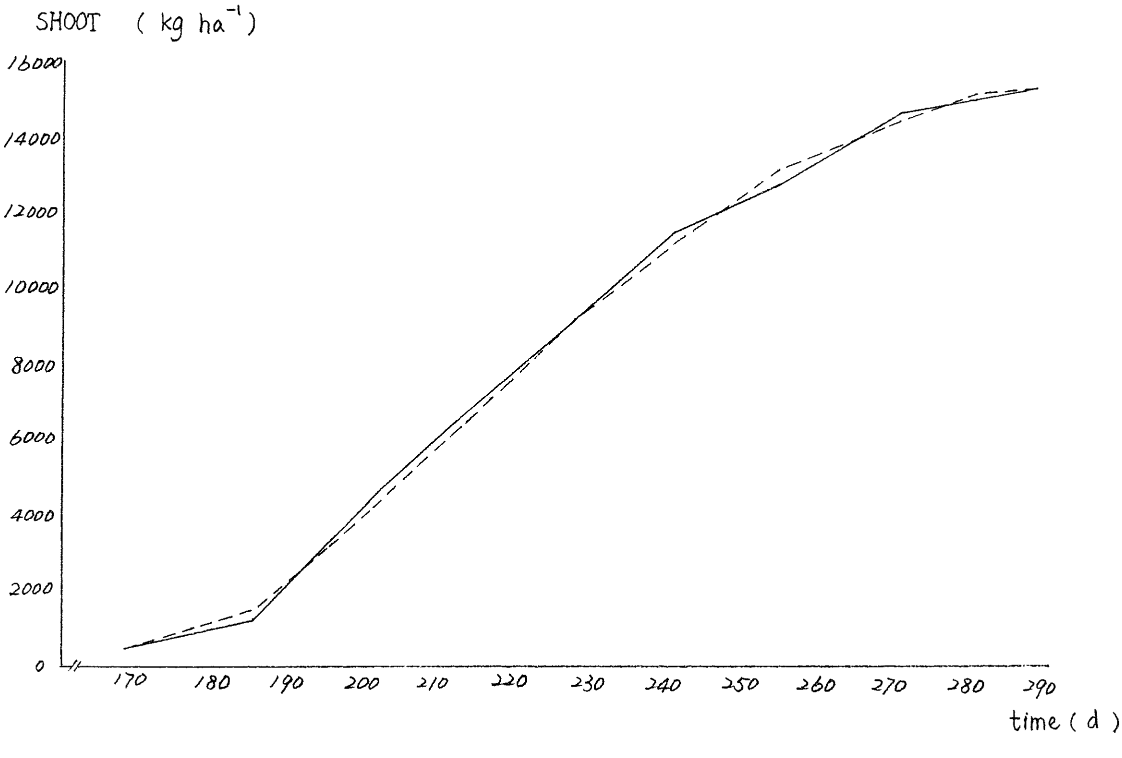


Fig.15. Above-ground dry matter SHOOT simulated by improved SUCROS (----) and the measured SHOOT (——).

Simulated daily gross assimilation is presented in Fig.16 and it has great change compared to those simulated by constant AMAX. By performing a half hour's gross assimilation of some days photosynthesis-light response curves were drawn according to the output. Some examples are given in Fig.17 and the measured data are also marked on the figures.

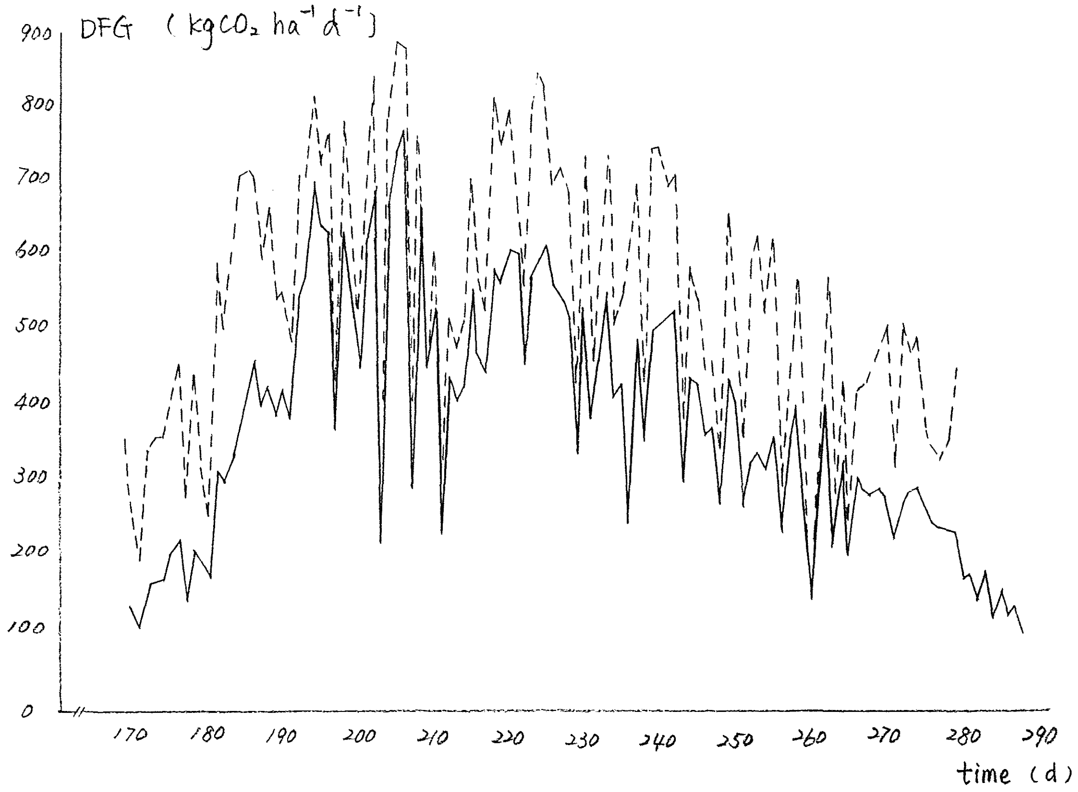


Fig.16. Simulated daily gross CO2 assimialtion with improved SUCROS model (——) and with constant AMAX (- - -).

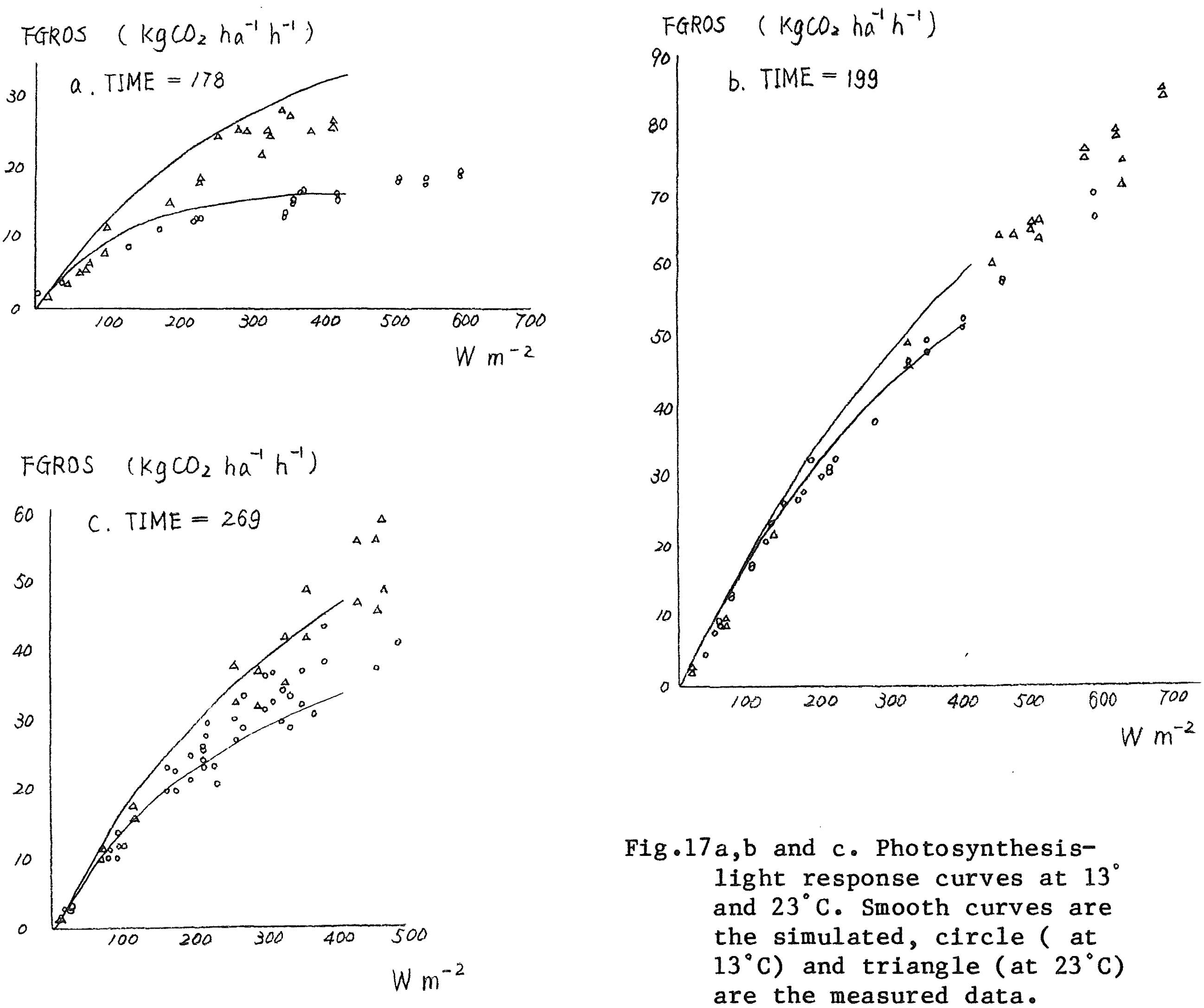


Fig.17a,b and c. Photosynthesis-light response curves at 13° and 23°C. Smooth curves are the simulated, circle (at 13°C) and triangle (at 23°C) are the measured data.

8. CONCLUSION

a. By using the model presented in this paper, it is possible to simulate(above-ground) plant dry matter production through estimation of the photosynthetic properties which are used as intermediate varibales in the model.

b. The effect of varying temperatures on canopy CO2 assimilation is different in three periods. During the 1st period,FOT and RD are larger under higher temperature. During the 2nd period,FOT are almost the same under 13°and 23°C, but RD are about doubled at 23°C. In the 3rd period, difference between FOT values under 13°and 23°C are increasingly more significant, and RD changes similarily as that in the 2nd period.

c. When -10% of each variable accordingly, the largest influence on final output of the model is less than 1.1 and the smallest is 0.12. The order of the sensitivity of the variables is: CRAD, EPS, LAI, RRESP, RD, FM, T and COLB.

d. Improving SUCROS by modifying maximum gross assimilation into a functoin of temperature and of time, the output are greatly improved.

9. REFERENCES

Wit, C.T. de et al., 1978. Simulation of assimilation, respiration and and transpiration of crops. Simulation Monopraphs. Pudoc, Wageningen, 140 pp.

Penning de Vries, F.W.T., & H.H. van Laar et al., 1982. Simulation of plant growth and crop production. Eds. Pudoc, Wageningen, 307 pp.

Goudriaan, J., 1985. In Annual Report CABO, Wageningen.

Louwerse, W. & J.W. Eikhoudt, 1975. A mobile laboratory for measuring photosynthesis,respiration and transpiration of field crops. Photosynthetica 9, 31-34.

Goudriaan, J., 1985. A simple and fast numerical method for the computation of daily totals of crop photosynthesis. Accepted by Agric and Forest Meteor.

Goudriaan, J., 1985. Elements of simulation in crop physiolopy. Lecture notes.

Heuvelink, E., 1984. ELGRO. Pudoc, Wageningen, 49 pp.

Kraalingen, D.v, 1986.

10. APPENDIX

Appendix1: MAIZE

Appendix2: SUCROS

```
TITLE  DRY WEIGHT PRODUCTION OF MAIZE(1985)

INITIAL

*----------------------------------------------------------------------
*  The transperent rate of chamber material to solar radiation
*  and latitude
*----------------------------------------------------------------------

      PARAM TRANSM=0.85
      PARAM LAT=52.

*----------------------------------------------------------------------
*  Initial plant weight ( Kg/Ha )
*----------------------------------------------------------------------

      INCON TWTI=491.

DYNAMIC

*----------------------------------------------------------------------
*  Integration of total dry matter weight ( TWT in Kg/Ha ) ,above
*  ground dry matter weight ( TWT1 in Kg/Ha )
*----------------------------------------------------------------------

      TWT=INTGRL(TWTI,GTW)
      TWT1=0.8*TWT+0.2*COLB

*----------------------------------------------------------------------
*  Daily average air temperature T ,daily total radiation
*  DGRAD and measured leaf area index LAI from the fields
*----------------------------------------------------------------------

      T=AFGEN(DATT,TIME)
      DGRAD=AFGEN(DGRADT,TIME)
      LAI=AFGEN(LAIT,TIME)

*----------------------------------------------------------------------
*  Dry matter growth rate of both root and shoot and root respiration
*  rate ( RRESP in KgCO2/HaDay )
*----------------------------------------------------------------------

      GTW=(DFN-(24.-DAYL)*RD-24.*RRESP)*(30./44.)*(40./45.)
      RRESP=0.05*(FM*(1.-EXP((-EPS*800.)/FM))-RD)

*----------------------------------------------------------------------
*  Call subroutine TIAN to compute the daylength DAYL and daily total
*  "SININT" of SINB*(1.+0.4*SINB) in hour
*----------------------------------------------------------------------

      DAYL,SININT,SINLD,COSLD=TIAN (TIME,LAT)

*----------------------------------------------------------------------
*  Call subroutine GUANG to calculate daily total net canopy CO2
*  assimilation of daytime
*----------------------------------------------------------------------

      EPS,FM,RD,DFN=GUANG (DAYL,TIME,LAI,TRANSM,TEF,T1,TE,TE1,TR,TR1,...
                           TEM,TEE,TEFF,SINLD,COSLD,DGRAD,SININT)
```

```
*---------------------------------------------------------------------
*  Temperature cofficient for calculating crop photosynthetic
*  properties FM, RD and EPS
*---------------------------------------------------------------------

      TEF =AFGEN(TEFT,T)
      TEE =AFGEN(TEEFT,T)
      TEFF=AFGEN(TEFFT,T)
      T1  =AFGEN(TT,T)
      TE  =AFGEN(TET,T)
      TE1 =AFGEN(TE1T,T)
      TR  =AFGEN(TRT,T)
      TR1 =AFGEN(TR1T,T)
      TEM =AFGEN(TEMT,T)

*---------------------------------------------------------------------
*  Measured above-ground dry matter weight TWTFI and colb in the fields
*---------------------------------------------------------------------

      TWTFI=AFGEN(TWTFIT,TIME)
      COLB=AFGEN(COLBT,TIME)

*---------------------------------------------------------------------
*  Simulation run specifications
*---------------------------------------------------------------------

      TIMER TIME=169.,FINTIM=289.,DELT=1.,PRDEL=1.,OUTDEL=1.
      METHOD RECT
      PRINT TWT1,TWTFI,DFN,FM,RD,RRESP,GTW,LAI,DAYL,EPS,T
      OUTPUT TWT1,TWTFI

*---------------------------------------------------------------------
*  The values of each function:
*  TT,TET,TE1T,TRT,TR1T and TEMT are temperature cofficents for
*  calculating FM as function of daily average air temperature;
*  TEFT,TEEFT and TEFFT are temperature cofficents for calculating RD
*  as function of daily average air temperature;
*  LAIT is leaf area index as function of time;
*  TWTFIT and COLBT are the measured above-ground dry matter weight
*  and colb dry weight separately;
*  DATT is daily average air temperature as function of time;
*  DGRAD is daily total global radiation ( in J/CM2 ).
*---------------------------------------------------------------------

FUNCTION TT   =5.,6.1,    13.,11.6,  23.,29.27

FUNCTION TET  =5.,40.1,   13.,66.67, 23.,80.

FUNCTION TE1T =5.,13.12,  13.,24.,   23.,60.

FUNCTION TRT  =5.,-46.44,13.,-71.77,23.,-100.

FUNCTION TR1T =5.,68.,    13.,124.,  23.,180.

FUNCTION TEMT =5.,11.25,  13.,30.16, 23.,44.26

FUNCTION TEFT =5.,0.,     13.,1.,    23.,2.11

FUNCTION TEEFT=5.,0.,     13.,0.9,   23.,1.5

FUNCTION TEFFT=5.,0.,     13.,1.4,   23.,3.7
```

```
FUNCTION LAIT=156.,0.42,169.,0.84,185.,1.8,199.,2.9,213.,4.,...
     227.,3.9,241.,3.7,255.,3.9,269.,3.3,281.,2.6,289.,2.4

FUNCTION DATT=168.,11.6,169.,14.3,170.,14.8,171.,13.2,172.,14.4,173.,...
     14.4,174.,13.4,175.,14.8,176.,14.4,177.,12.3,178.,12.3,179.,13.4,...
     180.,13.7,181.,16.,182.,16.1,183.,15.7,184.,18.3,185.,21.5,...
     186.,22.3,187.,17.1,188.,14.6,189.,14.4,190.,15.9,191.,14.3,...
     192.,16.5,193.,18.6,194.,22.1,195.,22.5,196.,16.6,197.,15.3,...
     198.,17.2,199.,17.7,200.,15.5,201.,14.9,202.,14.2,203.,15.3,...
     204.,16.6,205.,17.5,206.,20.9,207.,18.7,208.,17.4,209.,18.3,...
     210.,15.9,211.,15.5,212.,15.3,213.,14.6,214.,15.2,215.,15.,...
     216.,13.9,217.,15.2,218.,13.6,219.,14.5,220.,16.3,221.,19.2,...
     222.,14.1,223.,15.6,224.,15.7,225.,18.,226.,19.3,227.,16.,...
     228.,15.1,229.,13.2,230.,14.9,231.,16.3,232.,16.7,233.,17.2,...
     234.,16.1,235.,15.3,236.,14.8,237.,13.5,238.,12.5,239.,14.2,...
     240.,16.1,241.,18.4,242.,19.2,243.,17.,244.,15.,245.,15.1,...
     246.,14.5,247.,13.9,248.,13.7,249.,10.4,250.,11.2,251.,12.6,...
     252.,11.3,253.,12.4,254.,15.5,255.,16.5,256.,13.6,257.,12.,...
     258.,13.1,259.,12.6,260.,16.3,261.,16.,262.,17.6,263.,15.5,...
     264.,17.,265.,16.2,266.,15.3,267.,13.8,268.,13.5,269.,14.2,...
     270.,13.2,271.,12.8,272.,13.1,273.,15.4,274.,17.6,275.,17.6,...
     276.,19.1,277.,16.2,278.,13.9,279.,14.5,280.,15.1,281.,10.8,...
     282.,11.3,283.,13.3,284.,14.3,285.,10.1,286.,7.90,287.,11.3,...
     288.,12.5,289.,11.9,290.,12.0,291.,11.2,292.,9.40,293.,7.80,...
     294.,8.30,295.,7.60,296.,8.60,297.,8.10,298.,5.70,299.,4.10,...
     300.,2.30,301.,6.30,302.,6.00,303.,4.00,304.,2.8

FUNCTION DGRADT=166.,1892.,167.,1784.,168.,1579.,169.,1804.,...
     170.,1028.,171.,719.,172.,1383.,173.,1387.,174.,1326.,...
     175.,1525.,176.,1672.,177.,679.,178.,1467.,...
     179.,910.,180.,683.,181.,2070.,182.,1522.,...
     183.,2056.,184.,2672.,185.,2598.,186.,2303.,187.,1661.,...
     188.,1922.,189.,1359.,190.,1363.,191.,1144.,192.,1918.,...
     193.,1861.,194.,2432.,195.,1820.,196.,1956.,197.,849.,198.,1976.,...
     199.,1364.,200.,1046.,201.,1629.,202.,2204.,203.,422.,204.,1778.,...
     205.,2389.,206.,2246.,207.,573.,208.,1695.,209.,976.,210.,1225.,...
     211.,456.,212.,993.,213.,907.,214.,967.,215.,1476.,216.,1143.,...
     217.,1023.,218.,1870.,219.,1640.,220.,1819.,...
     221.,1594.,222.,1117.,223.,1698.,224.,2142.,225.,2073.,...
     226.,1487.,227.,1590.,228.,1456.,229.,763.,230.,1641.,...
     231.,884.,232.,1109.,233.,1715.,234.,991.,235.,1077.,...
     236.,502.,237.,1567.,238.,840.,239.,1894.,240.,1875.,...
     241.,1640.,242.,1737.,243.,631.,244.,1189.,245.,1103.,...
     246.,869.,247.,897.,248.,584.,249.,1531.,250.,1136.,...
     251.,574.,252.,1294.,253.,1438.,254.,1068.,255.,1397.,...
     256.,489.,257.,848.,258.,1244.,259.,629.,260.,276.,...
     261.,740.,262.,1299.,263.,472.,264.,871.,265.,441.,...
     266.,835.,267.,855.,268.,928.,269.,1059.,270.,1207.,...
     271.,633.,272.,1318.,273.,1094.,274.,1176.,275.,797.,...
     276.,686.,277.,761.,278.,1085.,279.,1039.,280.,489.,...
     281.,593.,282.,417.,283.,661.,284.,316.,285.,847.,...
     286.,1082.,287.,615.,288.,322.,289.,313.,290.,296.,291.,186.,...
     292.,642.,293.,952.,294.,945.,295.,851.,296.,845.,297.,754.,...
     298.,817.,299.,754.,300.,234.,301.,362.,302.,233.,303.,212.,...
     304.,145.

FUNCTION TWTFIT=156.,147.2,169.,392.7,185.,1275.,199.,4110.,213.,...
      6775.,227.,9040.,241.,11535.,255.,12825.,271.,14718.,281.,...
      15170.,289.,15388.
```

```
FUNCTION COLBT=168.,0.,210.,0.,213.,439.,227.,1496.,244.,...
    3436.,255.,5790.,269.,7653.,282.,8828.,289.,9600.

END
STOP

*------------------------------------------------------------------
*  Subroutine TIAN:
*------------------------------------------------------------------

      SUBROUTINE TIAN (TIME,LAT,DAYL,SININT,SINLD,COSLD)
      IMPLICIT REAL (A-Z)

*  Conversion from degrees to radians

      PI=3.1415926
      RAD=PI/180.

*  Declination "DEC" of the sun in degrees

      DEC=-23.45*COS(PI*(TIME+10.)/183.)
      SINLD=SIN(RAD*LAT)*SIN(RAD*DEC)
      COSLD=COS(RAD*LAT)*COS(RAD*DEC)
      AOB=SINLD/COSLD

*  Daylength DAYL and daily total SININT

      DAYL=12.*(1.+2.*ASIN(AOB)/PI)
      SININT=DAYL*(SINLD+0.4*(SINLD*SINLD+COSLD*COSLD*0.5))+
     $       12.*COSLD*(2.+3.*0.4*SINLD)*SQRT(1.-AOB*AOB)/PI

      RETURN
      END

*---------------------------------------------------------------------
*  Subroutine GUANG calculate daily total net CO2 assimilation of
*  daytime by using Ganssian three-point integration
*---------------------------------------------------------------------

      SUBROUTINE GUANG (DAYL,TIME,LAI,TRANSM,TEF,T1,TE,TE1,TR,TR1,TEM,
     $                  TEE,TEFF,SINLD,COSLD,DGRAD,SININT,EPS,FM,RD,DFN)
      IMPLICIT REAL (A-Z)
      INTEGER I

      PI=3.1415926

*  Initial light use effidiency EPS in KgCO2/J/CM2 SEC

      EPS=0.048*LAI/TRANSM

*  Dark respiration is related to leaf area index and temperature
*  Maximum gross assimilation rate FM varies with leaf area index
*  and temperature
```

```
      L1=LAI-2.05
      L2=LAI-3.55
      IF (TIME.LE.234.) THEN
         RD=LAI*TEF
         IF (LAI.LE.2.05) FM=T1*LAI
         IF (LAI.GT.2.05.AND.LAI.LE.3.55) FM=TE*L1+TE1
         IF (LAI.GT.3.55) FM=TR*L2+TR1
      ELSE
         FM=TEM*(LAI-0.95)
         RD=LAI*TEE+TEFF
      ENDIF

*  Daily total net CO2 assimilation of daytime set at zero

      DFN=0.
      DO I=1,3
      HOUR=DAYL*(0.5+(I-2)*SQRT(0.15))*0.5+12.

*  Calculate global radiation of three different time of the day,
*  Sine "SINB" of solar elevation

      SINB=AMAX1(0.,SINLD+COSLD*COS(2.*PI*(HOUR+12.)/24.))
      SFF=SINB*(1.+0.4*SINB)

*  Global radiation CRAD derived from daily total radiation DGRAD

      CRAD=10000.*SFF*DGRAD/(SININT*3600.)

*  Integration of DFN in KgCO2/HaDay

      FOT=FM*(1.-EXP((-EPS*CRAD)/FM))-RD
      IF(I.EQ.2) FOT=FOT*1.6
      DFN=DFN+FOT
      ENDDO
      DFN=DFN*DAYL/3.6

      RETURN
      END

ENDJOB
```

```
TITLE SUCROS - A SIMPLE AND UNIVERSAL CROP GROWTH SIMULATOR

*-------------------------------------------------------------------
* Initial part:
* setting of latitude, photosynthesis parameters, maintenance
* coefficients, growth respiration parameters and initial
* plant weights.
*-------------------------------------------------------------------

INITIAL

*-------------------------------------------------------------------
* Photosynthesis parameters and latitude
*-------------------------------------------------------------------

      PARAM EFF=0.5
      PARAM LAT=52.
      PARAM MULCON=1.E4

*-------------------------------------------------------------------
* Maintenance respiration parameters
*-------------------------------------------------------------------

      PARAM Q10=2.
      PARAM REFTMP=25.
      PARAM MAINLV=0.03
      PARAM MAINST=0.015
      PARAM MAINRT=0.01
      PARAM MAINSO=0.01

*-------------------------------------------------------------------
* Growth respiration parameters
*-------------------------------------------------------------------

      PARAM ASRQLV=1.39
      PARAM ASRQST=1.45
      PARAM ASRQRT=1.39
      PARAM ASRQSO=1.37
      PARAM ASRQRE=1.00

*-------------------------------------------------------------------
* Specific leaf area (HA/KG) and initial plant weights (KG/HA)
*-------------------------------------------------------------------

      INCON WLVI=270.
      INCON WSTI=122.7
      INCON WRTI=235.
      INCON WSOI=0.
      INCON WREI=0.

*-------------------------------------------------------------------
* Dynamic part
*-------------------------------------------------------------------
```

```
DYNAMIC

*------------------------------------------------------------------
* Integrals:
* integration of growth rates of leaves, stems, roots, and storage
* organs and integration of death rate of leaves and development rate
*------------------------------------------------------------------

      WLV = INTGRL(WLVI,GLV-DLV)
      WST = INTGRL(WSTI,GST)
      WRT = INTGRL(WRTI,GRT)
      WSO = INTGRL(WSOI,GSO)
      WRE = INTGRL(WREI,GRE-DRE)
      WLVD= INTGRL(0.,DLV)
      LAI = AFGEN(LAIT,DAY)
      DVS = INTGRL(0.,INSW(DVS-1.,DVRV,DVRR))
      FINISH DVS = 3.

*------------------------------------------------------------------
* The subroutine ASTRO is called to compute the photoperiodic and
* normal daylength (DAYLP and DAYL)
*------------------------------------------------------------------

      DAY = AMOD(TIME,365.)
      DAYL,DAYLP,SINLD,COSLD=ASTRO (DAY,LAT)

*------------------------------------------------------------------
*  Average daily temperature and daily total irradiation
*------------------------------------------------------------------

      TMPA  = AFGEN(DATT,DAY)
      AVRAD = MULCON*AFGEN(DGRADT,DAY)

*------------------------------------------------------------------
* Development rate for vegetative and reproductive growth phase
*------------------------------------------------------------------

      DVRV = 0.0252*AFGEN(DVRVTT,TMPA)*AFGEN(DVRVDT,DAYLP)
      DVRR = 0.0477*AFGEN(DVRRTT,TMPA)

*------------------------------------------------------------------
* Subroutine TOTASS computes daily total gross assimilation (DTGA)
*------------------------------------------------------------------

      DTGA,FRDIF=TOTASS (DAY,DAYL,AMAX,EFF,LAI,AVRAD,SINLD,COSLD)

*------------------------------------------------------------------
* Conversion from CO2 to CH2O
*------------------------------------------------------------------

      GPHOT=DTGA*30./44.

*------------------------------------------------------------------
* Maximum gross CO2 assimilation rate is function of temperature
* and time
*------------------------------------------------------------------

      AMAX = (TMPA-13.)*(FM23-FM13)/10.+FM13
      FM23 = AFGEN(FM23T,DAY)
      FM13 = AFGEN(FM13T,DAY)
```

```
*-----------------------------------------------------------------------
* Maintenance respiration
*-----------------------------------------------------------------------

      TEFF  =Q10**((TMPA-REFTMP)/10.)
      MAINTS=WLV*MAINLV+WST*MAINST+WRT*MAINRT+WSO*MAINSO
      MAINT =AMIN1(GPHOT,MAINTS*TEFF)

*-----------------------------------------------------------------------
* Fraction of dry matter growth occurring in shoots, leaves, stems,
* root and storage organ.
*-----------------------------------------------------------------------

      FSH = AFGEN(FSHT,DVS)
      FLV = AFGEN(FLVT,DVS)
      FST = AFGEN(FSTT,DVS)
      FRE = AFGEN(FRET,DVS)
      FRT = 1.-FSH
      FSO = 1.-FLV-FST

*-----------------------------------------------------------------------
* Assimilate requirements for dry matter conversion (KG CH2O/KG DM)
*-----------------------------------------------------------------------

      ASRQ = FSH*(FLV*ASRQLV+FST*ASRQST+FSO*ASRQSO)...
             +FRT*ASRQRT

*-----------------------------------------------------------------------
* Available assimilates for growth
*-----------------------------------------------------------------------

      AVASS = GPHOT-MAINT

*-----------------------------------------------------------------------
* Growth rates of roots and shoots (leaves, stems, storage organs)
* in KG DM/HA/DAY
*-----------------------------------------------------------------------

      GSH = FSH*AVASS/ASRQ
      GLV = FLV*GSH
      GST = FST*GSH
      GRT = FRT*AVASS/ASRQ
      GSO = FSO*GSH
      GRE = FRE*GSH

*-----------------------------------------------------------------------
* Dry matter growth rate of all organs combined, KG DM/HA/D
*-----------------------------------------------------------------------

      GTW = GSH+GRT-DLV

*-----------------------------------------------------------------------
* Death rate of leaves, in KG/HA/DAY
*-----------------------------------------------------------------------

      RDRLV = AFGEN(RDRLVT,DVS)
      DLV = WLV*RDRLV

*-----------------------------------------------------------------------
* Procedure calculates death rate of reserves (DRE)
*-----------------------------------------------------------------------
```

```
      PROCEDURE DRE=RES(SWITCH,DVS)

      IF (WRE.GT.0) THEN
         IF (DVS.GT.1.1.AND.SWITCH.EQ.0.) THEN
           SWITCH=1.
           DREDVS=WRE/(1.3-1.1)
         ENDIF
      ELSE
         DREDVS=0.
      ENDIF
      DRE=DREDVS*DVRR

      ENDPROCEDURE

*----------------------------------------------------------------------
* Simulation run specifications
*----------------------------------------------------------------------

      TIMER TIME=169., FINTIM=289., DELT=1., PRDEL=1., OUTDEL=1.
      METHOD RECT
      PRINT WLV,WLVD,WST,WSO,WRT,LAI,DVS,MAINT,DTGA,AMAX,ASRQ,...
            SWITCH,FSO,FLV,FSH,FRT,FST,DAYL,DAYLP,SINLD,COSLD
            SHOOT=WLV+WST+WSO+WLVD
      OUTPUT SHOOT

*----------------------------------------------------------------------
* Here, the values of the different functions are given
*  FM23:   maximum gross CO2 assimilation at temperature 23 C as
*          function of time
*  FM13:   maximum gross CO2 assimilation at temperature 13 C as
*          function of time
*  DATT:   daily average air temperature
*  RDRLVT: relative death rate of leaves as function of development
*          stage (DVS)
*  FSHT:   fraction of DM growth allocated to shoots as function of
*          development stage
*  FLVT:     ,,    ,, ,,   ,,      ,,     ,, leaves as function of
*          development stage
*  FSTT:     ,,    ,, ,,   ,,      ,,     ,, storage organs as
*          function of development stage
*  FRET:     ,,    ,, ,,   ,,      ,,     ,, reserves as
*          function of development stage
*  DVRVTT: development rate as function of average
*          temperature (TMPA)
*  DVRVDT: development rate as function of photoperiodic
*          daylength (DAYLP)
*  DVRRTT: development rate as function of average
*          temperature (TMPA)
*  LAIT:   leaf area index as function of day number
*  DGRADT: daily total global radiation (in MJ/m2/d) as
*          function of day number
*----------------------------------------------------------------------


      FUNCTION FM23T = 169.,23.8,185.,24.8,199.,51.4,...
                       213.,42.1,227.,33.8,241.,32.1,255.,33.8,...
                       269.,27.6,282.,18.75,296.,10.

      FUNCTION FM13T = 169.,10.2,185.,16.,199.,35.4,...
                       213.,25.,227.,24.3,241.,23.8,255.,25.,...
                       269.,15.,282.,13.4,296.,2.1
```

```
FUNCTION RDRLVT = 0.,0., 1.,0., 1.01,0.03, 2.,0.03, 3.,0.03

FUNCTION FSHT = 0.,0.606, 0.19,0.708, 0.4,0.8, 0.6,0.868,...
                0.8,0.93, 1.,1., 2.,1., 3.,1.

FUNCTION FLVT = 0.,0.671, 0.2,0.653, 0.4,0.606, 0.45,0.563,...
                0.6,0.437, 0.8,0.183, 1.,0.,...
                2.,0., 3.,0.

FUNCTION FSTT = 0.,0.329, 0.2,0.347, 0.4,0.394, 0.45,0.437,...
                0.6,0.563, 0.8,0.817, 1.,1.,...
                1.01,0., 2.,0., 3.,0.

FUNCTION FRET = 0.,0., 0.45,0., 0.8,0., 0.85,0., 1.,0.,...
            1.001,0., 3.,0.

FUNCTION DVRVTT = 10.,0.63, 15.,0.83, 20.,0.92, 25.,0.96,...
                  30.,0.98, 35.,0.99

FUNCTION DVRVDT = 10.,0.223, 11.,0.425, 12.,0.575, 13.,0.685,...
                  14.,0.767, 15.,0.828, 16.,0.872, 17.,0.906,...
                  18.,0.926

FUNCTION DVRRTT = 10.,0.08, 15.,0.38, 20.,0.575, 25.,0.71,...
                  30.,0.80, 35.,0.865

FUNCTION LAIT=156.,0.42,169.,0.84,185.,1.8,199.,2.9,213.,...
   4.,226.,3.9,241.,3.7,255.,3.9,271.,3.3,281.,2.6,289.,2.4
FUNCTION DATT=168.,11.6,169.,14.3,170.,14.8,171.,13.2,172.,...
   14.4,173.,14.4,174.,...
   13.4,175.,14.8,176.,14.4,177.,12.3,178.,12.3,179.,13.4,...
   180.,13.7,181.,16.,182.,16.1,183.,15.7,184.,18.3,185.,21.5,...
   186.,22.3,187.,17.1,188.,14.6,189.,14.4,190.,15.9,191.,14.3,...
   192.,16.5,193.,18.6,194.,22.1,195.,22.5,196.,16.6,197.,15.3,...
   198.,17.2,199.,17.7,200.,15.5,201.,14.9,202.,14.2,203.,15.3,...
   204.,16.6,205.,17.5,206.,20.9,207.,18.7,208.,17.4,209.,18.3,...
   210.,15.9,211.,15.5,212.,15.3,213.,14.6,214.,15.2,215.,15.,...
   216.,13.9,217.,15.2,218.,13.6,219.,14.5,220.,16.3,221.,19.2,...
   222.,14.1,223.,15.6,224.,15.7,225.,18.,226.,19.3,227.,16.,...
   228.,15.1,229.,13.2,230.,14.9,231.,16.3,232.,16.7,233.,17.2,...
   234.,16.1,235.,15.3,236.,14.8,237.,13.5,238.,12.5,239.,14.2,...
   240.,16.1,241.,18.4,242.,19.2,243.,17.,244.,15.,245.,15.1,...
   246.,14.5,247.,13.9,248.,13.7,249.,10.4,250.,11.2,251.,12.6,...
   252.,11.3,253.,12.4,254.,15.5,255.,16.5,256.,13.6,257.,12.,...
   258.,13.1,259.,12.6,260.,16.3,261.,16.,262.,17.6,263.,15.5,...
   264.,17.,265.,16.2,266.,15.3,267.,13.8,268.,13.5,269.,14.2,...
   270.,13.2,271.,12.8,272.,13.1,273.,15.4,274.,17.6,275.,17.6,...
   276.,19.1,277.,16.2,278.,13.9,279.,14.5,280.,15.1,281.,10.8,...
   282.,11.3,283.,13.3,284.,14.3,285.,10.1,286.,7.90,287.,11.3,...
   288.,12.5,289.,11.9,290.,12.0,291.,11.2,292.,9.40,293.,7.80,...
   294.,8.30,295.,7.60,296.,8.60,297.,8.10,298.,5.70,299.,4.10,...
   300.,2.30,301.,6.30,302.,6.00,303.,4.00,304.,2.8
FUNCTION DGRADT=166.,1892.,167.,1784.,168.,1579.,169.,1804.,...
   170.,1028.,171.,719.,172.,1383.,173.,1387.,174.,1326.,...
   175.,1525.,176.,1672.,177.,679.,178.,1467.,...
   179.,910.,180.,683.,181.,2070.,182.,1522.,...
   183.,2056.,184.,2672.,185.,2598.,186.,2303.,187.,1661.,...
   188.,1922.,189.,1359.,190.,1363.,191.,1144.,192.,1918.,...
   193.,1861.,194.,2432.,195.,1820.,196.,1956.,197.,849.,198.,...
   1976.,199.,1364.,200.,1046.,...
   201.,1629.,202.,2204.,203.,422.,204.,1778.,205.,2389.,...
   206.,2246.,207.,573.,208.,1695.,209.,976.,210.,1225.,...
   211.,456.,212.,993.,213.,907.,214.,967.,215.,1476.,216.,...
   1143.,217.,1023.,218.,1870.,219.,1640.,220.,1819.,...
```

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          221.,1594.,222.,1117.,223.,1698.,224.,2142.,225.,2073.,...
          226.,1487.,227.,1590.,228.,1456.,229.,763.,230.,1641.,...
          231.,884.,232.,1109.,233.,1715.,234.,991.,235.,1077.,...
          236.,502.,237.,1567.,238.,840.,239.,1894.,240.,1875.,...
          241.,1640.,242.,1737.,243.,631.,244.,1189.,245.,1103.,...
          246.,869.,247.,897.,248.,584.,249.,1531.,250.,1136.,...
          251.,574.,252.,1294.,253.,1438.,254.,1068.,255.,1397.,...
          256.,489.,257.,848.,258.,1244.,259.,629.,260.,276.,...
          261.,740.,262.,1299.,263.,472.,264.,871.,265.,441.,...
          266.,835.,267.,855.,268.,928.,269.,1059.,270.,1207.,...
          271.,633.,272.,1318.,273.,1094.,274.,1176.,275.,797.,...
          276.,686.,277.,761.,278.,1085.,279.,1039.,280.,489.,...
          281.,593.,282.,417.,283.,661.,284.,316.,285.,847.,286.,...
          1082.,287.,615.,288.,322.,289.,313.,290.,296.,291.,186.,...
          292.,642.,293.,952.,294.,945.,295.,851.,296.,845.,297.,...
          754.,298.,817.,299.,754.,300.,234.,301.,362.,302.,233.,...
          303.,212.,304.,145.

END
STOP

*-----------------------------------------------------------------------
* Subroutine ASTRO:
* Computation of daylength (DAYL) and photoperiodic daylength
* (DAYLP) from day number and latitude
*-----------------------------------------------------------------------

      SUBROUTINE ASTRO (DAY,LAT,DAYL,DAYLP,SINLD,COSLD)
      IMPLICIT REAL (A-Z)

*-----conversion factor from degrees to radians

      PI =3.1415926
      RAD=PI/180.

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

      DEC=-ASIN(SIN(23.45*RAD)*COS(2.*PI*(DAY+10.)/365.))

*-----SINLD, COSLD and AOB are intermediate variables

      SINLD=SIN(RAD*LAT)*SIN(DEC)
      COSLD=COS(RAD*LAT)*COS(DEC)
      AOB  =SINLD/COSLD

*-----daylength (DAYL) and photoperiodic daylength (DAYLP)

      DAYL =12.0*(1.+2.*ASIN(AOB)/PI)
      DAYLP=12.0*(1.+2.*ASIN((-SIN(-4.*RAD)+SINLD)/COSLD)/PI)

      RETURN
      END

*-----------------------------------------------------------------------
* Subroutine TOTASS:
* calculates daily total gross assimilation (DTGA) by performing
* a Gaussian integration over time. At three different times of
* the day, radiation is computed and used to determine assimilation
* whereafter integration takes place.
*-----------------------------------------------------------------------
```

```
      SUBROUTINE TOTASS (DAY,DAYL,AMAX,EFF,LAI,AVRAD,SINLD,COSLD,
     $                   DTGA,FRDIF)
      IMPLICIT REAL (A-Z)
      INTEGER IT

      PI=3.1415926

*-----assimilation set to zero and three different times of
*     the day (HOUR)

      DTGA=0.
      DO IT=-1,1
      HOUR=12.0+DAYL*0.5*(0.5+IT*SQRT(0.15))

*-----at the specified HOUR, radiation is computed and used to compute
*     assimilation

      CALL RADIAT (HOUR,DAY,DAYL,SINLD,COSLD,AVRAD,SINB,PARDIR,PARDIF)
      CALL ASSIM (AMAX,EFF,LAI,SINB,PARDIR,PARDIF,FGROS)

*-----integration of assimilation rate to a daily total (DTGA)

      IF (IT.EQ.0) FGROS=FGROS*1.6
      DTGA=DTGA+FGROS
      ENDDO
      DTGA=DTGA*DAYL/3.6

      RETURN
      END

*----------------------------------------------------------------------
* Subroutine RADIAT:
* computes diffuse and direct amount of photosynthetically active
* radiation from average global radiation (AVRAD), day of the year
* and hour of the day
*----------------------------------------------------------------------

      SUBROUTINE RADIAT (HOUR,DAY,DAYL,SINLD,COSLD,AVRAD,SINB,
     $                   PARDIR,PARDIF)
      IMPLICIT REAL (A-Z)
      PI=3.1415926

*-----sine of solar elevation (SINB), integral of SINB (DSINB)
*     and integral of SINB with correction for lower atmospheric
*     transmission at low solar elevations (DSINBE)

      AOB   =SINLD/COSLD
      SINB  =AMAX1(0.,SINLD+COSLD*COS(2.*PI*(HOUR+12.)/24.))
      DSINB =3600.*(DAYL*SINLD+24.*COSLD*SQRT(1.-AOB*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)

*-----solar constant (SC) and daily extraterrestrial radiation (DSO)

      SC =1370.*(1.+0.033*COS(2.*PI*DAY/365.))
      DSO=SC*DSINB

*-----diffuse light fraction (FRDIF) from atmospheric
*     transmission (ATMTR)

      ATMTR=AVRAD/DSO
      IF (ATMTR.GT.0.75) FRDIF=0.23
      IF (ATMTR.LE.0.75.AND.ATMTR.GT.0.35) FRDIF=1.33-1.46*ATMTR
      IF (ATMTR.LE.0.35.AND.ATMTR.GT.0.07) FRDIF=1.-2.3*(ATMTR-0.07)**2
      IF (ATMTR.LE.0.07) FRDIF=1.
```

```
*-----diffuse PAR (PARDIF) and direct PAR (PARDIR)

      PAR    =0.5*AVRAD*SINB*(1.+0.4*SINB)/DSINBE
      PARDIF=AMIN1(PAR,SINB*FRDIF*ATMTR*0.5*SC)
      PARDIR=AMAX1(0.1,PAR-PARDIF)

      RETURN
      END

*----------------------------------------------------------------------
* Subroutine ASSIM:
* performs a Gaussian integration over depth of canopy by
* selecting three different LAI's and computing assimilation at
* these LAI levels. The integrated variable is FGROS.
*----------------------------------------------------------------------

      SUBROUTINE ASSIM (AMAX,EFF,LAI,SINB,PARDIR,PARDIF,FGROS)
      IMPLICIT REAL (A-Z)
      INTEGER I

      KDIF=0.7155
      SCV =0.2
      REFV=(1.-SQRT(1.-SCV))/(1.+SQRT(1.-SCV))

*-----extinction coefficient for direct radiation and total
*     direct flux

      KDIRBL=(0.5/SINB)*KDIF/(0.8*SQRT(1.-SCV))
      KDIRT =KDIRBL*SQRT(1.-SCV)

*-----selection of depth of canopy, canopy assimilation
*     is set to zero

      FGROS=0.
      DO I=-1,1

      LAIC=LAI*0.5+LAI*I*SQRT(0.15)

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

      VISDF=(1.-REFV)*PARDIF*KDIF*EXP(-KDIF*LAIC)
      VIST =(1.-REFV)*PARDIR*KDIRT*EXP(-KDIRT*LAIC)
      VISD =(1.-SCV)*PARDIR*KDIRBL*EXP(-KDIRBL*LAIC)

*-----absorbed flux (J/M2 leaf/s) for shaded leaves and
*     assimilation of shaded leaves

      VISSHD=VISDF+VIST-VISD
      FGRSH =AMAX*(1.-EXP(-VISSHD*EFF/AMAX))

*-----direct flux absorbed by leaves perpendicular on
*     direct beam and assimilation of sunlit leaf area

      VISPP =(1.-SCV)*PARDIR/SINB
      FGRSUN =0.
      IF (VISPP.GT.0) FGRSUN=AMAX*(1.-(AMAX-FGRSH)*
     $             (1.-EXP(-VISPP*EFF/AMAX))/(EFF*VISPP))
```

```
*-----fraction sunlit leaf area (FSLLA) and local
*     assimilation rate (FGL)

      FSLLA=EXP(-KDIRBL*LAIC)
      FGL   =FSLLA*FGRSUN+(1.-FSLLA)*FGRSH

*-----integration of local assimilation rate to canopy
*     assimilation (FGROS)

      IF (I.EQ.0) FGL=FGL*1.6
      FGROS=FGROS+FGL
      ENDDO
      FGROS=FGROS*LAI/3.6

      RETURN
      END

ENDJOB
$
```

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No:

1 D. Barél, F. van Egmond, C. de Jonge, M.J.Frissel, M. Leistra, C.T. de Wit. 1969. Simulatie van de diffusie in lineaire, cylindrische en sferische systemen. Werkgroep: Simulatie van transport in grond en plant.

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