Simulation of crop growth for potential and water-limited production situations (as applied to spring wheat)

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Contents

Abstract

Two versions of the simulation model for crop growth, SUCROS (Simple and Universal CROp growth Simulator), are described, one for potential production (SUCROS) and one when water is limiting (SUCROS2).
The model is applied to spring wheat, with ample supply of nutrients, and without pests, diseases and weeds. Radiation and temperature (and precipitation in SUCROS2), being the most important environmental factors, and crop characteristics determine growth and development. Crop growth and development are simulated based on underlying chemical, physiological and physical processes. Dry matter accumulation is calculated from daily crop CO_2 assimilation based on leaf CO_2 assimilation and taking into account the respiration costs and allocation of carbohydrates to different plant parts.
Following the model listings, the statements are explained step by step.

In water-limited situations, the soil water balance is calculated according to the tipping-bucket system. The Penman.Monteith combination is used to calculate potential evapotranspiration.
To account for the effect of water shortage, potential daily total gross CO_2 assimilation of the crop is multiplied by the ratio between actual transpiration rate and potential transpiration rate. If this ratio becomes less than 0.5, at least during the vegetative phase, carbohydrate allocation is modified in favour of the roots.

1 Crop growth model for potential production (SUCROS1)

J. Goudriaan, H. van Keulen & H.H. van Laar

1.1 Introduction

Former versions of the simple and universal crop growth simulator SUCROS were described by van Keulen et al. (1982) and Spitters et al. (1989).

Crop growth is often described by empirical models, such as regression equations. Usually, environmental variables, such as radiation and rainfall, are incorporated in the regression, e.g. a simple approach is to relate total seasonal rainfall to yields measured at a given site or region (Le Houérou & Hoste, 1977; Lomas & Shashoua, 1974; Baier & Robertson, 1967). Such models can generate accurate yield predictions, provided the regression parameters are estimated on the basis of extensive sets of experimental data. The predictions, however, are restricted to the same environment and the same cultivar on which the regression is based. These empirical, descriptive models give, however, little insight in the causes of the observed variation in yields.

SUCROS1 is a mechanistic model that explains crop growth on the basis of the underlying processes, such as CO_2 assimilation and respiration, as influenced by environmental conditions. The predictive ability of mechanistic models does not always live up to expectations. It should be realized, however, that each parameter estimate and process formulation has its own inaccuracy, and that errors may accumulate in the prediction of final yield. However, yield prediction is a secondary aim of these models. Their primary aim is to increase insight in the system studied by quantitatively integrating the present knowledge in a dynamic simulation model. By studying the behaviour of the model, better insight in the real system is gained.

Crop growth can be limited by various factors, such as shortage of water, or nutrients, or reduced by pests and diseases. For this reason, different model versions have been developed to cope with the actual situation.

SUCROS1 simulates potential growth of a crop, i.e. its dry matter accumulation under ample supply of water and nutrients in a pest-, disease- and weed-free environment under the prevailing weather conditions. The rate of dry matter accumulation is a function of irradiation, temperature and crop characteristics. The basis for the calculation is the rate of CO_2 assimilation (photosynthesis) of the canopy. That rate is dependent on the radiant energy absorbed by the canopy, which is a function of incoming radiation and crop leaf area. From the absorbed radiation and the photosynthetic characteristics of individual leaves, the daily rate of gross CO_2 assimilation of the crop is calculated. These calculations are executed in a set of subroutines added to the model. For a detailed description, the reader is referred to Spitters (1986), Goudriaan (1986) and Spitters et al. (1986).

Part of the carbohydrates (CH_2O) produced is used to maintain the existing biomass. The remaining carbohydrates are converted into structural dry matter (plant organs). In the process of conversion, part of the weight is lost in growth respiration. The dry matter produced is partitioned among the various plant organs, using partitioning factors defined as a function of the phenological development stage of the crop. The dry weights of the plant organs are obtained by integration of their growth rates over time.

SUCROS1 requires as input physiological properties of the crop (in this case for spring wheat) and the actual weather conditions at the site, characterized by its geographical latitude, i.e. daily maximum and minimum temperatures and irradiation for each day of the year.

The crop growth models SUCROS1 and SUCROS2 (see Chapter 2) described here, are written in CSMP, Continuous System Modeling Program (IBM, 1975). The models can be executed on mainframe VAX computers and IBM PC-AT's, or compatibles (a PC version of IBM-CSMP, see Jansen et al., 1988). For SUCROS1, also a version in FORTRAN is available (van Kraalingen, 1991).

1.2 Initial conditions

```
INITIAL
PARAMETER DOYEM = 90.
INCON NPL       = 210.
INCON LA0       = 5.7E-5
INCON WLVI      = 0.
INCON WSTI      = 0.
INCON WRTI      = 0.
```

Usually, the model SUCROS1 starts at the moment of crop emergence (DOYEM), the number 90 representing the day of the year. The leaf area index at that moment is calculated in subroutine GLA (see explanation in Section 1.10) as the product of plant density (NPL, plants m^{-2}) and leaf area per plant at emergence (LA0, m^2 $plant^{-1}$). In the given example, plant density is set at 210 plants m^{-2}, and LA0 was measured at 5.7×10^{-5} m^2 $plant^{-1}$.

The initial amounts of dry matter in leaves (WLVI, kg DM ha^{-1}), stems (WSTI, kg DM ha^{-1}) and roots (WRTI, kg DM ha^{-1}) at emergence were not known. Model output is not sensitive to these values.

1.3 Crop development

```
DYNAMIC
  DVS   = INTGRL(0., DVR)
  DVR   = INSW(DVS - 1., AFGEN(DVRVT, DAVTMP),   ...
                         AFGEN(DVRRT, DAVTMP)) * EMERG
  EMERG = INSW(DOY - DOYEM, 0., 1.)
FUNCTION DVRVT = -10.,0.,  0.,0.,  30.,0.027
FUNCTION DVRRT = -10.,0.,  0.,0.,  30.,0.031
```

The pattern of dry matter distribution over the various plant organs is directly dependent on the phenological development stage of the crop. For many annual crops, the development stage

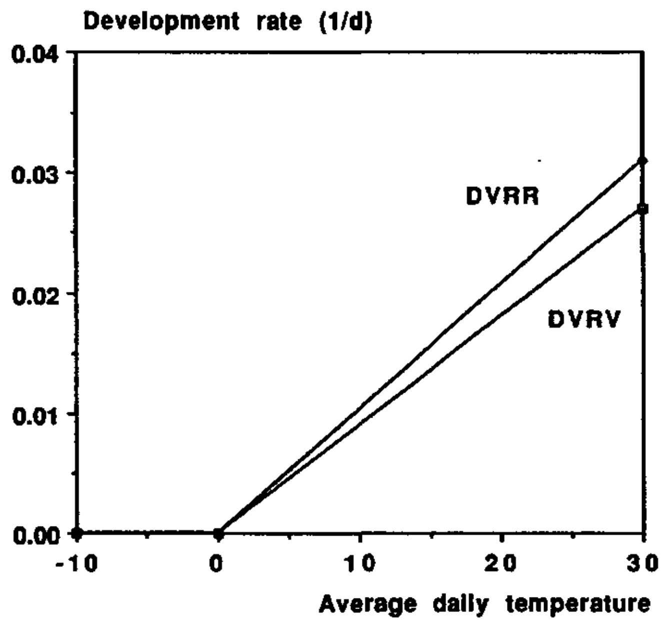


Figure 1.1. The development rate for pre-anthesis growth (DVRV, d^{-1}) and for post-anthesis growth (DVRR, d^{-1}) as a function of the average day temperature (DAVTMP, °C).

(DVS) can be conveniently expressed in a dimensionless variable, having the value 0 at seedling emergence, 1 at flowering and 2 at maturity. The development stage is calculated as the integral of the development rate (DVR, d^{-1}).

The development rate is calculated separately for the period from emergence till flowering (the pre-anthesis, DVRV), and the rate from flowering till maturity (the post-anthesis, grain filling, DVRR). Under temperate climatological conditions, temperature is the main environmental factor affecting the rate of development. So, DVRV and DVRR are defined as functions of average day temperature (DAVTMP, °C), as given in Figure 1.1.

Phenological development starts at seedling emergence. The factor EMERG equals 0 before emergence and 1 at after emergence.

1.4 Leaf CO_2 assimilation

```
   AMAX  = AMX * AMDVS * AMTMP
   AMDVS = AFGEN(AMDVST, DVS)
   AMTMP = AFGEN(AMTMPT, DDTMP)
PARAMETER AMX    = 40.
FUNCTION AMDVST = 0.,1., 1.,1., 2.,0.5, 2.5,0.0
FUNCTION AMTMPT = 0.,0.,10.,1.,25.,1., 35.,0., 50.,0.
```

The response of leaf CO_2 assimilation to light intensity is characterized by its slope at low light intensity and its maximum rate at light saturation (AMX, kg CO_2 ha^{-1} h^{-1}). The temperature effect (AMTMP) is a function of the average temperature during daytime (DDTMP, °C) as given in the function AMTMPT (Figure 1.2).

The value of AMX used in the model, refers to the assimilation capacity of full-grown leaves at the top of the canopy, as these leaves absorb most of the radiation. The maximum CO_2 assimilation capacity of leaves varies with crop species and cultivar. If no firmly based value of AMX is available, a value of 40 (kg CO_2 ha^{-1} h^{-1}) for C_3 species is, in general, a reasonable estimate.

The photosynthetic capacity of a leaf is also affected by its age: AMX reaches a maximum shortly after full expansion of the leaf, followed by a gradual decline with age (Rawson et al., 1983; Dwyer & Stewart, 1986). The effect of ageing of the canopy is introduced by a multiplication factor (AMDVS) defined as a function of the development stage. The shape of the function is given in Figure 1.3.

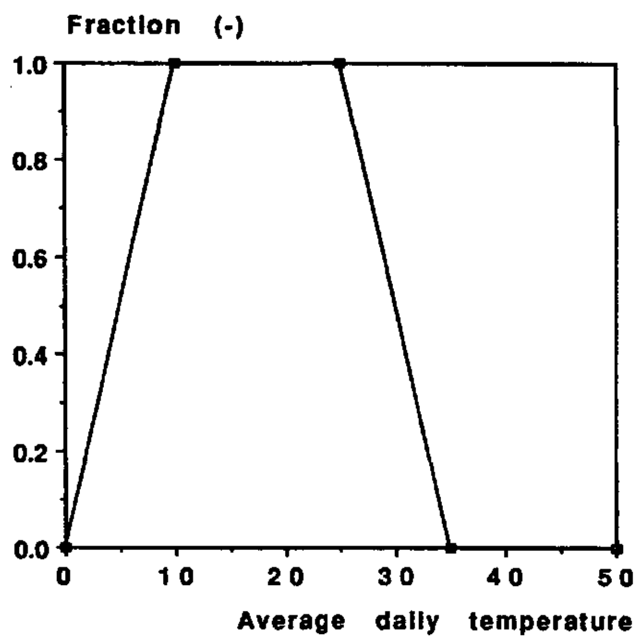


Figure 1.2. Multiplication factor for the effect of average daytime temperature (DDTMP, °C) on maximum leaf CO_2 assimilation (AMX).

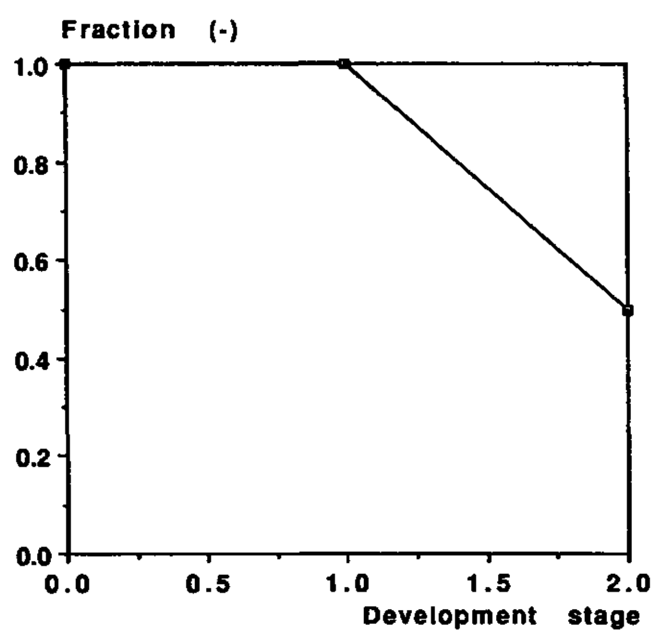


Figure 1.3. Multiplication factor for the effect of development stage (DVS) on maximum leaf CO_2 assimilation (AMX).

1.5 Daily gross CO_2 assimilation

```
   DAYL,DTGA,DSO = TOTASS(DOY,LAT,DTR,SCP,AMAX,EFF,KDF,LAI)
 PARAMETER EFF = 0.45
 PARAMETER KDF = 0.60
 PARAMETER SCP = 0.20
 PARAMETER LAT = 52.
```

Daily gross crop CO_2 assimilation (DTGA, kg CO_2 ha^{-1} d^{-1}) is calculated from the photosynthetically active radiation (PAR, J m^{-2} s^{-1}) absorbed by the canopy and the CO_2 assimilation - light response of individual leaves. If radiation intensities averaged over the day and over the canopy were applied, daily canopy CO_2 assimilation would be seriously overestimated, because CO_2 assimilation responds to light intensity in a non-linear way. In the model, the temporal and spatial variation in radiation intensity over the leaves is, therefore, taken into account.

The computation is performed in the subroutine TOTASS. This routine makes use of the routines ASTRO and ASSIM. SUCROS1 can be applied without a thorough understanding of these subroutines. Three parameters used in these subroutines, EFF, KDF and SCP, have to be specified and were derived from the literature.

Detailed discussions are given by Spitters et al. (1986) for the calculation of the diffuse and direct radiation fluxes above the canopy, by Spitters (1986) for the calculation of assimilation rates from these fluxes, and by Goudriaan (1986) for the Gaussian integration method used to integrate assimilation rates over the canopy and over the day.

The only site characteristic required for the calculation of potential production is the latitude. In the given example, a latitude of 52° for the Netherlands was used.

1.6 Carbohydrate production

```
   GPHOT = DTGA * 30./44.
```

In the leaves, the absorbed CO_2 is reduced to carbohydrates (CH_2O) using the energy supplied by the absorbed light. For each kg of CO_2 absorbed, 30/44 kg of CH_2O is formed, the numerical values representing the molecular weights of CH_2O and CO_2, respectively.

1.7 Maintenance

```
   MAINT  = MAINTS * TEFF * MNDVS
   MAINTS = MAINLV*WLV +MAINST*WST +MAINRT*WRT +MAINSO*WSO
   MNDVS  = WLVG / (WLV + NOT(WLV))
   TEFF   = Q10**((DAVTMP - TREF) / 10.)
 PARAMETER Q10    = 2., TREF = 25.
 PARAMETER MAINLV = 0.03,  MAINST = 0.015
 PARAMETER MAINRT = 0.015, MAINSO = 0.01
```

Part of the carbohydrates formed is respired to provide energy for maintaining the existing biostructures. In the model, fixed coefficients (for a plant species dependent reference temperature) are used to calculate the maintenance requirements of the various organs (leaves, stems, roots and grains) of the crop. Higher temperatures accelerate the turnover rates in plant tissue and hence increase the costs of maintenance (TEFF). An increase in temperature of 10 °C, increases maintenance respiration by a factor 2 (Penning de Vries & van Laar, 1982). For Mediterranean species the reference temperature (TREF) is at 25 °C.

When the crop ages, its metabolic activity decreases and hence its maintenance requirements. This is mimicked in the model by assuming that maintenance respiration is proportional to the fraction of the accumulated leaf weight that is still green. The reduction factor, MNDVS, is also applied to maintenance respiration of the other organs as it is assumed that dying of stem tissue and roots proceeds simultaneously to dying of leaves.

1.8 Dry matter partitioning

```
   FSH = AFGEN(FSHTB, DVS)

   FRT = 1. - FSH
FUNCTION FSHTB = 0.00,0.50,  0.10,0.50,  0.20,0.60, ...
                 0.35,0.78,  0.40,0.83,  0.50,0.87, ...
                 0.60,0.90,  0.70,0.93,  0.80,0.95, ...
                 0.90,0.97,  1.00,0.98,  1.10,0.99, ...
                 1.20,1.00,  2.50,1.00

   FLV = AFGEN(FLVTB, DVS)
FUNCTION FLVTB = 0.00,0.65,  0.10,0.65,  0.25,0.70, ...
     0.50,0.50,  0.70,0.15,  0.95,0.00,  2.50,0.00

   FST = AFGEN(FSTTB, DVS)
FUNCTION FSTTB = 0.00,0.35,  0.10,0.35,  0.25,0.30, ...
     0.50,0.50,  0.70,0.85,  0.95,1.00,  1.05,0.00, 2.5,0.

   FSO = 1. - FLV - FST
```

The primary assimilates in excess of the maintenance costs are available for conversion into vegetative plant material. Occasionally, the combination of low radiation, high temperature and high biomass may cause a *shortage* rather than an *excess* of primary assimilates. For reasons of model simplicity and lack of empirical evidence, no alternative assimilate route was formulated for such a situation. This implies that structural plant material is then used to support maintenance. Partitioning over the various plant organs is described by fixed distribution factors, defined as a function of development stage. This partitioning occurs in two steps. Dry matter is first partitioned between shoots (FSH) and roots (FRT) (Figure 1.4), followed by

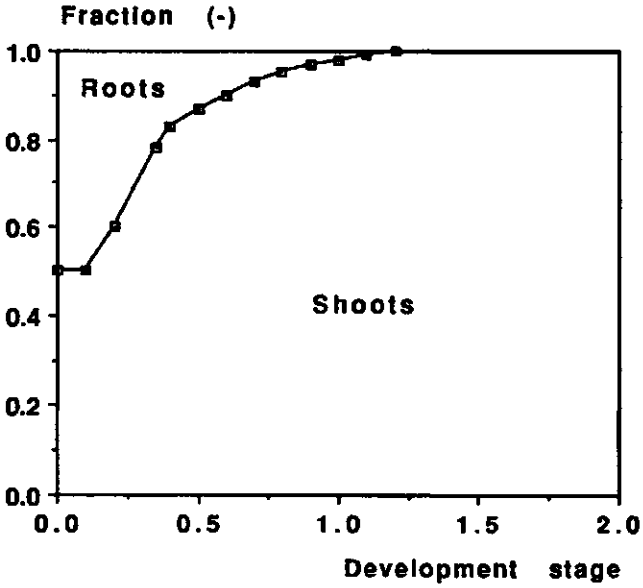


Figure 1.4. Distribution of dry matter (spring wheat) among shoot (FSH) and root (FRT) as a function of development stage (DVS).

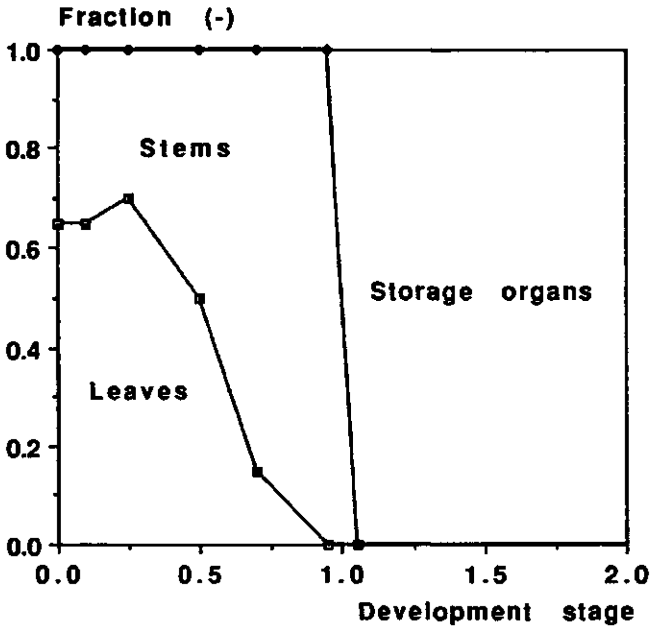


Figure 1.5. Distribution of dry matter (spring wheat) among leaves (FLV), stems (FST) and storage organs (FSO) as a function of development stage (DVS).

distribution of the shoot fraction among leaves (FLV), stems (FST) and storage organs (FSO). Distribution functions for spring wheat are given in Figure 1.5.

1.9 Growth of plant organs and translocation

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

TRANSL = INSW(DVS-1., 0., WST * DVR * FRTRL)
GTW    = (GPHOT-MAINT+0.947*TRANSL*CFST*30./12.)/ASRQ
GRT    = FRT  * GTW
```

```
    GLV    = FLV  * FSH * GTW
    GST    = FST  * FSH * GTW - TRANSL
    GSO    = FSO  * FSH * GTW

PARAMETER ASRQRT = 1.444,  ASRQLV = 1.463
PARAMETER ASRQST = 1.513,  ASRQSO = 1.415
PARAMETER FRTRL  = 0.20
```

The overall value of assimilate requirement for conversion of carbohydrates into dry matter (ASRQ, kg CH_2O kg^{-1} DM) for the crop as a whole is calculated as the weighted mean of the ASRQ's for the different plant organs. The assimilates required to produce a unit weight of a certain plant organ can be calculated from its chemical composition and the assimilate requirements of the various chemical compounds. Typical values for roots, leaves and stems are: 1.444, 1.463, and 1.513 kg CH_2O kg^{-1} dry matter, respectively. Storage organs (grains, tubers, etc.) vary too much in composition among species to give one general value for their assimilate requirement. For wheat grains, it is 1.415 kg CH_2O kg^{-1} dry matter (Penning de Vries & van Laar, 1982; Penning de Vries et al., 1989 (Table 11)). The growth rates of the various plant organs (kg dry matter ha^{-1} d^{-1}) are obtained by multiplying the overall growth rate by the fractions allocated to the various organs.

After anthesis, about 20% of the stem weight, assumed to consist of reserve carbohydrates (Spiertz & Ellen, 1978), is eventually translocated to the storage organs. The translocation rate (TRANSL, kg dry matter ha^{-1} d^{-1}) is introduced as a loss term in the rate of growth of stems (GST), and added to the assimilate flow that is available for growth (GTW). Upon conversion to structural dry matter, these assimilates are subject to losses due to growth respiration and, therefore, divided by the assimilate requirement factor ASRQ. No distinction is made between assimilates originating from current photosynthesis (GPHOT) and those derived from translocation. In addition, a small conversion loss occurs when stem reserves are remobilized presumably from starch to glucose (multiplication by a factor 0.947, Penning de Vries et al., 1989, pg 61). The rate of translocation depends directly on development rate, and is proportional to a factor FRTRL that expresses the fraction eventually translocated. The value of this factor should be determined by trial and error. It influences loss of stem weight in the grain filling period, and it will affect the final harvest index.

1.10 Leaf and ear development

```
    LAI  = 0.5 * EAI + INTGRL(0., GLAI - DLAI)
    GLAI = GLA(DOY, DOYEM, DTEFF, DVS, NPL, LA0, ...
               RGRL, DELT, SLA, LAI, GLV)
PARAMETER RGRL = 0.009
PARAMETER SLA  = 0.0022
```

The area of green leaves is the major determinant for light absorption and CO_2 assimilation of the crop, but in wheat 50% of the Ear Area Index (EAI) also contributes. The Leaf Area Index

(LAI, ha ha^{-1}) follows from the balance between growth rate (GLAI, ha ha^{-1} d^{-1}), and senescence rate (DLAI, ha ha^{-1} d^{-1}).

GLAI is calculated, in dependence of the phenological development stage, in the self-defined function GLA (see section Subroutines). Before seedling emergence (DOY < DOYEM), GLA equals zero. At emergence, GLA = (NPL*LA0)/DELT. After emergence, light intensity and temperature are the environmental factors influencing the rate of leaf area expansion.

During juvenile growth, temperature is the overriding factor, as the rate of leaf appearance and final leaf size are constrained by temperature through its effect on cell division and extension, rather than by the supply of assimilates. In these early stages, leaf area increases approximately exponentially over time. Examination of unpublished field data suggest that a safe approximation is to restrict the exponential phase to the situation where LAI < 0.75 and/or DVS < 0.3. Exponential leaf area development is described by:

```
LAI(t+DELT) = LAI(t) * EXP(RGRL * DTEFF * DELT)
```

so that the rate of increase in leaf area during juvenile growth is:

```
GLA = LAI(t+DELT) - LAI(t)
    = LAI(t) * (EXP(RGRL * DTEFF * DELT) - 1.)/DELT
```

in which LAI(t) is the current leaf area, RGRL is the relative growth rate of leaf area per degree-day ((°C $d)^{-1}$), DELT is the time step of integration (d) and DTEFF is the daily effective temperature (°C).

In later development stages, leaf area expansion is increasingly restricted by assimilate supply. Branching and tillering generate an increasing number of sites per plant where leaf initiation can take place and mutual shading of plants further reduces the assimilate supply per growing point. During this stage (LAI > 0.75 and DVS > 0.3), the model calculates the growth of leaf area by multiplying the simulated increase in leaf weight (GLV) by the specific leaf area of new leaves (SLA, ha kg^{-1}).

```
    EAI = INTGRL(0., REAI(DELT,DVS,EAR,TADRW,RDRDV,EAI))
PARAMETER EAR = 6.3E-5
```

The ear area index (EAI, ha ears (2 * one-sided projection) ha^{-1}) is set at zero for DVS < 0.8, and is calculated in the self-defined Fortran function REAI. At DVS = 0.8, EAI is set at a fixed proportion, the Ear Area Ratio (EAR, ha ear kg^{-1} dry matter) of the total above-ground dry matter (TADRW, kg ha^{-1})). Till DVS = 1.3, EAI remains at this value, and decreases thereafter.

```
DLAI   = LAI * RDR
RDR    = AMAX1(RDRDV, RDRSH)
RDRDV  = INSW(DVS - 1.0, 0., AFGEN(RDRT, DAVTMP))
RDRSH  = LIMIT(0., 0.03, 0.03 * (LAI - LAICR) / LAICR)
```

```
FUNCTION RDRT    = -10.,0.03, 10.,0.03, 15.,0.04, 30.,0.09
PARAMETER LAICR = 4.0
```

The senescence rate of LAI (DLAI, d^{-1}) is described on the basis of a relative death rate (RDR, d^{-1}), set at the maximum of a relative death rate due to ageing (RDRDV) and one due to self-shading, RDRSH. The latter equals zero for LAI smaller than 4, and from there on increases linearly with increasing LAI till a maximum value of 0.03 at LAI = 8 (i.e. the meaning of the (P)CSMP LIMIT function in combination with LAICR = 4.).

RDRDV equals zero as long as DVS < 1 (pre-anthesis stage) and is a function of the average daily temperature (DAVTMP, °C) for DVS > 1 (Figure 1.6).

```
DLV = WLVG * DLAI / (LAI + NOT(LAI))
```

The death rate of leaves (DLV, kg ha^{-1} d^{-1}) is defined as the relative senescence rate of LAI times the weight of the green leaves (WLVG).

1.11 Dry matter production

```
WRT   = INTGRL(WRTI, GRT)
WLVG  = INTGRL(WLVI, GLV - DLV)
WLVD  = INTGRL(0.,   DLV)
WST   = INTGRL(WSTI, GST)
WSO   = INTGRL(0.,   GSO)
```

Dry weights of the various plant organs (roots (WRT, kg ha^{-1}), green leaves (WLVG, kg ha^{-1}), dead leaves (WLVD, kg ha^{-1}), stems (WST, kg ha^{-1}), storage organs (WSO, kg ha^{-1})) is obtained through integration of the respective growth rates.

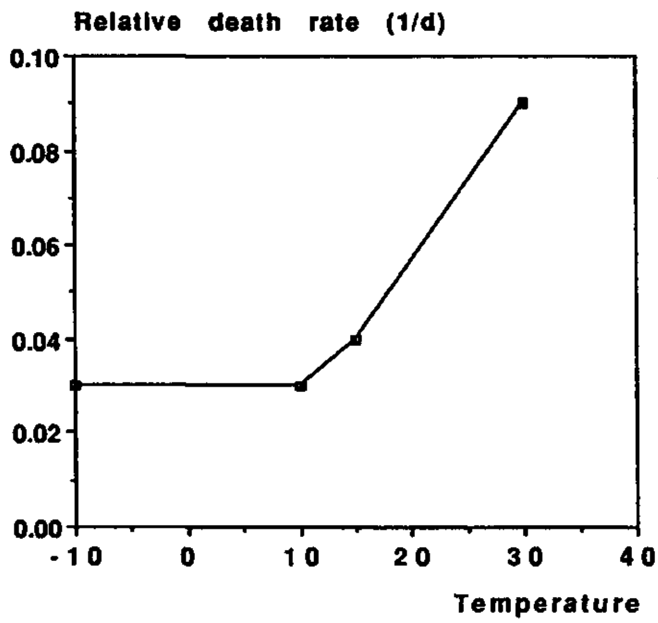


Figure 1.6. Relative death rate of leaves (RDR, d^{-1}), as a function of average daily temperature (DAVTMP, °C).

```
WLV    = WLVG  + WLVD
TADRW = WLV   + WST + WSO
TDRW  = TADRW + WRT
```

Some totals of dry matter production are calculated to be included in the output.

```
HI     = WSO / (TADRW + NOT(TADRW))
```

The harvest index (HI) is the weight of the grains divided by the above-ground biomass.

1.12 Weather data

```
DTR    = AFGEN(DTRT, DOY) * 1.E06
```

Actual daily total global radiation (DTR, J m^{-2} d^{-1}, the factor 1.E06 converts MJ into J) is read from the function DTRT which contains measured values for solar radiation (400 - 2000 nm) in MJ m^{-2} d^{-1} for all days of the year.

```
DTMAX  = AFGEN(TMAXT, DOY)
DTMIN  = AFGEN(TMINT, DOY)
DAVTMP = 0.5 * (DTMAX + DTMIN)
DDTMP  = DTMAX - 0.25 * (DTMAX - DTMIN)
```

Daily maximum and minimum temperatures (DTMAX and DTMIN, respectively, °C) are read from the functions TMAXT and TMINT containing measured values for all days of the year. For daytime temperature (DDTMP) we use an approximative formula. Weather data are read from tables with 365 data pairs each. The independent variable is the current daynumber of the year (DOY).

```
  DTEFF  = AMAX1(0., DAVTMP - TBASE)
PARAMETER TBASE = 0.
```

Since many growth processes are temperature dependent above a certain threshold temperature, an effective temperature (DTEFF) is calculated. For spring wheat, the threshold value is 0 °C.

Weather data given in the model are monthly averages (defined at the middle of each month) for Wageningen (the Netherlands) averaged over the years 1951 - 1980.

```
FUNCTION DTRT  = 15, 2.1,  46, 4.4,   74, 7.8,   105,13.0,...
      135,16.3, 166,17.5, 196,15.6,  227,13.8,  258,10.0,...
      288, 5.8, 319, 2.7, 349, 1.7
FUNCTION TMAXT = 15, 4.3,  46, 5.4,   74, 8.9,   105,12.4,...
     135,17.3,  166,20.5, 196,21.4,  227,21.5,  258,18.9,...
```

```
     288,14.3,  319, 8.6, 349, 5.5
FUNCTION TMINT = 15,-0.7,  46,-0.6,   74, 1.2,   105, 3.3,...
      135, 7.3, 166,10.3, 196,12.2,  227,12.0,   258, 9.7,...
      288, 6.5, 319, 2.9, 349, 0.6
```

1.13 Carbon balance check

The Carbon Balance Check compares the amount of carbon present in all organs at any point in time, with the integral of net carbon assimilation rate (TNASS). This rate consists of gross assimilation (DTGA), minus maintenance respiration (MAINT), minus losses due to growth respiration. These growth respiratory losses are defined as the organ growth rates times their CO_2 production factors (CO2RT, CO2LV, etc.), and in addition the loss (a fraction 1 – 0.947) that occurs during remobilization of stem starch to glucose.

In practice, the two terms CHKIN and CHKFL should never differ more than by a fraction 10^{-6}. A larger relative deviation (mostly of the order of a few percent) will be a sure signal of omission of a term somewhere in the program (CHKDIF), and the simulation will stop.

```
     CHKIN  = (WLV-WLVI) * CFLV + (WST-WSTI) * CFST + ...
              (WRT-WRTI) * CFRT + WSO * CFSO
     CHKFL  = TNASS * (12./44.)
     TNASS  = INTGRL(0., ((GPHOT - MAINT)*44./30.) - ...
                         (GRT*CO2RT + GLV*CO2LV    + ...
                 (GST+TRANSL)*CO2ST + GSO*CO2SO    + ...
                    (1.-0.947)*TRANSL*CFST*44./12.))
     CO2RT  = 44./12. * (ASRQRT*12./30. - CFRT)
     CO2LV  = 44./12. * (ASRQLV*12./30. - CFLV)
     CO2ST  = 44./12. * (ASRQST*12./30. - CFST)
     CO2SO  = 44./12. * (ASRQSO*12./30. - CFSO)

     CHKDIF = AND((CHKIN-CHKFL)/(NOT(CHKIN)+CHKIN))
FINISH CHKDIF = 1.0E-3

   PARAMETER CFLV=0.459, CFST=0.494, CFRT=0.467, CFSO=0.471
```

The parameters `CFLV`, `CFST`, `CFRT` and `CFSO` (kg C kg^{-1} DM) represent the C-contents of leaves, stems, roots and storage organs, respectively.

1.14 Run control

```
     DOY = AMOD(TIME, 365.)
```

In the given example, seedling emergence is at day of the year number 90, i.e. 31 March (PARAMETER DOYEM=90.). Simulation may start earlier and is specified in the (P)CSMP

TIMER statement.

```
FINISH DVS = 2.
```

The simulation stops if the crop is mature. This occurs if the development stage reaches the value 2.

```
TIMER TIME = 80., FINTIM = 300., DELT=1., PRDEL=5.
METHOD RECT
```

Simulation is executed in time steps of one day (DELT = 1.), with rectilinear integration of the growth rates (METHOD RECT). Output is produced every fifth day (PRDEL = 5). To make sure that the simulation does not continue endlessly, the finish time (FINTIM) is set at about 50 days later than the expected maturation date.

```
PRINT DOY, DTR, DVS, TDRW, TADRW, WLVG, WLVD, WLV,   ...
      WST, WSO, WRT, EAI, LAI, HI, DTMAX, DTMIN,     ...
      GPHOT, DAYL, TRANSL, CHKIN, CHKFL, CHKDIF
```

In this line any variable can be specified. Values occur for every print interval (PRDEL) in the output file FOR06.DAT.

END	completes the specifications of the model;
STOP	terminates the simulation run;

```
SUBROUTINES
```

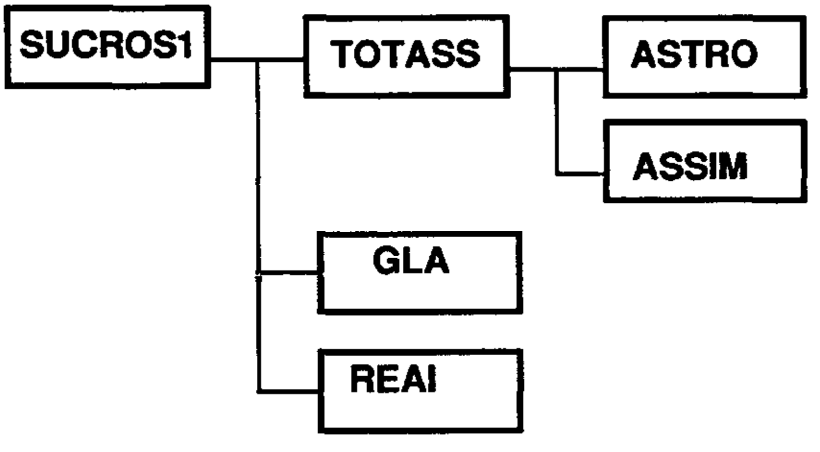
ENDJOB	terminates the job (this statement has to start in the first column!).

1.15 Subroutines

Subroutines are invoked between the STOP and ENDJOB statement.

```
*____________________________________________________________
* Subroutine TOTASS
* computes daily total gross CO2 assimilation rates (DTGA, kg CO2 ha-1 d-1)
*____________________________________________________________

*____________________________________________________________
* Subroutine ASTRO
* computes daylength and daily extra-terrestrial radiation from daynumber and latitude
*____________________________________________________________

*____________________________________________________________
* Subroutine ASSIM
* calculates instantaneous assimilation rates (FGROS, kg CO2 ha-1 h-1)
*____________________________________________________________

*____________________________________________________________
* Function GLA
* computes daily increase in leaf area index (LAI, ha leaf ha-1 ground d-1)
*____________________________________________________________

*____________________________________________________________
* Function REAI
* calculates ear area index (EAI)
*____________________________________________________________
```

The structure of the model:



1.16 Listing of the model SUCROS1

```
TITLE CROP GROWTH FOR POTENTIAL PRODUCTION (SUCROS1)

*     Spring wheat, Version September 1992


* 1.1 INTRODUCTION

*    The basis for this model is a simple and universal crop growth   *
*    simulator, named SUCROS87. The 1987 version of the model is      *
*    described by C.J.T. Spitters, H. van Keulen and D.W.G.           *
*    van Kraalingen in 'Simulation and Systems Management in Crop     *
*    Protection'. Eds R. Rabbinge, S.A. Ward and H.H. van Laar,       *
*    Simulation Monographs, Pudoc, Wageningen (1989), pp. 147-181.    *


* 1.2 INITIAL CONDITIONS

INITIAL
PARAMETER DOYEM  = 90.
INCON NPL        = 210.
INCON LA0        = 5.7E-5
INCON WLVI       = 0.
INCON WSTI       = 0.
INCON WRTI       = 0.


* 1.3 CROP DEVELOPMENT

DYNAMIC
      DVS        = INTGRL(0., DVR)
      DVR        = INSW(DVS-1., AFGEN(DVRVT, DAVTMP),...
                               AFGEN(DVRRT, DAVTMP)) * EMERG
      EMERG      = INSW(DOY-DOYEM, 0., 1.)
FUNCTION DVRVT   = -10.,0., 0.,0., 30.,0.027
FUNCTION DVRRT   = -10.,0., 0.,0., 30.,0.031


* 1.4 LEAF CO2 ASSIMILATION

      AMAX       = AMX * AMDVS * AMTMP
      AMDVS      = AFGEN(AMDVST, DVS)
      AMTMP      = AFGEN(AMTMPT, DDTMP)
PARAMETER AMX    = 40.
* 1.11 microgram CO2/m2/s  = 40 kg CO2/ha/h
FUNCTION AMDVST  = 0.0,1.0, 1.0,1.0, 2.0,0.5, 2.5,0.0
FUNCTION AMTMPT  = 0.,0., 10.,1., 25.,1., 35.,0., 50.,0.
```

```
* 1.5 DAILY GROSS CO2 ASSIMILATION

      DAYL,DTGA,DS0    = TOTASS(DOY,LAT,DTR,SCP,AMAX,EFF,KDF,LAI)
PARAMETER EFF      = 0.45
* 12.5 microgram CO2/J  = 0.45 kg (CO2/ha/h)/(J/m2/s)
PARAMETER KDF      = 0.60
PARAMETER SCP      = 0.20
PARAMETER LAT      = 52.


* 1.6 CARBOHYDRATE PRODUCTION

      GPHOT        = DTGA * 30./44.


* 1.7 MAINTENANCE

      MAINT        = MAINTS * TEFF * MNDVS
      MAINTS       = MAINLV*WLV + MAINST*WST + MAINRT*WRT + MAINSO*WSO
      MNDVS        = WLVG / (WLV+NOT(WLV))
      TEFF         = Q10**((DAVTMP-TREF)/10.)
PARAMETER Q10      = 2., TREF = 25.
PARAMETER MAINLV = 0.03, MAINST = 0.015
PARAMETER MAINRT = 0.015,MAINSO = 0.01


* 1.8 DRY MATTER PARTITIONING

      FSH          = AFGEN(FSHTB, DVS)
      FRT          = 1. - FSH
FUNCTION FSHTB     = 0.00,0.50, 0.10,0.50, 0.20,0.60, 0.35,0.78,...
                     0.40,0.83, 0.50,0.87, 0.60,0.90, 0.70,0.93,...
                     0.80,0.95, 0.90,0.97, 1.00,0.98, 1.10,0.99,...
                     1.20,1.00, 2.50,1.00

      FLV          = AFGEN(FLVTB, DVS)
FUNCTION FLVTB     = 0.00,0.65, 0.10,0.65, 0.25,0.70, 0.50,0.50,...
                     0.70,0.15, 0.95,0.00, 2.50,0.00

      FST          = AFGEN(FSTTB, DVS)
FUNCTION FSTTB     = 0.00,0.35, 0.10,0.35, 0.25,0.30, 0.50,0.50,...
                     0.70,0.85, 0.95,1.00, 1.05,0.00, 2.50,0.00

      FSO          = 1. - FLV - FST


* 1.9 GROWTH OF PLANT ORGANS AND TRANSLOCATION

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

```
                         ASRQRT*FRT

      TRANSL       = INSW(DVS-1., 0., WST * DVR * FRTRL)

      GTW          = (GPHOT - MAINT + 0.947*TRANSL*CFST*30./12.) / ASRQ
      GRT          = FRT * GTW
      GLV          = FLV * FSH * GTW
      GST          = FST * FSH * GTW - TRANSL
      GSO          = FSO * FSH * GTW

PARAMETER ASRQRT = 1.444, ASRQLV = 1.463
PARAMETER ASRQST = 1.513, ASRQSO = 1.415
PARAMETER FRTRL  = 0.20


* 1.10 LEAF AND EAR DEVELOPMENT

      LAI          = 0.5 * EAI + INTGRL(0., GLAI-DLAI)
      GLAI         = GLA(DOY, DOYEM, DTEFF, DVS, NPL, LA0, ...
                         RGRL, DELT, SLA  , LAI, GLV)
PARAMETER RGRL     = 0.009
PARAMETER SLA      = 0.0022

      EAI          = INTGRL(0., REAI(DELT,DVS,EAR,TADRW,RDRDV,EAI))
PARAMETER EAR      = 6.3E-5

      DLAI         = LAI * RDR
      RDR          = AMAX1(RDRDV, RDRSH)
      RDRDV        = INSW(DVS-1.0, 0., AFGEN(RDRT, DAVTMP))
      RDRSH        = LIMIT(0., 0.03, 0.03 * (LAI-LAICR) / LAICR)
FUNCTION RDRT      = -10.,0.03, 10.,0.03, 15.,0.04, 30.,0.09
PARAMETER LAICR    = 4.0

      DLV          = WLVG * DLAI/(LAI+NOT(LAI))


* 1.11 DRY MATTER PRODUCTION

      WRT          = INTGRL(WRTI, GRT)
      WLVG         = INTGRL(WLVI, GLV-DLV)
      WLVD         = INTGRL(0., DLV)
      WST          = INTGRL(WSTI, GST)
      WSO          = INTGRL(0., GSO)

      WLV          = WLVG  + WLVD
      TADRW        = WLV   + WST   + WSO
      TDRW         = TADRW + WRT
```

```
      HI            = WSO / (TADRW + NOT(TADRW))


* 1.12 WEATHER DATA

      DTR           = AFGEN(DTRT,  DOY) * 1.E06
      DTMAX         = AFGEN(TMAXT, DOY)
      DTMIN         = AFGEN(TMINT, DOY)
      DAVTMP        = 0.5 * (DTMAX + DTMIN)
      DDTMP         = DTMAX - 0.25 * (DTMAX-DTMIN)

      DTEFF         = AMAX1(0., DAVTMP-TBASE)
PARAMETER TBASE     = 0.

FUNCTION DTRT      =  15., 2.1,  46., 4.4,  74., 7.8, 105.,13.0, ...
       135.,16.3,  166.,17.5, 196.,15.6, 227.,13.8, 258.,10.0, ...
       288., 5.8,  319., 2.7, 349., 1.7
FUNCTION TMAXT     =  15., 4.3,  46., 5.4,  74., 8.9, 105.,12.4, ...
       135.,17.3,  166.,20.5, 196.,21.4, 227.,21.5, 258.,18.9, ...
       288.,14.3,  319., 8.6, 349., 5.5
FUNCTION TMINT     =  15.,-0.7,  46.,-0.6,  74., 1.2, 105., 3.3, ...
       135., 7.3,  166.,10.3, 196.,12.2, 227.,12.0, 258., 9.7, ...
       288., 6.5,  319., 2.9, 349., 0.6


* 1.13 CARBON BALANCE CHECK

      CHKIN         = (WLV - WLVI) * CFLV + (WST - WSTI) * CFST + ...
                      (WRT - WRTI) * CFRT + WSO * CFSO
      CHKFL         = TNASS * (12./44.)
      TNASS         = INTGRL(0., ((GPHOT - MAINT)*44./30.) -  ...
                                   (GRT*CO2RT + GLV*CO2LV +  ...
                              (GST+TRANSL)*CO2ST + GSO*CO2SO +  ...
                              (1.-0.947)* TRANSL*CFST*44./12.))
      CO2RT         = 44./12. * (ASRQRT*12./30. - CFRT)
      CO2LV         = 44./12. * (ASRQLV*12./30. - CFLV)
      CO2ST         = 44./12. * (ASRQST*12./30. - CFST)
      CO2SO         = 44./12. * (ASRQSO*12./30. - CFSO)

      CHKDIF        = ABS((CHKIN-CHKFL)/(NOT(CHKIN)+CHKIN))
FINISH CHKDIF = 1.0E-3

PARAM CFLV=0.459, CFST=0.494, CFRT=0.467, CFSO=0.471


* 1.14 RUN CONTROL

      DOY           = AMOD(TIME, 365.)
```

```
FINISH DVS      = 2.
TIMER TIME      = 80., FINTIM = 300., DELT = 1., PRDEL = 5.
METHOD RECT

PRINT DOY,DTR,DVS,TDRW,TADRW,WLVG,WLVD,WLV,WST,...
      WSO,WRT,LAI,EAI,HI,DTMAX,DTMIN,GPHOT,DAYL, ...
      TRANSL,CHKIN,CHKFL,CHKDIF
END
STOP


* 1.15 SUBROUTINES

* ---------------------------------------------------------------------*
*  FUNCTION GLA                                                        *
*  Purpose: This function computes daily increase of leaf area index   *
*           (ha leaf/ ha ground/ d)                                    *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name    type meaning                                  units  class *
*  ----    ---- -------                                  -----  ----- *
*  DOY      R4  Daynumber (Jan 1st = 1)                    -       I   *
*  DOYEM    R4  Daynumber of crop emergence                -       I   *
*  DTEFF    R4  Daily effective temperatute             degree C  I   *
*  DVS      R4  Development stage of the crop              -       I   *
*  NPL      R4  Plant density                          plants m-2 I   *
*  LA0      R4  Extrapolated leaf area at emergence    m2 plant-1 I   *
*  RGRL     R4  Relative leaf growth rate               ha ha-1    I   *
*  SLA      R4  Specific leaf area                      ha kg-1    I   *
*  LAI      R4  Leaf area index                         ha ha-1    I   *
*  GLV      R4  Growth rate of the leaves             kg ha-1 d-1 I   *
* ---------------------------------------------------------------------*

      REAL FUNCTION GLA (DOY,DOYEM,DTEFF,DVS,NPL,LA0,RGRL,DELT,SLA,
     $                   LAI,GLV)
      IMPLICIT REAL (A-Z)

*-----growth during maturation stage
      GLA  = SLA * GLV

*-----growth during juvenile stage
      IF ((DVS.LT.0.3).AND.(LAI.LT.0.75)) THEN
      GLA  = (LAI * (EXP(RGRL*DTEFF*DELT)-1.))/DELT
      ENDIF

*-----growth at day of seedling emergence
      IF ((DOY.GE.DOYEM).AND.(LAI.EQ.0.)) GLA = (NPL * LA0)/DELT
```

```
*-----growth before seedling emergence
      IF (DOY.LT.DOYEM) GLA = 0.

      RETURN
      END


*----------------------------------------------------------------------*
*  FUNCTION REAI                                                        *
*  Purpose: This function calculates ear area index                     *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                   units  class *
*  ----   ---- -------                                   -----  ----- *
*  DVS     R4  Development stage of the crop               -        I  *
*  EAR     R4  Ear weight                                kg ha-1    I  *
*  TADRW   R4  Total above-ground dry weight             kg ha-1    I  *
*  RDR     R4  Relative death rate                         d-1      I  *
*  EAI     R4  Ear area index                            ha ha-1    I  *
*----------------------------------------------------------------------*

      REAL FUNCTION REAI(DELT,DVS,EAR,TADRW,RDRDV,EAI)
      IMPLICIT REAL(A-Z)

      IF (DVS.LT.0.8) REAI = 0.
      IF (DVS.GE.0.8 .AND. EAI.EQ.0.) THEN
                      REAI = (EAR * TADRW)/DELT
      ELSE
                      REAI = 0.
      ENDIF
      IF (DVS.GE.1.3) REAI = -RDRDV * EAI
      RETURN
      END


*----------------------------------------------------------------------*
*  SUBROUTINE ASTRO                                                     *
*  Purpose: This subroutine calculates astronomic daylength,            *
*           diurnal radiation characteristics such as the daily         *
*           integral of sine of solar elevation and solar constant.     *
*                                                                       *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                   units  class *
*  ----   ---- -------                                   -----  ----- *
*  DOY     R4  Daynumber (Jan 1st = 1)                     -        I  *
*  LAT     R4  Latitude of the site                      degrees    I  *
*  SC      R4  Solar constant                            J m-2 s-1 O   *
*  DS0     R4  Daily extraterrestrial radiation          J m-2 d-1 O   *
*  SINLD   R4  Seasonal offset of sine of solar height     -        O  *
```

```
*  COSLD   R4  Amplitude of sine of solar height              -      O  *
*  DAYL    R4  Astronomic daylength (base = 0 degrees)        h      O  *
*  DSINB   R4  Daily total of sine of solar height            s      O  *
*  DSINBE  R4  Daily total of effective solar height          s      O  *
*                                                                       *
*  FATAL ERROR CHECKS (execution terminated, message)                   *
*  condition: LAT > 67, LAT < -67                                       *
*                                                                       *
*  FILE usage : none                                                    *
*-----------------------------------------------------------------------*

      SUBROUTINE ASTRO (DOY, LAT,
     &                  SC , DS0, SINLD, COSLD, DAYL, DSINB, DSINBE)
      IMPLICIT REAL (A-Z)

*-----PI and conversion factor from degrees to radians
      PI    = 3.141592654
      RAD   = PI/180.

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

*-----declination of the sun as function of daynumber (DOY)
      DEC   = -ASIN (SIN (23.45*RAD)*COS (2.*PI*(DOY+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)
      DAYL   = 12.0*(1.+2.*ASIN (AOB)/PI)

      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 (DS0)
      SC  = 1370.*(1.+0.033*COS (2.*PI*DOY/365.))
      DS0 = SC*DSINB

      RETURN
      END
```

```
*----------------------------------------------------------------------*
*  SUBROUTINE TOTASS                                                   *
*  Purpose: This subroutine 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.                        *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                 units  class *
*  ----   ---- -------                                 -----  ----- *
*  DOY     R4  Daynumber (January 1 = 1)                  -      I  *
*  LAT     R4  Latitude of the site                    degrees   I  *
*  DTR     R4  Daily total of global radiation         J/m2/d    I  *
*  SCP     R4  Scattering coefficient of leaves for visible          *
*              radiation (PAR)                            -      I  *
*  AMAX    R4  Assimilation rate at light saturation    kg CO2/  I  *
*                                                      ha leaf/h    *
*  EFF     R4  Initial light use efficiency            kg CO2/J/ I  *
*                                                      ha/h m2 s    *
*  KDF     R4  Extinction coefficient for diffuse light          I  *
*  LAI     R4  Leaf area index                          ha/ha    I  *
*  DAYL    R4  Astronomic daylength (base = 0 degrees)    h      O  *
*  DTGA    R4  Daily total gross assimilation      kg CO2/ha/d O    *
*  DS0     R4  Daily extraterrestrial radiation        J m-2 s-1 O  *
*                                                                      *
*                                                                      *
*  SUBROUTINES and FUNCTIONS called : ASTRO, ASSIM                     *
*  FILE usage : none                                                   *
*----------------------------------------------------------------------*

      SUBROUTINE TOTASS (DOY,  LAT , DTR, SCP, AMAX, EFF, KDF, LAI,
     &                   DAYL, DTGA, DS0)
      IMPLICIT REAL(A-Z)
      REAL XGAUSS(3), WGAUSS(3)
      INTEGER I1, IGAUSS

      DATA IGAUSS /3/
      DATA XGAUSS /0.112702, 0.500000, 0.887298/
      DATA WGAUSS /0.277778, 0.444444, 0.277778/

      PI    = 3.141592654

      CALL ASTRO(DOY,LAT,SC,DS0,SINLD,COSLD,DAYL,DSINB,DSINBE)

*-----assimilation set to zero and three different times of the day (HOUR)
      DTGA = 0.
```

```
      DO 10 I1=1,IGAUSS

*---------at the specified HOUR, radiation is computed and used to compute
*         assimilation
          HOUR = 12.0+DAYL*0.5*XGAUSS(I1)

*---------sine of solar elevation
          SINB  = AMAX1 (0., SINLD+COSLD*COS (2.*PI*(HOUR+12.)/24.))

*---------diffuse light fraction (FRDF) from atmospheric
*         transmission (ATMTR)
          PAR   = 0.5*DTR*SINB*(1.+0.4*SINB)/DSINBE
          ATMTR = PAR/(0.5*SC*SINB)

          IF (ATMTR.LE.0.22) THEN
             FRDF = 1.
          ELSE IF (ATMTR.GT.0.22 .AND. ATMTR.LE.0.35) THEN
             FRDF = 1.-6.4*(ATMTR-0.22)**2
          ELSE
             FRDF = 1.47-1.66*ATMTR
          END IF

          FRDF = AMAX1 (FRDF, 0.15+0.85*(1.-EXP (-0.1/SINB)))

*---------diffuse PAR (PARDF) and direct PAR (PARDR)
          PARDF = PAR * FRDF
          PARDR = PAR - PARDF

          CALL ASSIM (SCP,AMAX,EFF,KDF,LAI,SINB,PARDR,PARDF,FGROS)

*---------integration of assimilation rate to a daily total (DTGA)
          DTGA = DTGA+FGROS*WGAUSS(I1)

10    CONTINUE

      DTGA = DTGA * DAYL

      RETURN
      END


*----------------------------------------------------------------------*
*  SUBROUTINE ASSIM                                                    *
*  Purpose: This subroutine 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.                              *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
```

```
*  name   type meaning                                   units  class *
*  ----   ---- -------                                   -----  ----- *
*  SCP     R4  Scattering coefficient of leaves for visible             *
*              radiation (PAR)                              -      I  *
*  AMAX    R4  Assimilation rate at light saturation     kg CO2/   I  *
*                                                       ha leaf/h     *
*  EFF     R4  Initial light use efficiency             kg CO2/J/  I  *
*                                                       ha/h m2 s     *
*  KDF     R4  Extinction coefficient for diffuse light            I  *
*  LAI     R4  Leaf area index                            ha/ha    I  *
*  SINB    R4  Sine of solar height                         -      I  *
*  PARDR   R4  Instantaneous flux of direct radiation (PAR) W/m2   I  *
*  PARDF   R4  Instantaneous flux of diffuse radiation(PAR) W/m2   I  *
*  FGROS   R4  Instantaneous assimilation rate of        kg CO2/   O  *
*              whole canopy                             ha soil/h     *
*                                                                     *
*  SUBROUTINES and FUNCTIONS called : none                            *
*  FILE usage : none                                                  *
*---------------------------------------------------------------------*

      SUBROUTINE ASSIM (SCP, AMAX, EFF, KDF, LAI, SINB, PARDR, PARDF,
     &                  FGROS)
      IMPLICIT REAL(A-Z)
      REAL XGAUSS(3), WGAUSS(3)
      INTEGER I1, I2, IGAUSS

*-----Gauss weights for three point Gauss
      DATA IGAUSS /3/
      DATA XGAUSS /0.112702, 0.500000, 0.887298/
      DATA WGAUSS /0.277778, 0.444444, 0.277778/

*-----reflection of horizontal and spherical leaf angle distribution
      SQV  = SQRT(1.-SCP)
      REFH = (1.-SQV)/(1.+SQV)
      REFS = REFH*2./(1.+2.*SINB)

*-----extinction coefficient for direct radiation and total direct flux
      CLUSTF = KDF / (0.8*SQV)
      KBL    = (0.5/SINB) * CLUSTF
      KDRT   = KBL * SQV

*-----selection of depth of canopy, canopy assimilation is set to zero
      FGROS = 0.

      DO 10 I1=1,IGAUSS
         LAIC = LAI * XGAUSS(I1)

*--------absorbed fluxes per unit leaf area: diffuse flux, total direct
```

```
*         flux, direct component of direct flux.
          VISDF = (1.-REFH)*PARDF*KDF  *EXP (-KDF  *LAIC)
          VIST  = (1.-REFS)*PARDR*KDRT *EXP (-KDRT *LAIC)
          VISD  = (1.-SCP) *PARDR*KBL  *EXP (-KBL  *LAIC)

*---------absorbed flux (J/M2 leaf/s) for shaded leaves and assimilation of
*         shaded leaves
          VISSHD = VISDF + VIST - VISD
          IF (AMAX.GT.0.) THEN
             FGRSH  = AMAX * (1.-EXP(-VISSHD*EFF/AMAX))
          ELSE
             FGRSH = 0.
          END IF

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

          VISPP  = (1.-SCP) * PARDR / SINB
          FGRSUN = 0.
          DO 20 I2=1,IGAUSS
             VISSUN = VISSHD + VISPP * XGAUSS(I2)
             IF (AMAX.GT.0.) THEN
                FGRS = AMAX * (1.-EXP(-VISSUN*EFF/AMAX))
             ELSE
                FGRS = 0.
             END IF
             FGRSUN = FGRSUN + FGRS * WGAUSS(I2)
20        CONTINUE

*---------fraction sunlit leaf area (FSLLA) and local assimilation
*         rate (FGL)
          FSLLA = CLUSTF * EXP(-KBL*LAIC)
          FGL   = FSLLA  * FGRSUN + (1.-FSLLA) * FGRSH

*---------integration of local assimilation rate to canopy
*         assimilation (FGROS)
          FGROS = FGROS + FGL * WGAUSS(I1)

10     CONTINUE
       FGROS = FGROS * LAI

       RETURN
       END

ENDJOB
```

2 Crop growth model for water-limited conditions (SUCROS2)

H. van Keulen, J. Goudriaan, L. Stroosnijder, E.A. Lantinga & H.H. van Laar

2.1 Introduction

SUCROS2 describes production (as applied to spring wheat) under water-limited conditions by including water balances of crop and soil in the SUCROS1 model. Conditions are still optimal with respect to other growth factors, i.e. ample nutrients and a pest-, disease- and weed-free environment. With the SUCROS2 model, options for soil and water conservation can be studied. The crop / soil water balances in SUCROS2 are based on earlier versions documented by Stroosnijder (1982) and Penning de Vries et al. (1989).

SUCROS2 can only be understood on the basis of SUCROS1, the crop growth model for potential production described in Chapter 1. The effect of altered water relations is transmitted through two variables, one acting on daily gross CO_2 assimilation and the other one acting on root-shoot partitioning.

In Sections 2.1-2.22 of this report, the explanatory text follows as closely as possible the computer listing of the model, i.e. each section starts with a number of lines copied from this listing. In the following text, it is then possible to explain the inevitably awkward abbreviative terminology so typical for computer modelling, and to treat the dimensions of all variables and data. Another feature is that parameter and function values are defined directly after they are used for the first time. In this way, it is indicated where the model depends on user-specified input emphasizing that the accuracy of model results not only depends on correct understanding and description of the processes involved, but also on availability and quality of the input data. The way in which SUCROS2 is presented here, is different from the modular structure of most current models in which separate data blocks for soil, crop and climate are added at the end of a main program.

In the description of Sections 2.1-2.12, only differences between SUCROS2 and SUCROS1 will be discussed.

2.2 Initial conditions

```
INITIAL
PARAMETER DOYEM = 90.
INCON NPL       = 210.
INCON LAO       = 5.7E-5
INCON WLVI      = 0.
INCON WSTI      = 0.
INCON WRTI      = 0.
INCON ZRTI      = 5.
  WL1I    = WCLI1 * TKL1
  WL2I    = WCLI2 * TKL2
```

```
  WL3I     = WCLI3 * TKL3
INCON WCLI1      = 0.20
INCON WCLI2      = 0.20
INCON WCLI3      = 0.20

  WCUMI    = WL1I + WL2I + WL3I
  PCEW     = 1.
```

In addition to the statements explained in SUCROS1, a number of additional initial conditions are specified.

ZRTI (in mm) is the rooted depth (Section 2.15) at emergence (i.e. DOYEM). WCLI1, WCLI2 and WCLI3 are the initial moisture contents ($cm^3\ cm^{-3}$) in the three soil layers distinguished in this model (Section 2.14). Model results are rather sensitive to these initial values because they define the moisture reserves in the soil. It is, therefore, advisable to start model execution well before the emergence date (in (semi-)arid regions before the onset of the rainy season), so that realistic values for initial moisture conditions can be defined. If measured values at emergence are available, they can be directly incorporated.

In the given example, where the total depth of the soil profile (sum of TKL1, TKL2 and TKL3) is 1200 mm (Subsection 2.14.1), the amount of stored water (WCUMI) is 240 mm. When all layers are at wilting point (Sections 2.14 and 2.18) the profile contains 90 mm of water. Hence, at the start of the simulation, there is 150 mm (240 – 90) of water available for the crop. PCEW is a factor describing the effect of water stress on CO_2 assimilation (Section 2.18).

2.3 Crop development

```
DYNAMIC
  DVS     = INTGRL(0., DVR)
  DVR     = INSW(DVS - 1.,AFGEN(DVRVT, DAVTMP),...
                          AFGEN(DVRRT, DAVTMP)) * EMERG
  EMERG   = INSW(DOY - DOYEM, 0., 1.)
FUNCTION DVRVT = -10.,0.,  0.,0.,  30.,0.027
FUNCTION DVRRT = -10.,0.,  0.,0.,  30.,0.031
```

2.4 Leaf CO_2 assimilation

```
  AMAX    = AMX * AMDVS * AMTMP
  AMDVS   = AFGEN(AMDVST, DVS)
  AMTMP   = AFGEN(AMTMPT, DDTMP)
PARAMETER AMX    = 40.
FUNCTION AMDVST = 0.,1.0, 1.0,1.0, 2.0,0.5, 2.5,0.0
FUNCTION AMTMPT = 0.,0.,10.,1.,25.,1., 35.,0., 50.,0.
```

2.5 Daily gross CO_2 assimilation

```
  DAYL,DTGA,DSO = TOTASS(DOY,LAT,DTR,SCP,AMAX,EFF,KDF,LAI)
PARAMETER EFF  = 0.45
PARAMETER KDF  = 0.60
PARAMETER SCP  = 0.20
PARAMETER LAT  = 52.
```

2.6 Carbohydrate production

```
  GPHOT = DTGA * PCEW * 30./44.
```

PCEW is a factor that accounts for reduced photosynthesis due to water stress, its value is calculated in Section 2.18.

2.7 Maintenance

```
  MAINT  = MAINTS * TEFF * MNDVS
  MAINTS = MAINLV*WLV +MAINST*WST +MAINRT*WRT +MAINSO*WSO
  MNDVS  = WLVG / (WLV + NOT(WLV))
  TEFF   = Q10**((DAVTMP - TREF)/10.)
PARAMETER Q10    = 2.,    TREF = 25.
PARAMETER MAINLV = 0.03,  MAINST = 0.015
PARAMETER MAINRT = 0.015, MAINSO = 0.01
```

2.8 Dry matter partitioning

```
  FSHP  = AFGEN(FSHTB, DVS)
  FSH   = (FSHP * CPEW) / (1. + (CPEW - 1.) * FSHP)
  FRT   = 1. - FSH
FUNCTION FSHTB =  0.00,0.50,  0.10,0.50,  0.20,0.60,  ...
      0.35,0.78,  0.40,0.83,  0.50,0.87,  0.60,0.90,  ...
      0.70,0.93,  0.80,0.95,  0.90,0.97,  1.00,0.98,  ...
      1.10,0.99,  1.20,1.00,  2.50,1.00
  FLV   = AFGEN(FLVTB, DVS)
  FST   = AFGEN(FSTTB, DVS)
  FSO   = 1. - FLV - FST
FUNCTION FLVTB = 0.00,0.65, 0.10,0.65, 0.25,0.70,  ...
      0.50,0.50, 0.70,0.15, 0.95,0.00, 2.50,0.00
FUNCTION FSTTB = 0.00,0.35, 0.10,0.35, 0.25,0.30,  ...
   0.50,0.50, 0.70,0.85, 0.95,1.00, 1.05,0.00, 2.50,0.00
```

CPEW is a factor accounting for the effect of water stress on dry matter partitioning leading to higher investments in the root, its value is calculated in Section 2.18 (Subsection 2.18.3).

2.9 Growth of plant organs and translocation

```
  ASRQ   = FSH * (ASRQLV*FLV + ASRQST*FST + ASRQSO*FSO) ...
                + ASRQRT*FRT
  TRANSL = INSW(DVS-1., 0., WST * DVR * FRTRL)
  GTW    = (GPHOT-MAINT+0.947*TRANSL*CFST*30./12.)/ASRQ
  GRT    = FRT  * GTW
  GLV    = FLV  * FSH * GTW
  GST    = FST  * FSH * GTW - TRANSL
  GSO    = FSO  * FSH * GTW

PARAMETER ASRQRT = 1.444,  ASRQLV = 1.463
PARAMETER ASRQST = 1.513,  ASRQSO = 1.415
PARAMETER FRTRL  = 0.20
```

2.10 Leaf and ear development

```
  TLAI   = 0.5 * EAI + INTGRL(0.,GLAI       )
  LAI    = 0.5 * EAI + INTGRL(0.,GLAI - DLAI)
  GLAI   = GLA(DOY,DOYEM,DTEFF,DVS,NPL,LA0,RGRL,DELT,...
              SLA,LAI,GLV)
PARAMETER RGRL = 0.009
PARAMETER SLA  = 0.0022

  EAI    = INTGRL(0., REAI(DELT,DVS,EAR,TADRW,RDRDV,EAI))
PARAMETER EAR  = 6.3E-5

  DLAI   = LAI * RDR
  RDR    = AMAX1(RDRDV,RDRSH)
  RDRDV  = INSW(DVS - 1.0, 0., AFGEN(RDRT, DAVTMP))
  RDRSH  = LIMIT(0., 0.03, 0.03 * (LAI - LAICR) / LAICR)
FUNCTION RDRT   = -10.,0.03, 10.,0.03, 15.,0.04, 30.,0.09
PARAMETER LAICR = 4.0

  DLV    = WLVG * DLAI/(LAI + NOT(LAI))
```

2.11 Dry matter production

```
  WRT    = INTGRL(WRTI, GRT)
  WLVG   = INTGRL(WLVI, GLV - DLV)
  WLVD   = INTGRL(0.,   DLV)
  WST    = INTGRL(WSTI, GST)
```

```
      WSO      = INTGRL(0.,    GSO)
      WLV      = WLVG  + WLVD
      TADRW    = WLV   + WST   + WSO
      TDRW     = TADRW + WRT

      HI       = WSO / (TADRW + NOT(TADRW))
```

2.12 Weather data

```
      DTR    = AFGEN(DTRT, DOY) * 1.E06

      DTMAX    = AFGEN(TMAXT, DOY)
      DTMIN    = AFGEN(TMINT, DOY)
      DAVTMP   = 0.5 * (DTMAX + DTMIN)
      DDTMP    = DTMAX - 0.25 * (DTMAX - DTMIN)

      DTEFF    = AMAX1(0.,DAVTMP - TBASE)
    PARAMETER TBASE = 0.

      AVP      = AFGEN(VAPHTB, DOY) * 10.
      WDS      = AFGEN(WSTB,   DOY)
      RAIN     = AFGEN(RAINTB, DOY)
      TRAIN    = INTGRL(0., RAIN)
```

In addition to the variables explained in SUCROS1, actual vapour pressure (AVP, mbar), wind speed (WDS, m s^{-1}) and rainfall (RAIN, mm) are read from tabulated functions for each day of the simulation (Section 2.20). Actual vapour pressure is read in kPa and converted into mbar (=100 Pa). Total rainfall (TRAIN) is computed to be included in the output and in the water balance check (Subsection 2.14.11).

2.13 Penman-Monteith combination equation

2.13.1 *Introduction*

Strictly speaking, transpiration is the loss of water from the plants, and evaporation is the loss of water from the soil or from a free-water surface. Evapotranspiration covers both transpiration and evaporation, but we will use the term evaporation as short cut to cover both.

The principal driving force for evaporation is the gradient of vapour pressure from the evaporating surface to the surrounding air. The vapour pressure at the evaporating surface is equal to the saturated vapour pressure at the prevailing temperature of that surface. The vapour pressure in the air is a function of ambient temperature and its relative humidity. The rate of evaporation depends on the diffusion resistances between the evaporating surface and the air.

The magnitude of the resistances is strongly related to wind speed. The two environmental variables, air humidity and wind speed combined determine the 'evaporative demand' of the air or 'drying power' of the air.

The problem in the approach above is that the temperature of the evaporating surface is usually not known from standard meteorological observations. Evaporation of a 1 mm layer of water requires 2.4 MJ m^{-2} of energy and can, therefore, be described through quantification of an energy balance. The energy dissipation required for evaporation leads to cooling of the evaporating surface which reduces the vapour gradient. Hence, a source of power is required to maintain the corresponding surface temperature, and hence, maintain the vapour pressure gradient. This energy is supplied by solar radiation. The net radiation received by the canopy/soil is, therefore, the driving force for evaporation.

Net radiation is the balance between incoming (short-wave) radiation from the sun and radiation losses due to reflection and outgoing (long-wave) radiation. Heat supplied by moving air is another source of energy, but this is usually negligible, except in situations where the vegetation is surrounded by extensive bare areas (oasis). Only 5 - 8% of incoming radiation is dissipated in photosynthesis, which is, therefore, disregarded here. Respiration yields an insignificant amount of energy. To simplify the treatment of evapotranspiration, it is considered to be governed by two factors: radiation and drying power.

Penman (1948) was the first to describe evapotranspiration in physical-mathematical terms. He calculated evaporation from free-water surfaces, bare soil and low grass swards for 10-day periods. There is ongoing discussion in the literature whether his formulae are also applicable if daily values are used. If used with daily values, 24 hour average values should be used. For large day/night differences (e.g. in wind speed), Doorenbos & Kassam (1979) suggested the use of correction factors.

The value calculated according to the Penman equations is the potential evapotranspiration (ET), i.e. without limitations with respect to the supply of liquid water to the evaporating surface. This ET (Penman) value is often used as a reference value, to which actual crop water demand is related. To translate ET into crop water requirements, so-called crop factors are used (e.g. Doorenbos & Pruitt, 1977; Feddes, 1987). In the model, the following set of equations is used:

```
    PENMAN = EVAPR + EVAPD
```

The Penman reference value for potential evapotranspiration (PENMAN, mm d^{-1} or kg m^{-2} d^{-1}) is calculated as the sum of two terms, a radiation term (EVAPR) and a drying power term (EVAPD).

2.13.2 *Radiation term*

```
    EVAPR  = (1./LHVAP) * (SLOPE/(SLOPE+PSYCH)) * NRAD
    SLOPE  = 4158.6 * SVP / (DAVTMP + 239.)**2
    SVP    = 6.11 * EXP(17.4 * DAVTMP / (DAVTMP + 239.))
  PARAMETER LHVAP = 2.4E6
```

```
PARAMETER PSYCH = 0.67
```

The radiation term depends on net radiation (NRAD, J m^{-2} d^{-1}), the latent heat of evaporation (LHVAP equal to 2.4×10^6 J kg^{-1} at 30 °C with only a small temperature dependence) and a weighting factor (SLOPE/(SLOPE+PSYCH)) in which SLOPE (mbar $°C^{-1}$) is the tangent of the relation between saturated vapour pressure (mbar) and temperature (°C) and PSYCH (0.67 mbar $°C^{-1}$ at 0 meter elevation) the psychrometer constant (Monteith, 1965).

SLOPE and SVP can be found in look-up tables (check for the correct units!) but here parameterized equations are used.

2.13.3 *Net radiation*

```
  NRAD  = (1.- ALB) * DTR - RLWN
  ALB   = ALBS * EXP(-0.5*LAI) + 0.25*(1.- EXP(-0.5*LAI))
  ALBS  = 0.25 * (1.- 0.5 * WCL1/WCST1)
```

Net radiation depends on incoming short-wave radiation (measured DTR, J m^{-2} d^{-1}), the reflection or albedo value (ALB, unitless), and net outgoing long-wave radiation.

The albedo for the canopy/soil is composed of that for the soil (ALBS) and that for the canopy (0.25). The relative contributions of both albedos depend on the shading of the soil by the crop and is calculated on the basis of the leaf area index (LAI). An extinction coefficient (for short-wave radiation penetrating the crop) of 0.5 is used here.

The soil's albedo depends on the surface color and the moisture content. Albedo values for dry soil vary from 0.15 (clay) to 0.40 (dune sand). Here, an average value of 0.25 is used. The dependence on soil moisture is described in relation to the average water content of the top soil layer (ten Berge, 1989).

2.13.4 *Net long-wave radiation*

```
  RLWN   = BBRAD * FVAP * FCLEAR * 86400.
  BBRAD  = BOLTZM * (DAVTMP + 273.)**4
PARAMETER BOLTZM = 5.668E-8
  FVAP   = 0.56 - 0.079 * SQRT(AVP)
  FCLEAR = 0.1  + 0.9 * CLEAR
  CLEAR  = LIMIT(0., 1.,((DTR/DSO) - A)/B)
PARAMETER A = 0.25, B = 0.45
```

Net long-wave radiation (RLWN, J m^{-2} d^{-1}) is approximated by three semi-empirical functions, (Penman, 1956; derived from the original Brunt (1932) formula), accounting for temperature (BBRAD, J m^{-2} s^{-1}), vapour pressure in the atmosphere (FVAP, unitless) and sky clearness (FCLEAR, unitless). Note that the parameters used in these functions are not unitless so that in the literature a large number of values exist leading to a lot of confusion

Table 2.1. Indicative values for empirical constants in the Ångström formula in relation to latitude and climate used by the FAO (Frère & Popov, 1979).

	A	B
Cold and temperate zones	0.18	0.55
Dry tropical zones	0.25	0.45
Humid tropical zones	0.29	0.42

about the 'Penman' formula. Penman's original sky clearness factor (CLEAR, unitless) contains *n*/*N*, in which *n* is the actual sunshine duration (h d^{-1}), as measured with a Campbell-Stokes solarimeter, and *N* is the maximum possible sunshine duration (dependent on latitude and time of the year). If *n* is not available, but DTR instead, the ratio *n*/*N* can be estimated from the atmospheric transmission ratio DTR/DSO using the Ångström formula:

$$n/N = (\mathrm{DTR/DS0} - \mathrm{A}) / \mathrm{B}$$

where A and B are empirical constants (see Table 2.1) and DS0 is the extra-terrestrial radiation, i.e. the radiation intensity at the top of the atmosphere, also called Angot's value. Its value depends on location on earth (latitude) and time of the year. Values are usually tabulated (in look-up tables), but can also be calculated using a set of equations as in one of the model's subroutines. The actual vapour pressure (AVP, mbar (daily average)) is read from the meteorological input data. If its value is not known, FVAP can be replaced by the Swinbank equation (Swinbank, 1963), which uses temperature alone. This equation is:

```
FVAP    = 1. - 9.35E-6 * (DAVTMP + 273.)**2
```

2.13.5 *Drying power term*

```
WDF     = 0.263 * (1.0 + 0.54 * WDS)
DRYP    = (SVP - AVP) * WDF
EVAPD   = DRYP/(SLOPE + PSYCH)
```

The numerical values in the equation for DRYP (mm d^{-1} mbar $°C^{-1}$) are not unitless and, therefore, depend on the dimensions of wind speed (WDS) and the vapour pressures, SVP and AVP. The numerical values applied here refer to WDS in m s^{-1}, measured at a standard height of 2 meter, and SVP and AVP expressed in mbar. The wind function (WDF, mm d^{-1} $°C^{-1}$) estimates the conductance for transfer of latent and sensible heat from the surface to the standard height and depends on roughness of the surface and atmospheric stability. In this model, the wind function for short, closed grass crops is used (Penman, 1956).

2.13.6 *Output variables*

```
TPENM  = INTGRL(0.,PENMAN)
TEVAPR = INTGRL(0.,EVAPR)
TEVAPD = INTGRL(0.,EVAPD)
```

Cumulative potential evapotranspiration since the start of the simulation (TPENM, mm) is computed as well as the cumulative values for radiation and drying power terms, respectively.

2.14 The soil water balance

The soil water balance is modelled in a simplified way. For a discussion about parametric versus deterministic modelling of the soil water balance reference is made to Stroosnijder (1982). The water balance processes considered are interception, runoff, infiltration, redistribution, external drainage, waterlogging, evaporation and transpiration.

2.14.1 *Soil compartments and soil physical characteristics*

```
PARAMETER TKL1 = 200., TKL2 = 400., TKL3 = 600.
  TKLT    = TKL1 + TKL2 + TKL3
```

The root system is usually in contact with various parts of the soil profile that may differ in texture, density and water content. Most soil water balance processes are more intensive near the surface. To take this into account, the soil profile is divided into three layers, called soil compartments. Thickness and physical characteristics of each layer are inputs to the model. The upper layer (TKL1) should be 100 to 200 mm thick, the second (TKL2) 200 to 400 mm, and the third (TKL3) 400 to 1000 mm. Their sum (TKLT, mm) should at least exceed the maximum rooting depth. The model can easily be extended to account for more heterogeneous situations by increasing the number of compartments and defining specific characteristics for each of them.

For parametric simulation, four specific points of the soil water content - water potential relation (soil moisture characteristic or pF-curve) are needed: the volumetric water contents (cm^3 H_2O cm^{-3} soil) at saturation (WCST), at field capacity (WCFC), at wilting point (WCWP) and when air dry (WCAD).

Soil water content at saturation (WCST) is equal to soil porosity. 'Field capacity' is the volumetric water content of the soil after wetting and initial (1 - 3 days) redistribution (Veihmeyer & Hendrickson, 1931). It is often treated as a soil characteristic (van Keulen, 1975; Stroosnijder, 1982; Driessen, 1986; Jansen & Gosseye, 1986), although it also depends on boundary conditions. Field capacity is usually defined as the volumetric water content at a soil moisture suction of 100 mbar or pF 2.0.

As the soil dries out, it becomes increasingly difficult for plants to extract water. At high soil water suctions (the actual value depending on environmental conditions), plants may wilt during the day and recover at night when evaporative demand is low. Above a certain value of moisture suction, plants do not recover at night and wilt permanently. The soil moisture suction then usually has a value of about 16,000 mbar or pF 4.2; the value varies among plant species. The volumetric water content at this suction value is called the permanent wilting point (or simply wilting point) of the soil. Its value depends strongly on soil type.

The amount of water available for uptake by the crop is the total amount in the soil, minus that retained at permanent wilting point. The soil water content when air dry is one third or less of that at wilting point. This concept is physically not well-defined, but simulation results are not sensitive to the value of this characteristic. The soil moisture suction of an air dry soil is assumed to be 10^7 mbar or pF 7.0 (van Keulen, 1975).

2.14.2 *Interception*

```
    AINTC  = AMIN1(RAIN, INTC*LAI)
  PARAMETER INTC = 0.25
```

The amount of rainfall intercepted by the canopy (AINTC, mm d^{-1}) equals the interception capacity per layer of leaves (INTC, mm d^{-1}) times the leaf area index (LAI). Obviously, this amount can only be intercepted if rainfall intensity (RAIN) is higher, hence the use of the AMIN1 function.

2.14.3 *Runoff*

```
    RNOFF  = AMAX1(0., (0.15 * (RAIN - AINTC - 10.)))
```

Not all the water that reaches the surface infiltrates into the soil, especially not during heavy rain. Runoff from a field can be 0 - 20% of precipitation, and even higher on unfavourable surfaces (Stroosnijder & Koné, 1982) or with large and intense showers. Runoff may be avoided under proper soil management. Runoff occurs when the rate of water supply at the soil surface exceeds the infiltration capacity and the excess water accumulated at the soil surface exceeds the surface storage capacity. Infiltration capacity is a function of the water content of the top soil layer. In the model these processes are not described explicitly, because of lack of information, and alternatively an empirical relation between runoff and rainfall is used.

2.14.4 *Infiltration*

```
    WLFL1 = AMAX1(0., RAIN-AINTC-RNOFF)
```

The infiltration rate (WLFL1, mm d^{-1}) is equal to precipitation minus interception and runoff.

2.14.5 *Redistribution*

```
    WLFL2 = AMAX1(0., WLFL1 - (WCFC1*TKL1 - WL1))
```

```
    WLFL3 = AMAX1(0., WLFL2 - (WCFC2*TKL2 - WL2))
    WLFL4 = AMAX1(0., WLFL3 - (WCFC3*TKL3 - WL3))
PARAMETER WCFC1 = 0.23
PARAMETER WCFC2 = 0.23
PARAMETER WCFC3 = 0.23
```

Most redistribution of water infiltrated in the soil profile occurs within 24 hours (except in heavy clay soils). Since a one-day time step is used in this model, it is assumed that redistribution occurs within that time step. Simulation is, therefore, straightforward; if on any day more water infiltrates a soil layer than can be retained at field capacity, the excess drains into the next layer, i.e. WLFL2, WLFL3, WLFL4 (mm d^{-1}, positive in downward direction).

2.14.6 *External drainage*

```
    DRAIN = AMIN1(DRATE, WLFL4)
    WLFL5 = INSW((DRATE - WLFL4), (WLFL4 - DRATE), 0.)
PARAMETER DRATE = 50.0
```

If more water enters the deepest layer than can be retained at field capacity, the excess is either drained below the root zone (DRAIN) or fills up (WLFL5) the soil compartments above field capacity causing waterlogging. Drainage is limited by the maximum drainage rate of the subsoil (DRATE, mm d^{-1}). A high value implies perfect drainage. A low value implies restricted drainage and waterlogged conditions may occur during wet periods. A zero value means no drainage at all (impermeable layer).

2.14.7 *Waterlogging*

```
    WLFL6  = INSW((DRATE - WLFL4),...
                  AMAX1(0., WLFL5-(WCST3*TKL3 - WL3)), 0.)
    WLFL7  = INSW((DRATE - WLFL4),...
                  AMAX1(0., WLFL6-(WCST2*TKL2 - WL2)), 0.)
    WLFL8  = INSW((DRATE - WLFL4),...
                  AMAX1(0., WLFL7-(WCST1*TKL1 - WL1)), 0.)
PARAMETER WCST1 = 0.40
PARAMETER WCST2 = 0.40
PARAMETER WCST3 = 0.40
```

Water that cannot drain, fills up the soil layers till saturation. This occurs first in the deepest layer (WLFL5, mm d^{-1}, this flow is assumed to be upward!) simulating the formation of a pseudo-groundwater table. If still more excess water is to be stored in the soil profile overlying compartments are successively filled up (through WLFL6 and WLFL7) till saturation as well. If the whole soil profile is saturated, water flows of above the surface (WLFL8). This parametric way to account for waterlogged conditions will not always be satisfactory. Dynamic simulation of waterlogging can be executed with a model named SAWAH (ten Berge et al., 1992) when the transport characteristics of the soil are known.

2.14.8 *Evaporation and transpiration*

The rate of water extraction due to evaporation (EVSW1-3, mm d^{-1}) and transpiration (TRWL1-3, mm d^{-1}) for each of the three layers is calculated later in the model (Sections 2.17 and 2.16, respectively).

2.14.9 *Calculation of soil water content*

```
WL1 = INTGRL(WL1I,(WLFL1+WLFL7-WLFL2-WLFL8-EVSW1-TRWL1))
WL2 = INTGRL(WL2I,(WLFL2+WLFL6-WLFL3-WLFL7-EVSW2-TRWL2))
WL3 = INTGRL(WL3I,(WLFL3+WLFL5-WLFL4-WLFL6-EVSW3-TRWL3))
WCL1  = WL1/TKL1
WCL2  = WL2/TKL2
WCL3  = WL3/TKL3
RWCL1 = (WCL1 - WCWP1)/(WCFC1 - WCWP1)
RWCL2 = (WCL2 - WCWP2)/(WCFC2 - WCWP2)
RWCL3 = (WCL3 - WCWP3)/(WCFC3 - WCWP3)
```

First, the amount of water (WL1-3, mm) in each of the layers is tracked by integration of all water fluxes into and out of the layers. Then the volumetric water content is computed by dividing the amount of water by the thickness of the respective layers.

2.14.10 *Output variables*

```
TDRAIN = INTGRL(0., DRAIN)
TSTORE = INTGRL(0., WLFL8)
TAINTC = INTGRL(0., AINTC)
TRNOFF = INTGRL(0., RNOFF)
```

A number of output variables are computed. Total drainage since the start of the simulation (TDRAIN, mm), total surface storage due to waterlogging (TSTORE, mm), total interception (TAINTC, mm) and total runoff (TRNOFF, mm).

2.14.11 *Checking the balances*

```
WCUM  = WL1 + WL2 + WL3
CHECK = TRAIN + WCUMI - TAINTC - TRNOFF - TDRAIN - ...
                  TSTORE - WCUM - TATRAN - TAEVAP
```

Finally, some check values are computed, the total amount of water in the soil profile (WCUM, mm) and a check on the water balance (CHECK, mm). Ideally, the latter should be zero. For TATRAN and TAEVAP see Subsection 2.16.5.

2.15 Rooted depth

2.15.1 *Introduction*

```
      ZRT    = INTGRL(ZRTI, EZRT)
```

The rooted depth (ZRT, mm) is defined as the lower depth from which the crop effectively extracts water. A root density of 0.10 cm root length per cm^3 of soil volume may be adopted as the lower density limit. This is a low threshold value as water is mobile and flows relatively easily to roots. The rooted depth is computed as the integral of the rate of root elongation (EZRT, mm d^{-1}) with the initial value of the integral at emergence (ZRTI, mm) defined in the initial section of the model.

2.15.2 *Elongation rate of roots*

```
      EZRT   = EZRTC * WSERT * AND(ZRTM - ZRT, 1.0 - DVS) *...
                               INSW(-DVS, 1., 0.)
      WSERT  = WSRT(ZRT, TKL1,TKL2,TKL3, WCL1,WCL2,WCL3,    ...
                               WCWP1,WCWP2,WCWP3)
   PARAMETER EZRTC = 12.
```

The length of fibrous roots can vary enormously without much dependence on root weight. Hence, rooted depth is calculated independently of the growth of the root mass. Rooted depth elongation rate (EZRTC) can increase at a maximum rate of 10 - 30 mm d^{-1}, but it is affected by soil physical, soil chemical and biological factors, i.e. for spring wheat a value of 12 mm d^{-1} is taken (van Keulen & Seligman, 1987).

Root growth generally stops around flowering or earlier if the maximum rooted depth (ZRTM) is reached. These limitations are introduced through the (P)CSMP AND-function (for DVS>1.0 or ZRT>ZRTM this function assumes the value 0).

Low soil temperatures reduce root growth. For conditions with average daytime temperatures between 20 - 30 °C, there is no temperature effect on EZRT.

It is assumed that root extension ceases when the root tip reaches a soil compartment with a moisture content at or below wilting point, as described in the self-defined FORTRAN function WSRT.

2.15.3 *Maximum depth of roots*

```
      ZRTM   = AMIN1(ZRTMC, ZRTMS, TKLT)
   PARAMETER ZRTMS = 1200.
   PARAMETER ZRTMC = 1200.
```

The model takes for the maximum rooted depth the minimum of the values set by soil properties (ZRTMS, mm), crop characteristics (ZRTMC, mm), or in the model (TKLT, mm).

Roots grow to a certain maximum depth (ZRTM) if they are not restricted by soil conditions. The maximum depth depends on plant species (ZRTMC) and ranges from 0.5 - 1.5 m or more. Significant differences between cultivars for this characteristic have been reported (Teare & Peet, 1983).

A very dense soil offers mechanical resistance which hampers root extension and reduces the maximum attainable depth. An obvious case is where shallow soil overlies bedrock. High soil densities can also be found at depths of 0.3 - 0.8 m in deep soils, particularly just below the plough layer (hardpan). Its creation may be intentional, such as during soil preparation in irrigated rice where a hardpan is needed to reduce drainage. A compacted layer can also develop unintentionally, such as when harvesting crops with heavy machinery. A physical limitation to rooting depth is approximated by specification of a maximum depth as a soil characteristic (ZRTMS).

Sensitivity analysis has established that the maximum rooting depth is an important characteristic, though little is known about it in field crops. Maximum rooting depth should be determined around flowering, i.e. by using root observation tubes (Vos & Groenwold, 1983), or indirectly by monitoring (with neutron probes) the depths from which water is withdrawn in the absence of drainage.

2.16 Transpiration

2.16.1 *Introduction*

In the model, potential transpiration rate (PTRANS, mm d^{-1}) is calculated on the basis of the Penman-Monteith combination equation. Under ample soil moisture supply, the rate of water uptake follows this potential rate very closely. However, if insufficient water is available in the soil, uptake cannot meet the demand, i.e. actual transpiration (ATRANS, mm d^{-1}) is below the potential and stomata close as a consequence. Transpiration then follows the rate of water uptake.

Water in the crop provides only a small buffer between daily uptake and daily transpiration loss and their daily totals can be considered equal. The ratio ATRANS/PTRANS is an indicator for the degree of water stress under which the crop grows.

Maximum available water in the soil (i.e. all water held between field capacity and wilting point) varies from 0.5 - 2.5 mm water per cm rooted depth for different soils. This implies that, if soil evaporation could be avoided, a C_3 crop could produce 170 - 800 kg ha^{-1} total dry matter on the water stored in each 10 cm of rooted depth and a C_4 crop about twice as much. Obviously, water stored in the soil provides an important buffer in periods with deficient rainfall. Dry season cropping is, in fact, possible in many climates, provided that at the start there is a wet soil profile and at least 0.5 - 0.7 m of rootable soil profile.

A crop may die from water stress even before the lower soil layer reaches wilting point. The rate at which water is extracted near wilting point is so low that photosynthesis provides insufficient energy for maintenance respiration and the crop dies.

2.16.2 *Potential canopy transpiration*

```
PTRANS = (1.- EXP(-0.5*LAI)) * EVAPR +     ...
          EVAPD * AMIN1(2.0, LAI) - 0.5 * AINTC
```

Only part of the radiation term (EVAPR) of potential evapotranspiration will be used by the crop, if not all radiation is intercepted by the canopy, which is exponentially related to leaf area. Radiation not used by the canopy will reach the soil and contribute to potential soil evaporation. The average extinction coefficient for visible and near infrared radiation is about 0.5.

The drying power of the air is only effective up to a cumulative leaf area index of 2. Lower leaves do not contribute much to transpiration because little light penetrates deep into the canopy, hence their stomatal resistance is higher. Also air humidity is higher and wind speed is reduced. Potential transpiration is reduced by half (as the average of values 0.3 - 1.0 as reported by Singh & Szeicz (1979)) the amount of interception.

2.16.3 *Actual transpiration*

```
FUNCTION EDPTFT = -.10,0., -.05,0., 0.0,.15, .15,.6, ...
                          .30,.8, 0.5,1., 1.1,1.
   ERLB   = ZRT1 * AFGEN(EDPTFT, RWCL1) + ...
            ZRT2 * AFGEN(EDPTFT, RWCL2) + ...
            ZRT3 * AFGEN(EDPTFT, RWCL3)
   TRRM   = PTRANS/(ERLB + 1.E-10)

   TRWL1  = TRRM * WSE1 * ZRT1 * AFGEN(EDPTFT, RWCL1)
   TRWL2  = TRRM * WSE2 * ZRT2 * AFGEN(EDPTFT, RWCL2)
   TRWL3  = TRRM * WSE3 * ZRT3 * AFGEN(EDPTFT, RWCL3)
   ZRT1   = LIMIT(0., TKL1, ZRT)
   ZRT2   = LIMIT(0., TKL2, ZRT - TKL1)
   ZRT3   = LIMIT(0., TKL3, ZRT - TKL1 - TKL2)
   ATRANS = TRWL1 + TRWL2 + TRWL3
```

Uptake of water takes place from the rooted soil volume. To simulate water uptake in semi-arid regions, van Keulen (1975) assumed that soil moisture uptake is evenly distributed over the rooted depth, in a uniformly wetted profile. This implies that the major resistance to water flow is assumed in the soil and not in the roots.

Usually, soil water content is not uniform. In the model, each layer is treated separately. Compensatory effects can be accommodated, so that when part of the root system is in dry soil compartments, those parts that are in wetter compartments, will take up more water (cf. Lawlor, 1973). The root activity coefficient (EDPTFT) varies between 0 and 1 and is inversely related to the relative amount of available water in a soil compartment (van Keulen & Seligman, 1987, Figure 31). The effect of this factor is to decrease potential uptake per unit depth of root penetration for that part of the root system that is in dry soil compartments, thus allowing increased uptake by roots in wetter compartments. Effective root length for each soil layer is obtained by multiplying the root penetration depth with the root activity coefficient.

The potential rate of water uptake (TRRM) per millimeter of effective rooted depth is calculated by dividing the potential transpiration rate of the canopy (PTRANS) by the cumulative effective root length (ERLB, the factor 1.E-10 is introduced to avoid zero division!).

The uptake per compartment (TRWL1-3) is equal to the potential uptake rate per millimeter of effective rooted depth (TRRM) multiplied by a factor accounting for the effect of low soil moisture contents (WSE1-3), and by the effective root length per soil compartment. Total water uptake (ATRANS) is the sum of water withdrawn from the individual soil compartments.

2.16.4 *Effect of water stress*

The multiplication factors for moisture uptake due to low soil moisture contents (between 1 and 0) for the individual soil compartments (WSE1-WSE3) are discussed in Section 2.19.

2.16.5 *Output variables*

```
TPTRAN = INTGRL(0., PTRANS)
TATRAN = INTGRL(0., ATRANS)
```

Total potential canopy transpiration since the start of the simulation (TPTRAN, mm) and total water uptake (actual transpiration, TATRAN, mm) are computed.

2.17 Evaporation

Soil evaporation is important under incomplete soil cover, but is much lower than transpiration under a well developed crop canopy. Evaporation continues, albeit at a decreasing rate, until the soil is airdry.

2.17.1 *Potential soil evaporation*

```
PEVAP  = EXP(-0.5*TLAI) * (EVAPR + EVAPD)
```

Shading (also by dead leaves) is accounted for in this computation; the extinction coefficient for short-wave radiation (together with near infrared radiation) in the crop canopy is about 0.5.

2.17.2 *Effect of soil dryness*

```
DSLR   = INTGRL(1., INSW(AFGEN(RAINTB, DOY+1.)-0.5, ...
                        1.,1.00001 - DSLR)/DELT)
```

Actual evaporation rate depends on the water content of the top soil compartments. The latter cannot be correctly predicted by the model since a thin top layer cannot be simulated using time steps of one day. Therefore, an alternative formulation has been selected, based on the number of days since the last rain (DSLR) (Stroosnijder, 1982). Days with less than 0.5 mm of rain are not taken into account.

2.17.3 *Actual evaporation*

```
   AEVAP   = INSW(DSLR - 1.1, EVSH, EVSD)
   EVSH    = AMIN1(PEVAP,(WL1 - WCAD1*TKL1)/DELT + WLFL1)
PARAMETER WCAD1 = 0.025
```

In calculating the actual evaporation (AEVAP, mm d^{-1}) a distinction is made (using the value of DSLR) between days with rain (EVSH, mm d^{-1}) and days without rain (EVSD, mm d^{-1}). The former is set equal to the potential evaporation rate (PEVAP, mm d^{-1}) under the limiting condition that the top soil layer cannot be depleted beyond the airdry water content (WCAD). For days without rain the evaporation rate (EVSD) is below the potential rate calculated as:

```
   EVSD    = AMIN1(PEVAP, 0.6 * PEVAP * (SQRT(DSLR) -...
                    SQRT(DSLR - 1.)) + WLFL1)
```

The evaporation rate decreases as the topsoil starts drying. The reduction in potential evaporation rate during drying is approximated using the experimental field observation that cumulative evaporation is proportional to the square root of time (Stroosnijder, 1982, 1987). The proportionality factor (mm $(\sqrt{d})^{-1}$) is assumed to be equal to 60% of the potential evaporation rate. Rainfall too small to trigger resetting of days since the last rain are added to evaporation, since they are assumed to be lost the same day.

2.17.4 *Extraction of water from soil layers*

```
   FEVL1 = AMAX1(WL1 - WCAD1*TKL1, 0.1) * ...
                 EXP(-EES * (0.25 * TKL1))
   FEVL2 = AMAX1(WL2 - WCAD2*TKL2, 0.1) * ...
                 EXP(-EES * (TKL1 + (0.25 * TKL2)))
   FEVL3 = AMAX1(WL3 - WCAD3*TKL3, 0.1) * ...
                 EXP(-EES * (TKL1 + TKL2 + (0.25 * TKL3)))
PARAMETER EES   = 0.002
PARAMETER WCAD2 = 0.025
PARAMETER WCAD3 = 0.025
```

Partitioning parameters (FEVL1-3) are computed for the three layers. In this way, redistribution of water due to developing potential gradients is mimicked by extracting water for evaporation from all compartments with a water content above air dryness. This is achieved through the use of a soil-specific extinction coefficient (EES, mm^{-1}) (van Keulen, 1975). Weighting also accounts for the depth and thickness of layers (TKL) and their water content.

The extinction coefficient, that in principle has to be determined on the basis of experimental data, is approximately 10^{-3} mm^{-1} for heavy (clay) soils and 3×10^{-3} mm^{-1} for light (sandy) soils.

```
FEVLT  = FEVL1 + FEVL2 + FEVL3
EVSW1  = AEVAP * (FEVL1/FEVLT)
EVSW2  = AEVAP * (FEVL2/FEVLT)
EVSW3  = AEVAP * (FEVL3/FEVLT)
```

Finally, the contribution from the individual layers (EVSW1-3, mm d^{-1}) is computed by multiplying the actual evaporation rate (AEVAP) by the weighing factor for each compartment.

2.17.5 *Output variables*

```
TPEVAP = INTGRL(0., PEVAP)
TAEVAP = INTGRL(0., AEVAP)
```

Cumulative potential soil evaporation since the start of the simulation (TPEVAP, mm) and cumulative actual soil evaporation (TAEVAP, mm) are computed.

2.18 Effects of water stress

2.18.1 *Effect of soil water content on water uptake*

Both water and air must be present in sufficient amounts in the soil for optimal uptake of soil water by roots. Since water content (WCL, θ) and air content are complementary (soil porosity), the dependence of actual water uptake rate on soil water content shows an optimum (Feddes et al., 1978). Starting from wilting point (θ_{wp}), water uptake rate first rises linearly with increasing soil water content until it reaches the potential transpiration rate (the evaporative demand, T_m). The water content at which this occurs is called the critical soil water content θ_c. Transpiration rate remains at its potential level over a range of water contents reaching to well over field capacity. At some point beyond field capacity (θ_{fc}), transpiration is hampered again. The shape of this response curve is depicted in Figure 2.1, where the actual transpiration rate T is given scaled to the potential transpiration rate T_m. In contrast to Feddes et al. (1978), not soil water potential, but soil water content is chosen as the independent variable (Gollan et al., 1986; Schulze, 1986). In the computational procedure (FUNCTION FUFR), the current value of water content determines which linear segment must be used.

It is convenient to scale water content in the lower dry part as a fraction of the range $\theta_{fc} - \theta_{wp}$, to the so-called *reduced water content* (Bresler, 1991):

$$S = \frac{(\theta - \theta_{wp})}{(\theta_{fc} - \theta_{wp})}$$

The critical moisture content θ_c, that denotes the transition from water-limited to potential transpiration rate is not at a fixed value. Restriction of water uptake rate due to water shortage starts at a higher water content when potential transpiration rate is higher, in other words θ_c then shifts to higher values. This phenomenon was documented by Denmead & Shaw (1962). Driessen (1986) listed the dependence of the relative position of this point in his Table 20, for five groups of plants that differ in drought sensitivity. This table can be summarized in the following way:

i) The crop groups are characterized by the potential transpiration rate at which the critical soil water content θ_c is just halfway wilting point and field capacity, in other words where S is 0.5. This characteristic potential transpiration rate $T_{S=0.5}$ is given in Table 2.2 for the five crop groups of Table 20 of Driessen (1986).

ii) The soil water depletion fraction p is then calculated as:

$$p = T_{S=0.5} \,/\, (T_m + T_{S=0.5})$$

or

$$1 - p = T_m \,/\, (T_m + T_{S=0.5})$$

The soil water content at which transpiration starts to fall short of the potential, the so-called critical soil water content, is given by:

$$\theta_c = \theta_{wp} + (1 - p)\ (\theta_{fc} - \theta_{wp})$$

iii) The ratio between actual transpiration rate in the lower, dry part of the curve and the potential rate is now given by:

$$f_r = \frac{S}{(1 - p)}$$

After substitution of the equation for p we find a simple expression for the actual transpiration rate:

$$T = (T_m + T_{S=0.5})\ S$$

This latter expression is not actually used in the program, but the ratio f_r is used instead. Here it serves to show the resulting dependence of actual transpiration on the two environmental conditions, potential rate T_m and actual water content θ (WCL), on the two soil parameters θ_{fc} and θ_{wp}, and on the plant parameter $T_{S=0.5}$.

Table 2.2. Characteristic potential transpiration rates for five crop groups according to Driessen (1986). (Source: Doorenbos et al., 1978).

Crop group	$T_{S=0.5}$ (mm d^{-1})	Crops (example)
1	1.8	leaf vegetables
2	3	clover, carrot
3	4.5	pea, potato
4	6	groundnut
5	9	most grains, soybean

Implementation in the model:

```
          P            = TRANSC/(TRANSC + PTRANS)
PARAMETER TRANSC = 8.

          WSE1         = FUFR(WCL1,WCFC1,P,WCWP1,WCWET1,WCST1)
          WSE2         = FUFR(WCL2,WCFC2,P,WCWP2,WCWET2,WCST2)
          WSE3         = FUFR(WCL3,WCFC3,P,WCWP3,WCWET3,WCST3)

PARAMETER WCWET1 = 0.35
PARAMETER WCWET2 = 0.35
PARAMETER WCWET3 = 0.35
PARAMETER WCWP1  = 0.075
PARAMETER WCWP2  = 0.075
PARAMETER WCWP3  = 0.075
```

The effect of availability of soil water on uptake in a compartment is presented by a factor (WSE1-3), with a value between 0.0 and 1.0. Figure 2.1 schematically shows the relation between this stress factor and the soil water content.

These WSE-factors are computed in the function FUFR. This function requires as inputs, the water content in the soil layer (WCL), the soil depletion factor (P), the water contents at field capacity (WCFC), wilting point (WCWP) and saturation (WCST), and the sensitivity coefficient for waterlogging (WCWET).

Description of the function FUFR:

```
          REAL FUNCTION FUFR(WCL,WCFC,P,WCWP,WCWET,WCST)
          IMPLICIT REAL (A-Z)
```

In the model the critical water content (WCCR) is first calculated on the basis of the critical transpiration rate (P, a crop property):

```
WCCR = WCWP + (1. - P) * (WCFC - WCWP)

IF(WCL.GT.WCWET) THEN
   FR = (WCST-WCL)/(WCST-WCWET)
ELSE
    IF(WCL.GT.WCCR) THEN
       FR = 1.
    ELSE
       FR = (WCL-WCWP)/(WCCR - WCWP)
    ENDIF
ENDIF

FUFR = AMIN1(1.,AMAX1(0., FR))

RETURN
END
```

Water stress factors for the individual layers (WSE1-3) are used to compute total water uptake in Section 2.16. This leads to the actual transpiration (ATRANS).

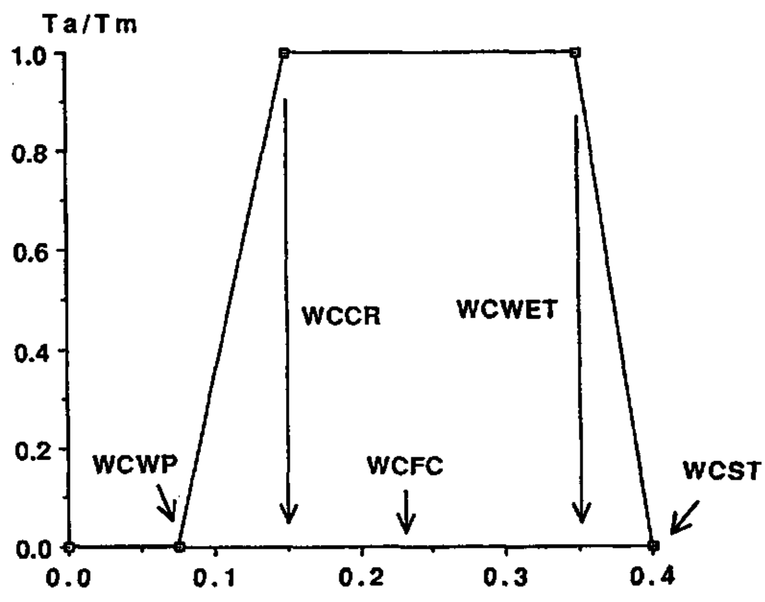


Figure 2.1. Water stress factor (WSE) as a function of soil moisture content. Wilting point (WCWP, θ_{wp}), field capacity (WCFC, θ_{fc}) and saturation (WCST, θ_{st}) are soil characteristics. Values for WCCR depend on the potential transpiration/leaf area ratio and the sensitivity.

2.18.2 *Effect on CO_2 assimilation*

```
PCEW  = ATRANS/(PTRANS + 1.E-10)
```

The most significant influence of water stress is on photosynthesis. Under ample moisture supply, leaf conductance is proportional to rate of photosynthesis so that photosynthesis rate largely determines transpiration rate (Goudriaan & van Laar, 1978). When water is in short supply, the inverse is true, as the rate of water uptake from the soil is then of crucial importance in governing stomatal opening and CO_2 assimilation is below its potential.

The factor used to reduce photosynthesis is PCEW. Where in the model daily total gross CO_2 assimilation (DTGA, kg CO_2 ha^{-1} ground d^{-1}) is calculated (see Section 2.6) this is multiplied by PCEW.

2.18.3 *Effect on carbohydrate partitioning*

```
CPEW  = AMIN1(1., 0.5 + ATRANS/(PTRANS + 1.E-10))
```

The ratio of actual transpiration (ATRANS) and potential transpiration (PTRANS) is also used to represent the influence of water shortage on dry matter partitioning. When this ratio is above 0.5, the effect on physiological processes is usually small.

Carbohydrate partitioning between shoot and root under water stress is altered in favour of the root biomass. Brouwer (1962) described the physiological principle of this mechanism, based on the functional equilibrium. Yet it is difficult to quantify the instantaneous growth stimulation of root biomass in response to water stress. It is assumed that up to a moderate stress level (ATRANS/PTRANS > 0.5), there is no significant effect on partitioning. At higher stress levels during the vegetative phase, the share that goes to the roots increases by up to 50% of the amount that otherwise would go to the shoot.

It is assumed that the relative partitioning of carbohydrates within the shoots between leaves, stems and storage organs is affected similarly to the partitioning between shoots and roots.

The parameter CPEW (between 1 and 0) is used in the model as a multiplier in the calculation of the fraction of total dry matter increase allocated to the shoots (FSH) and to the leaves (FLV) and stems (FST), see Section 2.8.

2.19 Water use efficiency

```
TDTGA  = INTGRL(0., DTGA)
TAR    = TATRAN * 1.E4/(TDTGA + 1.E-10)
TRC    = TATRAN * 1.E4/(TDRW  + NOT(TDRW))
CROPF  = (PTRANS + PEVAP)/PENMAN
```

Various terms are used to express water use by crops. The most general one is the term 'crop water requirement' (Doorenbos & Kassam, 1979), i.e. the total amount of water needed to grow a crop. This amount includes both transpiration and evaporation. Values vary substantially among locations and years due to this inclusion of the soil evaporation. Hence, this value is not used here.

Crop water requirements are often expressed in terms of the Penman reference evaporation through the use of 'crop factors', CROPF (see e.g. Doorenbos & Pruitt, 1977; Feddes, 1987). In SUCROS2, we do not use this approach but CROPF is calculated to facilitate comparison with this common approach.

The 'transpiration coefficient', TRC, or its inverse the 'water use efficiency', is defined as the total amount of water transpired (TATRAN), divided by the total amount of biomass produced (TDRW, kg DM ha^{-1}). Note that soil evaporation is not included in this coefficient. It was established many years ago (de Wit, 1958; Tanner & Sinclair, 1982), that the transpiration coefficient during water stress is equal to that without stress. This is due to the constancy of the ratio of internal over external CO_2 concentration at different stress levels. Obviously, there are considerable, but predictable, differences in transpiration coefficient among environments and species.

Transpiration coefficient is still a crude concept in crop physiological studies, so a 'water use coefficient' of the crop, TAR (transpiration/assimilation ratio), defined as the amount of water transpired per unit gross photosynthesis in kilogram water per kilogram CO_2, is also used (van Keulen & van Laar, 1986). This TAR can be calculated on a daily basis (ATRANS/DTGA) as well as using cumulative values (TATRAN/TDTGA). Values for this water use coefficient range from about 50 or less to 200 or more. The lower values apply to C_4 crops in humid conditions and the high values to C_3 crops in dry climates.

2.20 Weather characteristics

Weather data given in the model are for Wageningen (the Netherlands) averaged over the years 1951 - 1980. FUNCTION DTRT is a tabulated function for measured daily global radiation (MJ m^{-2}), TMAXT and TMINT are tabulated functions for measured daily maximum and minimum temperature, respectively (°C).

```
FUNCTION DTRT  =15, 2.1,   46, 4.4,   74, 7.8,   105,13.0,...
    135,16.3,  166,17.5,  196,15.6,  227,13.8,  258,10.0,...
    288,5.8,   319, 2.7,  349, 1.7
FUNCTION TMAXT =15, 4.3,   46, 5.4,   74, 8.9,   105,12.4,...
    135,17.3,  166,20.5,  196,21.4,  227,21.5,  258,18.9,...
    288,14.3,  319, 8.6,  349, 5.5
FUNCTION TMINT =15,-0.7,   46,-0.6,   74, 1.2,   105, 3.3,...
    135, 7.3,  166,10.3,  196,12.2,  227,12.0,  258, 9.7,...
    288, 6.5,  319, 2.9,  349, 0.6

FUNCTION RAINTB = 1., 5.,    365.,5.
FUNCTION VAPHTB = 1., 1.5    365.,1.5
FUNCTION WSTB   = 1., 2.,    365.,2.
```

FUNCTION RAINTB, VAPHTB and WSTB are tables which also should contain 365 data pairs of daily values of recorded rainfall (mm), measured daily average values of vapour pressure in the air (kPa) and measured daily average values of wind speed (m s^{-1}), respectively. In here, some artificial numbers are given.

2.21 Carbon balance check

```
      CHKIN  = (WLV-WLVI) * CFLV + (WST-WSTI) * CFST + ...
               (WRT-WRTI) * CFRT + WSO * CFSO
      CHKFL  = TNASS * (12./44.)
      TNASS  = INTGRL(0., ((GPHOT - MAINT)*44./30.) - ...
                          (GRT*CO2RT + GLV*CO2LV    + ...
                  (GST+TRANSL)*CO2ST + GSO*CO2SO    + ...
                     (1.-0.947)*TRANSL*CFST*44./12.))
      CO2RT  = 44./12. * (ASRQRT*12./30. - CFRT)
      CO2LV  = 44./12. * (ASRQLV*12./30. - CFLV)
      CO2ST  = 44./12. * (ASRQST*12./30. - CFST)
      CO2SO  = 44./12. * (ASRQSO*12./30. - CFSO)

      CHKDIF = ABS((CHKIN-CHKFL)/(NOT(CHKIN)+CHKIN))
FINISH CHKDIF = 1.0E-3

   PARAMETER CFLV=0.459, CFST=0.494, CFRT=0.467, CFSO=0.471
```

2.22 Run control

```
     DOY    = AMOD(TIME, 365.)
   FINISH DVS    = 2.
   TIMER TIME    = 80., FINTIM=300., DELT=1., PRDEL=5.
   METHOD RECT

   PRINT DOY,DVS,TDRW,TADRW,WLVG,WLVD,WLV,WST,WSO,WRT,LAI,HI,...
         TPENM,TEVAPR,TEVAPD,TRAIN,TAINTC,TRNOFF,TDRAIN,      ...
         TSTORE,TPTRAN,TATRAN,TPEVAP,TAEVAP,CHECK,TAR,TRC,    ...
         EVAPR,EVAPD,CROPF,WSE1,WSE2,WSE3,PCEW,CPEW,ZRT,WCUM
```

In addition to the variables treated in SUCROS1, a number of additional variables, which reflect the crop and soil water balances, are specified. All values are stored in the output file FOR06.DAT at every print interval (PRDEL).

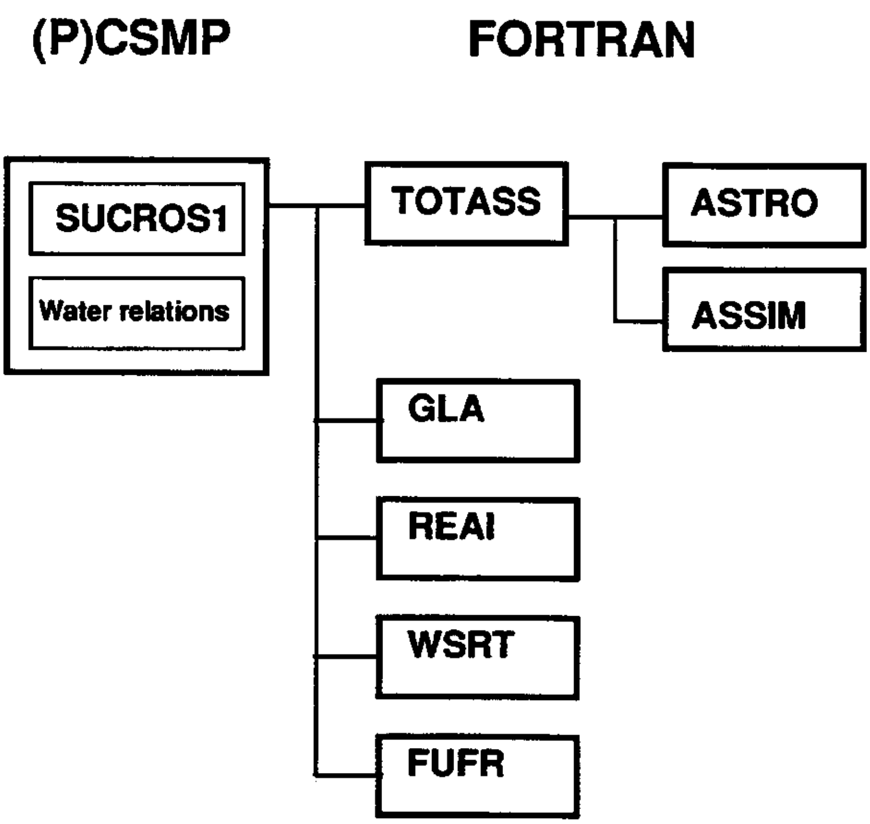
`END` completes the specifications of the model;
`STOP` terminates the simulation run;

`SUBROUTINES`

`ENDJOB` terminates the job.

2.23 Subroutines

The structure of the model SUCROS2 is given below. Double framed rectangle indicates the main program, written in (P)CSMP, calling FORTRAN subroutines. SUCROS2 is an extension of SUCROS1. There are two additional subroutines/functions (FUFR is used to compute water stress factors for each soil layer and WSRT to decide whether root extension growth continues or ceases), and the main programme in (P)CSMP is extended with a section on water relations.



2.24 Listing of the model SUCROS2

```
TITLE CROP GROWTH FOR WATER-LIMITED PRODUCTION (SUCROS2)

*     Spring wheat, Version September 1992


* 2.1 INTRODUCTION

*    The basis for this model is a simple and universal crop growth   *
*    simulator, named SUCROS87. The 1987 version of the model is      *
*    described by C.J.T. Spitters, H. van Keulen and D.W.G.           *
*    van Kraalingen in 'Simulation and Systems Management in Crop     *
*    Protection'. Eds R. Rabbinge, S.A. Ward and H.H. van Laar,       *
*    Simulation Monographs, Pudoc, Wageningen (1989), pp. 147-181.    *

*    This model describes production under rainfed conditions by      *
*    including crop and soil water balances into the model for        *
*    potential production. Crop and water balances are based on       *
*    earlier versions documented e.g. by Stroosnijder (1982) in       *
*    'Simulation of plant growth and crop production'. Eds F.W.T.     *
*    Penning de Vries and H.H. van Laar, Simulation Monographs,       *
*    Pudoc, Wageningen, pp. 175-193.                                  *


* 2.2 INITIAL CONDITIONS

INITIAL
PARAMETER DOYEM  = 90.
INCON NPL        = 210.
INCON LAO        = 5.7E-5
INCON WLVI       = 0.
INCON WSTI       = 0.
INCON WRTI       = 0.

INCON ZRTI       = 5.
WL1I             = WCLI1 * TKL1
WL2I             = WCLI2 * TKL2
WL3I             = WCLI3 * TKL3
INCON WCLI1      = 0.20
INCON WCLI2      = 0.20
INCON WCLI3      = 0.20
WCUMI            = WL1I + WL2I + WL3I
PCEW             = 1.


* 2.3 CROP DEVELOPMENT
```

```
DYNAMIC
      DVS          = INTGRL(0., DVR)
      DVR          = INSW(DVS-1., AFGEN(DVRVT, DAVTMP),...
                                  AFGEN(DVRRT, DAVTMP)) * EMERG
      EMERG        = INSW(DOY-DOYEM, 0., 1.)
FUNCTION DVRVT     = -10.,0., 0.,0., 30.,0.027
FUNCTION DVRRT     = -10.,0., 0.,0., 30.,0.031


* 2.4 LEAF CO2 ASSIMILATION

      AMAX         = AMX * AMDVS * AMTMP
      AMDVS        = AFGEN(AMDVST, DVS)
      AMTMP        = AFGEN(AMTMPT, DDTMP)
PARAMETER AMX      = 40.
FUNCTION AMDVST    = 0.0,1.0, 1.0,1.0, 2.0,0.5, 2.5,0.0
FUNCTION AMTMPT    = 0.,0., 10.,1., 25.,1., 35.,0., 50.,0.


* 2.5 DAILY GROSS CO2 ASSIMILATION

 DAYL,DTGA,DSO     = TOTASS(DOY,LAT,DTR,SCP,AMAX,EFF,KDF,LAI)
PARAMETER EFF      = 0.45
PARAMETER KDF      = 0.60
PARAMETER SCP      = 0.20
PARAMETER LAT      = 52.


* 2.6 CARBOHYDRATE PRODUCTION

      GPHOT        = DTGA  * PCEW * 30./44.


* 2.7 MAINTENANCE

      MAINT        = MAINTS * TEFF * MNDVS
      MAINTS       = MAINLV*WLV + MAINST*WST + MAINRT*WRT + MAINSO*WSO
      MNDVS        = WLVG / (WLV+NOT(WLV))
      TEFF         = Q10**((DAVTMP-TREF)/10.)
PARAMETER Q10      = 2.,    TREF = 25.
PARAMETER MAINLV = 0.03,  MAINST = 0.015
PARAMETER MAINRT = 0.015, MAINSO = 0.01


* 2.8 DRY MATTER PARTITIONING

      FSHP         = AFGEN(FSHTB, DVS)
      FSH          = (FSHP * CPEW) / (1. + (CPEW-1.) * FSHP)
```

```
      FRT          = 1. - FSH
FUNCTION FSHTB     = 0.00,0.50, 0.10,0.50, 0.20,0.60, 0.35,0.78,...
                     0.40,0.83, 0.50,0.87, 0.60,0.90, 0.70,0.93,...
                     0.80,0.95, 0.90,0.97, 1.00,0.98, 1.10,0.99,...
                     1.20,1.00, 2.50,1.00

      FLV          = AFGEN(FLVTB, DVS)
      FST          = AFGEN(FSTTB, DVS)
      FSO          = 1. - FLV - FST
FUNCTION FLVTB     = 0.00,0.65, 0.10,0.65, 0.25,0.70, 0.50,0.50,...
                     0.70,0.15, 0.95,0.00, 2.50,0.00
FUNCTION FSTTB     = 0.00,0.35, 0.10,0.35, 0.25,0.30, 0.50,0.50,...
                     0.70,0.85, 0.95,1.00, 1.05,0.00, 2.50,0.00


* 2.9 GROWTH OF PLANT ORGANS AND TRANSLOCATION

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

      TRANSL       = INSW(DVS-1., 0., WST * DVR * FRTRL)

      GTW          = (GPHOT - MAINT + 0.947*TRANSL*CFST*30./12.) / ASRQ
      GRT          = FRT * GTW
      GLV          = FLV * FSH * GTW
      GST          = FST * FSH * GTW - TRANSL
      GSO          = FSO * FSH * GTW

PARAMETER ASRQRT = 1.444, ASRQLV = 1.463
PARAMETER ASRQST = 1.513, ASRQSO = 1.415
PARAMETER FRTRL  = 0.20


* 2.10 LEAF AND EAR DEVELOPMENT

      TLAI         = 0.5 * EAI + INTGRL(0., GLAI)
      LAI          = 0.5 * EAI + INTGRL(0., GLAI-DLAI)
      GLAI         = GLA(DOY, DOYEM, DTEFF, DVS, NPL, LA0, ...
                        RGRL, DELT,   SLA, LAI, GLV)
PARAMETER RGRL     = 0.009
PARAMETER SLA      = 0.0022

       EAI         = INTGRL(0., REAI(DELT,DVS,EAR,TADRW,RDRDV,EAI))
PARAMETER EAR      = 6.3E-5

      DLAI         = LAI * RDR
      RDR          = AMAX1(RDRDV, RDRSH)
      RDRDV        = INSW(DVS-1.0, 0., AFGEN(RDRT, DAVTMP))
      RDRSH        = LIMIT(0., 0.03, 0.03 * (LAI-LAICR) / LAICR)
```

```
FUNCTION RDRT     = -10.,0.03, 10.,0.03, 15.,0.04, 30.,0.09
PARAMETER LAICR   = 4.0

      DLV         = WLVG * DLAI/(LAI+NOT(LAI))


* 2.11 DRY MATTER PRODUCTION

      WRT         = INTGRL(WRTI, GRT)
      WLVG        = INTGRL(WLVI, GLV-DLV)
      WLVD        = INTGRL(0.,   DLV)
      WST         = INTGRL(WSTI, GST)
      WSO         = INTGRL(0.,   GSO)

      WLV         = WLVG  + WLVD
      TADRW       = WLV   + WST   + WSO
      TDRW        = TADRW + WRT

      HI          = WSO / (TADRW + NOT(TADRW))


* 2.12 WEATHER DATA

      DTR         = AFGEN(DTRT,   DOY) * 1.E06

      DTMAX       = AFGEN(TMAXT, DOY)
      DTMIN       = AFGEN(TMINT, DOY)
      DAVTMP      = 0.5 * (DTMAX + DTMIN)
      DDTMP       = DTMAX - 0.25 * (DTMAX-DTMIN)

      DTEFF       = AMAX1(0., DAVTMP-TBASE)
PARAMETER TBASE   = 0.

      AVP         = AFGEN(VAPHTB, DOY) * 10.
      WDS         = AFGEN(WSTB,    DOY)
      RAIN        = AFGEN(RAINTB, DOY)

      TRAIN       = INTGRL(0., RAIN)


* 2.13 PENMAN-MONTEITH COMBINATION EQUATION

      PENMAN      = EVAPR + EVAPD

      EVAPR       = (1./LHVAP) * (SLOPE/(SLOPE+PSYCH)) * NRAD
      SLOPE       = 4158.6 * SVP / (DAVTMP + 239.)**2
      SVP         = 6.11 * EXP(17.4 * DAVTMP / (DAVTMP + 239.))
PARAMETER LHVAP   = 2.4E6
```

```
PARAMETER PSYCH  = 0.67

      NRAD       = (1.-ALB)* DTR - RLWN
      ALB        = ALBS*EXP(-0.5*LAI) + 0.25*(1.-EXP(-0.5*LAI))
      ALBS       = 0.25 * (1.-0.5*WCL1/WCST1)

      RLWN       = BBRAD * FVAP * FCLEAR * 86400.
      BBRAD      = BOLTZM * (DAVTMP+273.)**4
PARAMETER BOLTZM = 5.668E-8
      FVAP       = 0.56-0.079*SQRT(AVP)
      FCLEAR     = 0.1+0.9*CLEAR
      CLEAR      = LIMIT(0., 1., ((DTR/DS0)-A)/B)
PARAMETER A      = 0.25, B=0.45

      WDF        = 0.263 * (1.0 + 0.54 * WDS)
      DRYP       = (SVP-AVP) * WDF
      EVAPD      = DRYP/(SLOPE+PSYCH)

      TPENM      = INTGRL(0., PENMAN)
      TEVAPR     = INTGRL(0., EVAPR)
      TEVAPD     = INTGRL(0., EVAPD)


* 2.14 THE SOIL WATER BALANCE

PARAMETER TKL1   = 200., TKL2   = 400., TKL3   = 600.
      TKLT       = TKL1 + TKL2 + TKL3

      AINTC      = AMIN1(RAIN, INTC*LAI)
PARAMETER INTC   = 0.25

      RNOFF      = AMAX1(0., 0.15*(RAIN-AINTC-10.))

      WLFL1      = AMAX1(0., RAIN-AINTC-RNOFF)

      WLFL2      = AMAX1(0., WLFL1-(WCFC1*TKL1-WL1))
      WLFL3      = AMAX1(0., WLFL2-(WCFC2*TKL2-WL2))
      WLFL4      = AMAX1(0., WLFL3-(WCFC3*TKL3-WL3))
PARAMETER WCFC1  = 0.23
PARAMETER WCFC2  = 0.23
PARAMETER WCFC3  = 0.23

      DRAIN      = AMIN1(DRATE, WLFL4)
      WLFL5      = INSW((DRATE-WLFL4), (WLFL4-DRATE), 0.)
PARAMETER DRATE  = 50.0

      WLFL6      = INSW((DRATE-WLFL4),...
                   AMAX1(0., WLFL5-(WCST3*TKL3-WL3)), 0.)
      WLFL7      = INSW((DRATE-WLFL4),...
```

```
                  AMAX1(0., WLFL6-(WCST2*TKL2-WL2)), 0.)
      WLFL8     = INSW((DRATE-WLFL4),...
                  AMAX1(0., WLFL7-(WCST1*TKL1-WL1)), 0.)
PARAMETER WCST1 = 0.40
PARAMETER WCST2 = 0.40
PARAMETER WCST3 = 0.40

      WL1       = INTGRL(WL1I, (WLFL1+WLFL7-WLFL2-WLFL8-EVSW1-TRWL1))
      WL2       = INTGRL(WL2I, (WLFL2+WLFL6-WLFL3-WLFL7-EVSW2-TRWL2))
      WL3       = INTGRL(WL3I, (WLFL3+WLFL5-WLFL4-WLFL6-EVSW3-TRWL3))
      WCL1      = WL1/TKL1
      WCL2      = WL2/TKL2
      WCL3      = WL3/TKL3
      RWCL1     = (WCL1-WCWP1)/(WCFC1-WCWP1)
      RWCL2     = (WCL2-WCWP2)/(WCFC2-WCWP2)
      RWCL3     = (WCL3-WCWP3)/(WCFC3-WCWP3)

      TDRAIN    = INTGRL(0., DRAIN)
      TSTORE    = INTGRL(0., WLFL8)
      TAINTC    = INTGRL(0., AINTC)
      TRNOFF    = INTGRL(0., RNOFF)

      WCUM      = WL1+WL2+WL3
      CHECK     = TRAIN+WCUMI-TAINTC-TRNOFF-TDRAIN-TSTORE-WCUM-...
                  TATRAN-TAEVAP


* 2.15 ROOTED DEPTH

      ZRT       = INTGRL(ZRTI, EZRT)

      EZRT      = EZRTC * WSERT * AND(ZRTM-ZRT, 1.0-DVS) *...
                  INSW(-DVS, 1., 0.)
      WSERT     = WSRT(ZRT,TKL1,TKL2,TKL3,WCL1,WCL2,WCL3, ...
                       WCWP1,WCWP2,WCWP3)
PARAMETER EZRTC = 12.

      ZRTM      = AMIN1(ZRTMC, ZRTMS, TKLT)
PARAMETER ZRTMS = 1200.
PARAMETER ZRTMC = 1200.


* 2.16 TRANSPIRATION

      PTRANS    = (1. - EXP(-0.5*LAI)) * EVAPR + EVAPD * ...
                   AMIN1(2.0, LAI) - 0.5 * AINTC

FUNCTION EDPTFT = -.10,0., -.05,0., 0.,.15, .15,.6, .3,.8, .5,1., 1.1,1.
```

```
      ERLB          = ZRT1*AFGEN(EDPTFT, RWCL1) +...
                      ZRT2*AFGEN(EDPTFT, RWCL2) +...
                      ZRT3*AFGEN(EDPTFT, RWCL3)
      TRRM          = PTRANS/(ERLB+1.E-10)

      TRWL1         = TRRM*WSE1*ZRT1*AFGEN(EDPTFT, RWCL1)
      TRWL2         = TRRM*WSE2*ZRT2*AFGEN(EDPTFT, RWCL2)
      TRWL3         = TRRM*WSE3*ZRT3*AFGEN(EDPTFT, RWCL3)
      ZRT1          = LIMIT(0., TKL1, ZRT)
      ZRT2          = LIMIT(0., TKL2, ZRT-TKL1)
      ZRT3          = LIMIT(0., TKL3, ZRT-TKL1-TKL2)

      ATRANS        = TRWL1+TRWL2+TRWL3

      TPTRAN        = INTGRL(0., PTRANS)
      TATRAN        = INTGRL(0., ATRANS)


* 2.17 EVAPORATION

      PEVAP         = EXP(-0.5*TLAI) * (EVAPR + EVAPD)

      DSLR          = INTGRL(1., INSW(AFGEN(RAINTB, DOY+1.)-0.5, 1.,...
                                     1.00001-DSLR)/DELT)

      AEVAP         = INSW(DSLR-1.1, EVSH, EVSD)
      EVSH          = AMIN1(PEVAP, (WL1-WCAD1*TKL1)/DELT+WLFL1)
PARAMETER WCAD1     = 0.025

      EVSD          = AMIN1(PEVAP, 0.6*PEVAP*(SQRT(DSLR)-...
                      SQRT(DSLR-1.))+WLFL1)

      FEVL1         = AMAX1(WL1-WCAD1*TKL1, 0.1)*EXP(-EES*(0.25*TKL1))
      FEVL2         = AMAX1(WL2-WCAD2*TKL2, 0.1)*EXP(-EES*(TKL1+...
                      (0.25*TKL2)))
      FEVL3         = AMAX1(WL3-WCAD3*TKL3, 0.1)*EXP(-EES*(TKL1+TKL2+...
                      (0.25*TKL3)))
PARAMETER EES       = 0.002
PARAMETER WCAD2     = 0.025
PARAMETER WCAD3     = 0.025

      FEVLT         = FEVL1+FEVL2+FEVL3
      EVSW1         = AEVAP*(FEVL1/FEVLT)
      EVSW2         = AEVAP*(FEVL2/FEVLT)
      EVSW3         = AEVAP*(FEVL3/FEVLT)

      TPEVAP        = INTGRL(0., PEVAP)
      TAEVAP        = INTGRL(0., AEVAP)
```

```
* 2.18 EFFECTS OF WATER STRESS

      P            = TRANSC/(TRANSC+PTRANS)
PARAMETER TRANSC = 8.

      WSE1         = FUFR(WCL1,WCFC1,P,WCWP1,WCWET1,WCST1)
      WSE2         = FUFR(WCL2,WCFC2,P,WCWP2,WCWET2,WCST2)
      WSE3         = FUFR(WCL3,WCFC3,P,WCWP3,WCWET3,WCST3)
PARAMETER WCWET1 = 0.35
PARAMETER WCWET2 = 0.35
PARAMETER WCWET3 = 0.35
PARAMETER WCWP1  = 0.075
PARAMETER WCWP2  = 0.075
PARAMETER WCWP3  = 0.075

      PCEW         = ATRANS/(PTRANS+1.E-10)
      CPEW         = AMIN1(1., 0.5+ATRANS/(PTRANS+1.E-10))


* 2.19 WATER USE EFFICIENCY

      TDTGA        = INTGRL(0., DTGA)
      TAR          = TATRAN*1.E4/(TDTGA+1.E-10)
      TRC          = TATRAN*1.E4/(TDRW+NOT(TDRW))
      CROPF        = (PTRANS+PEVAP)/PENMAN


* 2.20 WEATHER CHARACTERISTICS

FUNCTION DTRT    =  15., 2.1,  46., 4.4,  74., 7.8, 105.,13.0, ...
       135.,16.3,  166.,17.5, 196.,15.6, 227.,13.8, 258.,10.0, ...
       288., 5.8,  319., 2.7, 349., 1.7
FUNCTION TMAXT   =  15., 4.3,  46., 5.4,  74., 8.9, 105.,12.4, ...
       135.,17.3,  166.,20.5, 196.,21.4, 227.,21.5, 258.,18.9, ...
       288.,14.3,  319., 8.6, 349., 5.5
FUNCTION TMINT   =  15.,-0.7,  46.,-0.6,  74., 1.2, 105., 3.3, ...
       135., 7.3,  166.,10.3, 196.,12.2, 227.,12.0, 258., 9.7, ...
       288., 6.5,  319., 2.9, 349., 0.6

FUNCTION RAINTB  = 1.,5.,    365.,5.
FUNCTION VAPHTB  = 1.,1.5,   365.,1.5
FUNCTION WSTB    = 1.,2.,    365.,2.


* 2.21 CARBON BALANCE CHECK

      CHKIN        = (WLV - WLVI) * CFLV + (WST - WSTI) * CFST + ...
                     (WRT - WRTI) * CFRT + WSO * CFSO
```

```
      CHKFL        = TNASS * (12./44.)
      TNASS        = INTGRL(0., ((GPHOT - MAINT)*44./30.) -  ...
                               (GRT*CO2RT + GLV*CO2LV    + ...
                         (GST+TRANSL)*CO2ST + GSO*CO2SO    + ...
                            (1.-0.947)*TRANSL*CFST*44./12.))
      CO2RT        = 44./12. * (ASRQRT*12./30. - CFRT)
      CO2LV        = 44./12. * (ASRQLV*12./30. - CFLV)
      CO2ST        = 44./12. * (ASRQST*12./30. - CFST)
      CO2SO        = 44./12. * (ASRQSO*12./30. - CFSO)

      CHKDIF       = ABS((CHKIN-CHKFL)/(NOT(CHKIN)+CHKIN))
FINISH CHKDIF      = 1.0E-3

PARAM CFLV=0.459, CFST=0.494, CFRT=0.467, CFSO=0.471


* 2.22 RUN CONTROL

      DOY          = AMOD(TIME, 365.)
FINISH DVS         = 2.

TIMER TIME         = 80., FINTIM = 300., DELT = 1., PRDEL = 5.
METHOD RECT

PRINT DOY,DVS,TDRW,TADRW,WLVG,WLVD,WLV,WST,...
      WSO,WRT,LAI,EAI,HI,...
      TPENM,TEVAPR,TEVAPD,TRAIN,TAINTC,TRNOFF,TDRAIN,TSTORE,...
      TPTRAN,TATRAN,TPEVAP,TAEVAP,CHECK,TAR,TRC,EVAPR,...
      EVAPD,CROPF,WSE1,WSE2,WSE3,PCEW,CPEW,ZRT,ERLB,WCUM,...
      CHKDIF

*OUTPUT WLVG,WST,WSO,TADRW
*PAGE GROUP, NTAB=0, WIDTH=80

END
STOP


* 2.23 SUBROUTINES

*----------------------------------------------------------------------*
*  FUNCTION GLA                                                        *
*  Purpose: This function computes daily increase of leaf area index   *
*           (ha leaf/ ha ground/ d)                                    *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                     units  class *
*  ----   ---- -------                                     -----  ----- *
```

```
*  DOY      R4  Daynumber (Jan 1st = 1)                         -      I  *
*  DOYEM    R4  Daynumber of crop emergence                     -      I  *
*  DTEFF    R4  Daily effective temperatute                degree C   I  *
*  DVS      R4  Development stage of the crop                   -      I  *
*  NPL      R4  Plant density                           plants m-2 I  *
*  LA0      R4  Extrapolated leaf area at emergence     m2 plant-1 I  *
*  RGRL     R4  Relative leaf growth rate                  ha ha-1    I  *
*  SLA      R4  Specific leaf area                         ha kg-1    I  *
*  LAI      R4  Leaf area index                            ha ha-1    I  *
*  GLV      R4  Growth rate of the leaves              kg ha-1 d-1 I  *
*----------------------------------------------------------------------*

      REAL FUNCTION GLA (DOY,DOYEM,DTEFF,DVS,NPL,LA0,RGRL,DELT,SLA,
     $                   LAI,GLV)
      IMPLICIT REAL (A-Z)

*-----growth during maturation stage
      GLA  = SLA * GLV

*------growth during juvenile stage
      IF ((DVS.LT.0.3).AND.(LAI.LT.0.75)) THEN
      GLA  = (LAI * (EXP(RGRL*DTEFF*DELT)-1.))/DELT
      ENDIF

*-----growth at day of seedling emergence
      IF ((DOY.GE.DOYEM).AND.(LAI.EQ.0.)) GLA = (NPL * LA0)/DELT

*-----growth before seedling emergence
      IF (DOY.LT.DOYEM) GLA = 0.

      RETURN
      END


*----------------------------------------------------------------------*
*  FUNCTION REAI                                                       *
*  Purpose: This function calculates ear area index                    *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name     type meaning                               units  class *
*  ----     ---- -------                               -----  ----- *
*  DVS      R4  Development stage of the crop             -       I  *
*  EAR      R4  Ear weight                             kg ha-1    I  *
*  TADRW    R4  Total above-ground dry weight          kg ha-1    I  *
*  RDR      R4  Relative death rate                      d-1      I  *
*  EAI      R4  Ear area index                         ha ha-1    I  *
*----------------------------------------------------------------------*

      REAL FUNCTION REAI(DELT,DVS,EAR,TADRW,RDRDV,EAI)
```

```
      IMPLICIT REAL(A-Z)

      IF (DVS.LT.0.8) REAI = 0.
      IF (DVS.GE.0.8 .AND. EAI.EQ.0.) THEN
                      REAI = (EAR * TADRW)/DELT
      ELSE
                      REAI = 0.
      ENDIF
      IF (DVS.GE.1.3) REAI = -RDRDV * EAI
      RETURN
      END


*----------------------------------------------------------------------*
*  SUBROUTINE ASTRO                                                    *
*  Purpose: This subroutine calculates astronomic daylength,           *
*           diurnal radiation characteristics such as the daily        *
*           integral of sine of solar elevation and solar constant.    *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                    units  class *
*  ----   ---- -------                                    -----  ----- *
*  DOY     R4  Daynumber (Jan 1st = 1)                      -      I   *
*  LAT     R4  Latitude of the site                       degrees  I   *
*  SC      R4  Solar constant                             J m-2 s-1 O  *
*  DS0     R4  Daily extraterrestrial radiation           J m-2 d-1 O  *
*  SINLD   R4  Seasonal offset of sine of solar height      -      O   *
*  COSLD   R4  Amplitude of sine of solar height            -      O   *
*  DAYL    R4  Astronomic daylength (base = 0 degrees)      h      O   *
*  DSINB   R4  Daily total of sine of solar height          s      O   *
*  DSINBE  R4  Daily total of effective solar height        s      O   *
*                                                                      *
*  FATAL ERROR CHECKS (execution terminated, message)                  *
*  condition: LAT > 67, LAT < -67                                      *
*                                                                      *
*  FILE usage : none                                                   *
*----------------------------------------------------------------------*

      SUBROUTINE ASTRO (DOY, LAT,
     &                  SC , DS0, SINLD, COSLD, DAYL, DSINB, DSINBE)
      IMPLICIT REAL (A-Z)

*-----PI and conversion factor from degrees to radians
      PI    = 3.141592654
      RAD   = PI/180.

*-----check on input range of parameters
      IF (LAT.GT.67.)  STOP 'ERROR IN ASTRO: LAT> 67'
```

```
      IF (LAT.LT.-67.) STOP 'ERROR IN ASTRO: LAT>-67'

*-----declination of the sun as function of daynumber (DOY)
      DEC   = -ASIN (SIN (23.45*RAD)*COS (2.*PI*(DOY+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)
      DAYL   = 12.0*(1.+2.*ASIN (AOB)/PI)

      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 (DS0)
      SC  = 1370.*(1.+0.033*COS (2.*PI*DOY/365.))
      DS0 = SC*DSINB

      RETURN
      END


*----------------------------------------------------------------------*
* SUBROUTINE TOTASS                                                    *
* Purpose: This subroutine 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.                         *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning                                   units  class *
* ----   ---- -------                                   -----  ----- *
* DOY     R4  Daynumber (January 1 = 1)                   -      I   *
* LAT     R4  Latitude of the site                      degrees  I   *
* DTR     R4  Daily total of global radiation           J/m2/d   I   *
* SCP     R4  Scattering coefficient of leaves for visible           *
*             radiation (PAR)                             -      I   *
* AMAX    R4  Assimilation rate at light saturation     kg CO2/  I   *
*                                                      ha leaf/h     *
* EFF     R4  Initial light use efficiency             kg CO2/J/ I   *
*                                                      ha/h m2 s     *
* KDF     R4  Extinction coefficient for diffuse light           I   *
* LAI     R4  Leaf area index                            ha/ha   I   *
* DAYL    R4  Astronomic daylength (base = 0 degrees)      h     O   *
```

```
*  DTGA     R4  Daily total gross assimilation          kg CO2/ha/d O  *
*  DS0      R4  Daily extraterrestrial radiation          J m-2 s-1 O  *
*                                                                      *
*                                                                      *
*  SUBROUTINES and FUNCTIONS called : ASTRO, ASSIM                     *
*  FILE usage : none                                                   *
*----------------------------------------------------------------------*

      SUBROUTINE TOTASS (DOY,  LAT , DTR, SCP, AMAX, EFF, KDF, LAI,
     &                   DAYL, DTGA, DS0)
      IMPLICIT REAL(A-Z)
      REAL XGAUSS(3), WGAUSS(3)
      INTEGER I1, IGAUSS

      DATA IGAUSS /3/
      DATA XGAUSS /0.112702, 0.500000, 0.887298/
      DATA WGAUSS /0.277778, 0.444444, 0.277778/

      PI    = 3.141592654

      CALL ASTRO(DOY,LAT,SC,DS0,SINLD,COSLD,DAYL,DSINB,DSINBE)

*-----assimilation set to zero and three different times of the day (HOUR)
      DTGA = 0.

      DO 10 I1=1,IGAUSS

*---------at the specified HOUR, radiation is computed and used to compute
*         assimilation
         HOUR = 12.0+DAYL*0.5*XGAUSS(I1)

*--------sine of solar elevation
         SINB  = AMAX1 (0., SINLD+COSLD*COS (2.*PI*(HOUR+12.)/24.))

*--------diffuse light fraction (FRDF) from atmospheric
*         transmission (ATMTR)
         PAR    = 0.5*DTR*SINB*(1.+0.4*SINB)/DSINBE
         ATMTR = PAR/(0.5*SC*SINB)

         IF (ATMTR.LE.0.22) THEN
            FRDF = 1.
         ELSE IF (ATMTR.GT.0.22 .AND. ATMTR.LE.0.35) THEN
            FRDF = 1.-6.4*(ATMTR-0.22)**2
         ELSE
            FRDF = 1.47-1.66*ATMTR
         END IF

         FRDF = AMAX1 (FRDF, 0.15+0.85*(1.-EXP (-0.1/SINB)))
```

```
*--------diffuse PAR (PARDF) and direct PAR (PARDR)
         PARDF = PAR * FRDF
         PARDR = PAR - PARDF

         CALL ASSIM (SCP,AMAX,EFF,KDF,LAI,SINB,PARDR,PARDF,FGROS)

*--------integration of assimilation rate to a daily total (DTGA)
         DTGA = DTGA+FGROS*WGAUSS(I1)

10    CONTINUE

      DTGA = DTGA * DAYL

      RETURN
      END


*----------------------------------------------------------------------*
*  SUBROUTINE ASSIM                                                    *
*  Purpose: This subroutine 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.                              *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                   units  class *
*  ----   ---- -------                                   -----  ----- *
*  SCP     R4  Scattering coefficient of leaves for visible            *
*              radiation (PAR)                             -       I  *
*  AMAX    R4  Assimilation rate at light saturation     kg CO2/   I  *
*                                                       ha leaf/h     *
*  EFF     R4  Initial light use efficiency             kg CO2/J/  I  *
*                                                       ha/h m2 s     *
*  KDF     R4  Extinction coefficient for diffuse light            I  *
*  LAI     R4  Leaf area index                            ha/ha    I  *
*  SINB    R4  Sine of solar height                         -      I  *
*  PARDR   R4  Instantaneous flux of direct radiation (PAR) W/m2   I  *
*  PARDF   R4  Instantaneous flux of diffuse radiation(PAR) W/m2   I  *
*  FGROS   R4  Instantaneous assimilation rate of        kg CO2/   O  *
*              whole canopy                             ha soil/h     *
*                                                                      *
*  SUBROUTINES and FUNCTIONS called : none                             *
*  FILE usage : none                                                   *
*----------------------------------------------------------------------*

      SUBROUTINE ASSIM (SCP, AMAX, EFF, KDF, LAI, SINB, PARDR, PARDF,
     &                  FGROS)
      IMPLICIT REAL(A-Z)
```

```
      REAL XGAUSS(3), WGAUSS(3)
      INTEGER I1, I2, IGAUSS

*-----Gauss weights for three point Gauss
      DATA IGAUSS /3/
      DATA XGAUSS /0.112702, 0.500000, 0.887298/
      DATA WGAUSS /0.277778, 0.444444, 0.277778/

*-----reflection of horizontal and spherical leaf angle distribution
      SQV  = SQRT(1.-SCP)
      REFH = (1.-SQV)/(1.+SQV)
      REFS = REFH*2./(1.+2.*SINB)

*-----extinction coefficient for direct radiation and total direct flux
      CLUSTF = KDF / (0.8*SQV)
      KBL    = (0.5/SINB) * CLUSTF
      KDRT   = KBL * SQV

*-----selection of depth of canopy, canopy assimilation is set to zero
      FGROS = 0.

      DO 10 I1=1,IGAUSS
         LAIC = LAI * XGAUSS(I1)

*--------absorbed fluxes per unit leaf area: diffuse flux, total direct
*        flux, direct component of direct flux.
         VISDF = (1.-REFH)*PARDF*KDF  *EXP (-KDF  *LAIC)
         VIST  = (1.-REFS)*PARDR*KDRT *EXP (-KDRT *LAIC)
         VISD  = (1.-SCP) *PARDR*KBL  *EXP (-KBL  *LAIC)

*--------absorbed flux (J/M2 leaf/s) for shaded leaves and assimilation of
*        shaded leaves
         VISSHD = VISDF + VIST - VISD
         IF (AMAX.GT.0.) THEN
            FGRSH  = AMAX * (1.-EXP(-VISSHD*EFF/AMAX))
         ELSE
            FGRSH = 0.
         END IF

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

         VISPP  = (1.-SCP) * PARDR / SINB
         FGRSUN = 0.
         DO 20 I2=1,IGAUSS
            VISSUN = VISSHD + VISPP * XGAUSS(I2)
            IF (AMAX.GT.0.) THEN
               FGRS = AMAX * (1.-EXP(-VISSUN*EFF/AMAX))
            ELSE
```

```
            FGRS = 0.
          END IF
          FGRSUN = FGRSUN + FGRS * WGAUSS(I2)
20      CONTINUE

*--------fraction sunlit leaf area (FSLLA) and local assimilation
*        rate (FGL)
        FSLLA = CLUSTF * EXP(-KBL*LAIC)
        FGL   = FSLLA  * FGRSUN + (1.-FSLLA) * FGRSH

*--------integration of local assimilation rate to canopy
*        assimilation (FGROS)
        FGROS = FGROS + FGL * WGAUSS(I1)

10    CONTINUE
      FGROS = FGROS * LAI

      RETURN
      END


*----------------------------------------------------------------------*
* FUNCTION WSRT                                                        *
* Purpose: To decide whether root extension growth continues or ceases *
*          (value either 0 or 1)                                       +
*----------------------------------------------------------------------*

      REAL FUNCTION WSRT(ZRT,TKL1,TKL2,TKL3,WCL1,WCL2,WCL3,
     $                   WCWP1,WCWP2,WCWP3)
      IMPLICIT REAL(A-Z)

      WSRT = 1.
      IF (ZRT.LT.TKL1 .AND. WCL1.LT.WCWP1) WSRT = 0.
      IF (ZRT.GT.TKL1 .AND. ZRT.LT.(TKL1+TKL2) .AND.
     $    WCL2.LT.WCWP2) WSRT = 0.
      IF (ZRT.GT.(TKL1+TKL2) .AND. ZRT.LT.(TKL1+TKL2+TKL3) .AND.
     $    WCL3.LT.WCWP3)  WSRT = 0.
      RETURN
      END


*----------------------------------------------------------------------*
* FUNCTION FUFR                                                        *
* Purpose: To compute factors accounting for water stress effect on    *
*          water uptake                                                *
*----------------------------------------------------------------------*

      REAL FUNCTION FUFR(WCL,WCFC,P,WCWP,WCWET,WCST)
```

```
      IMPLICIT REAL (A-Z)

      WCCR = WCWP + (1.-P) * (WCFC - WCWP)

      IF (WCL.GT.WCWET) THEN
          FR = (WCST-WCL)/(WCST-WCWET)
      ELSE
          IF (WCL.GT.WCCR) THEN
              FR = 1.
          ELSE
              FR = (WCL-WCWP)/(WCCR-WCWP)
          ENDIF
      ENDIF

      FUFR = AMIN1(1.,AMAX1(0., FR))

      RETURN
      END

ENDJOB
```

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Appendix: Definition of the abbreviations used in the models SUCROS1 and SUCROS2

Name	Description	Units
A	Parameter in Ångström formula	-
AEVAP	Actual soil evaporation rate, derived from Penman evaporation	mm d^{-1}
AINTC	Actual amount of precipitation intercepted by the canopy	mm d^{-1}
ALB	Albedo, reflection coefficient, for short-wave radiation	-
ALBS	Albedo, reflection coefficient, for soil surface	-
AMAX	Actual CO_2 assimilation rate at light saturation for individual leaves	kg CO_2 ha^{-1} leaf h^{-1}
AMDVS	Factor accounting for effect of development stage on AMX	-
AMDVST	Table of AMDVS as a function of DVS	-, -
AMTMP	Factor accounting for effect of daytime temperature on AMX	-
AMTMPT	Table of AMTMP as function of DDTMP	-, °C
AMX	Potential CO_2 assimilation rate at light saturation for individual leaves	kg CO_2 ha^{-1} leaf h^{-1}
AOB	Intermediate variable	-
ASIN	Arcsine function (intrinsic FORTRAN function)	-
ASRQ	Assimilate (CH_2O) requirement for dry matter production	kg CH_2O kg^{-1} DM
ASRQLV	Assimilate requirement for leaf dry matter production	kg CH_2O kg^{-1} DM leaf
ASRQRT	Assimilate requirement for root dry matter production	kg CH_2O kg^{-1} DM root
ASRQSO	Assimilate requirement for storage organ dry matter production	kg CH_2O kg^{-1} DM stor.organ
ASRQST	Assimilate requirement for stem dry matter production	kg CH_2O kg^{-1} DM stem
ASSIM	Subroutine to calculate FGROS	-
ASSSH	CO_2 assimilation rate of shaded leaf area	kg CO_2 ha^{-1} leaf h^{-1}
ASSSL	CO_2 assimilation rate of sunlit leaf area	kg CO_2 ha^{-1} leaf h^{-1}
ASTRO	Subroutine to compute e.g. daylength	-
ATMTR	Atmospheric transmission coefficient	-
ATRANS	Total actual transpiration rate of the (mixed) canopy	mm d^{-1}
AVP	Actual vapour pressure	mbar
B	Parameter in Ångström formula	-
BBRAD	Black body radiation	J m^{-2} s^{-1}
BOLTZM	Stefan-Boltzmann constant	J m^{-2} d^{-1} $°K^{-4}$
CFLV	Mass fraction carbon in the leaves	kg C kg^{-1} DM
CFRT	Mass fraction carbon in the roots	kg C kg^{-1} DM
CFSO	Mass fraction carbon in the storage organs	kg C kg^{-1} DM
CFST	Mass fraction carbon in the stems	kg C kg^{-1} DM
CHECK	Variable to check the water balance	mm
CHKDIF	Difference between carbon added to the crop since initialization and the net total of integrated carbon fluxes, relative to their sum	-
CHKIN	Carbon in the crop accumulated since simulation started	kg C ha^{-1}
CHLFL	Sum of integrated carbon fluxes into and out of the crop	kg C ha^{-1}
CLEAR	Penman's original clearness factor	-
CLUSTF	Cluster factor	-
COS	Cosine function (intrinsic FORTRAN function)	-
COSLD	Intermediate variable in calculating solar height	-
CO2LV	CO_2 production factor for growth of leaves	kg CO_2 kg^{-1} DM
CO2RT	CO_2 production factor for growth of roots	kg CO_2 kg^{-1} DM
CO2SO	CO_2 production factor for growth of storage organs	kg CO_2 kg^{-1} DM
CO2ST	CO_2 production factor for growth of stems	kg CO_2 kg^{-1} DM
CPEW	Factor accounting for effect of water stress on dry matter partitioning	-
CROPF	Crop factor for crop water requirement (output variable)	-

DAVTMP	Daily average temperature	°C
DOY	Day number since 1 January (day of year)	d
DOYEM	Day of year of crop emergence	d
DAYL	Daylength	h d^{-1}
DDTMP	Daily average daytime temperature	°C
DEC	Declination of the sun	radians
DELT	Time interval of integration	d
DLAI	Death rate of leaf area	ha ha^{-1} d^{-1}
DLV	Death rate of leaves	kg leaf ha^{-1} d^{-1}
DPAR	Daily photosynthetically active radiation	J m^{-2} d^{-1}
DRAIN	Drainage rate below the root zone	mm d^{-1}
DRATE	Drainage rate of the subsoil	mm d^{-1}
DRYP	Drying power term in Penman equation	mm d^{-1} mbar $°C^{-1}$
DS0	Daily extra-terrestrial radiation	J m^{-2} d^{-1}
DSINB	Integral of SINB over the day	s d^{-1}
DSINBE	As DSINB, but with a correction for lower atmospheric transmission at lower solar elevations	s d^{-1}
DSLR	Number of days since last rain	d
DTEFF	Daily effective temperature	°C
DTGA	Daily total gross CO_2 assimilation of the crop	kg CO_2 ha^{-1} ground d^{-1}
DTMAX	Daily maximum temperature	°C
DTMIN	Daily minimum temperature	°C
DTR	Daily solar radiation	J m^{-2} d^{-1}
DTRT	Table of DTR as function of day of the year	J m^{-2} d^{-1}, d
DVR	Development rate	d^{-1}
DVRRT	Table of DVR in pre-anthesis phase as function of temperature	d^{-1}, °C
DVRVT	Table of DVR in post-anthesis phase as function of temperature	d^{-1}, °C
DVS	Development stage of the crop	-
EAI	Ear area index	m^2 ear m^{-2} ground
EAR	Ear area ratio	ha ear kg^{-1} DM TADRW
EDPTFT	Table to read the root activity coefficient	-
EES	Soil-specific extinction coefficient	mm^{-1}
EFF	Initial light use efficiency for individual leaves	kg CO_2 ha^{-1} leaf h^{-1} (J m^{-2} leaf $s^{-1})^{-1}$
EMERG	Parameter to indicate emergence	-
ERLB	Cumulative effective root length	mm
EVAPD	Potential soil evaporation due to drying power of the air	mm d^{-1}
EVAPR	Potential soil evaporation due to radiation	mm d^{-1}
EVSD	Evaporation rate on days without rain	mm d^{-1}
EVSH	Evaporation rate on days with rain	mm d^{-1}
EVSW1-3	Rate of evaporation	mm d^{-1}
EZRT	Rate of root elongation	mm d^{-1}
EZRTC	Constant for root elongation	mm d^{-1}
FCLEAR	Sky clearness function in calculation of net long-wave radiation	-
FEVL1-3	Distribution factors for soil water extraction over compartments	-
FELVT	Sum of FEVL	-
FGL	CO_2 assimilation rate at one depth in the canopy	kg CO_2 ha^{-1} leaf h^{-1}
FGROS	Instantaneous canopy CO_2 assimilation	kg CO_2 ha^{-1} ground h^{-1}
FGRS	Intermediate variable for calculation of assimilation of sunlit leaves	-
FGRSH	CO_2 assimilation rate at one depth in the canopy for shaded leaves	kg CO_2 ha^{-1} leaf h^{-1}
FGRSUN	CO_2 assimilation rate at one depth in the canopy for sunlit leaves	kg CO_2 ha^{-1} leaf h^{-1}

FINTIM	Period of simulation	d
FLV	Fraction of shoot dry matter allocated to leaves	-
FLVTB	Table of FLV as function of DVS	-, -
FRDF	Fraction diffuse in incoming radiation	-
FRT	Fraction of total dry matter allocated to roots	-
FRTRL	Fraction of stem weight eventually translocated to storage organs	-
FSH	Fraction of total dry matter allocated to shoots	-
FSHP	Fraction of total dry matter allocated to shoots (water-limited production)	-
FSHTB	Table of FSH as function of DVS	-, -
FSLLA	Fraction of sunlit leaf area	-
FSO	Fraction of shoot dry matter allocated to storage organs	-
FST	Fraction of shoot dry matter allocated to stems	-
FSTTB	Table of FST as function of DVS	-, -
FUFR	FORTRAN function	-
FVAP	Vapour pressure effect on RLWN (Brunt equation)	-
GLA	Fortran function to calculate GLAI	-
GLAI	Net growth rate of leaf area index	ha leaf ha^{-1} ground d^{-1}
GLV	Dry matter growth rate of leaves	kg DM ha^{-1} ground d^{-1}
GPHOT	Daily total gross CH_2O assimilation of the crop	kg CH_2O ha^{-1} ground d^{-1}
GRT	Dry matter growth rate of roots	kg DM ha^{-1} ground d^{-1}
GSDST	Distance in Gaussian integration	-
GSO	Dry matter growth rate of storage organs	kg DM ha^{-1} ground d^{-1}
GST	Dry matter growth rate of stems	kg DM ha^{-1} ground d^{-1}
GSWT	Weighing factor in Gaussian integration	-
GTW	Gross growth rate of crop dry matter, including translocation	kg DM ha^{-1} ground d^{-1}
HI	Harvest index	kg stor. organs kg^{-1} TADRW
HOUR	Selected hour during the day	h
I2	Do-loop counter	-
INTC	Interception capacity of precipitation of one layer of leaves	mm d^{-1}
KBL	Extinction coefficient for direct component of direct PAR flux	ha ground ha^{-1} leaf
KDF	Extinction coefficient for leaves	ha ground ha^{-1} leaf
KDRT	Extinction coefficient for total direct PAR flux	ha ground ha^{-1} leaf
LA0	Initial leaf area (at field emergence)	m^2 $plant^{-1}$
LAI	Leaf area index	ha leaf ha^{-1} ground
LAIC	Leaf area index above selected height in canopy	ha leaf ha^{-1} ground
LAICR	Critical leaf area index beyond which death to self-shading occurs	ha leaf ha^{-1} ground
LAITB	Table of LAI as function of day of the year	ha leaf ha^{-1} ground, d
LAT	Latitude of the weather station	degrees
LHVAP	Latent heat of evaporation of water	J kg^{-1} H_2O
MAINLV	Maintenance respiration coefficient of leaves	kg CH_2O kg^{-1} DM d^{-1}
MAINRT	Maintenance respiration coefficient of roots	kg CH_2O kg^{-1} DM d^{-1}
MAINSO	Maintenance respiration coefficient of storage organs	kg CH_2O kg^{-1} DM d^{-1}
MAINST	Maintenance respiration coefficient of stems	kg CH_2O kg^{-1} DM d^{-1}
MAINT	Maintenance respiration rate of the crop	kg CH_2O ha^{-1} d^{-1}
MAINTS	Maintenance respiration rate of the crop at reference temperature	kg CH_2O ha^{-1} d^{-1}
MNDVS	Factor accounting for effect of DVS on maintenance respiration	-

NPL	Plant density	plants m^{-2}
NRAD	Net radiation	J m^{-2} d^{-1}
NTAB	CSMP parameter to specify tabulated output in print-plot	-
P	Soil water depletion fraction	-
PAR	Instantaneous flux of photosynthetically active radiation	J m^{-2} ground s^{-1}
PARDF	Instantaneous diffuse flux of incoming PAR	J m^{-2} ground s^{-1}
PARDR	Instantaneous direct flux of incoming PAR	J m^{-2} ground s^{-1}
PARLDF	Absorbed diffuse PAR per unit leaf area	J m^{-2} ground s^{-1}
PARLDR	Absorbed direct component of direct PAR per unit leaf area	J m^{-2} ground s^{-1}
PARLPP	Direct PAR absorbed by leaves perpendicular to direct beam	J m^{-2} ground s^{-1}
PARLSH	Absorbed PAR for shaded leaves (per unit leaf area)	J m^{-2} ground s^{-1}
PARLSL	Absorbed PAR for sunlit leaves (per unit leaf area)	J m^{-2} ground s^{-1}
PARLT	Absorbed total direct PAR per unit leaf area	J m^{-2} ground s^{-1}
PCEW	Factor that accounts for reduced photosynthesis due to water stress	-
PENMAN	Penman reference value for potential evapotranspiration	mm d^{-1}
PEVAP	Potential soil evaporation	mm d^{-1}
PI	Ratio of circumference to diameter of circle	-
PRDEL	Time interval for printing	d
PSYCH	Psychrometric instrument constant	mbar °C^{-1}
PTRANS	Potential transpiration rate derived from Penman evaporation	mm d^{-1}
Q10	Factor accounting for increase of maintenance respiration with a 10 °C rise temperature	-
RAD	Factor to convert degrees to radians	radians $degree^{-1}$
RAIN	Water input through rainfall	mm d^{-1}
RAINTB	Table of RAIN as function of day of the year	mm, d
RDR	Relative death rate of leaves	d^{-1}
RDRDV	Relative death rate due to developmental ageing	d^{-1}
RDRSH	Relative death rate due to self-shading at high LAI	d^{-1}
RDRT	Table of RDR as function of DAVTMP	d^{-1}, °C
REAI	Function to compute ear area index	-
REDF	Factor accounting for effect of temperature on AMAX	-
REFH	Reflection coefficient for diffuse PAR	-
REFS	Reflection coefficient for direct PAR	-
RGRL	Relative growth rate of leaf area during exponential growth	$(°C\ d)^{-1}$
RLWN	Net long-wave radiation	J m^{-2} d^{-1}
RNOFF	Runoff	mm d^{-1}
RWCL1-3	Reduced volumetric water content in soil layers	-
SC	Solar constant, corrected for varying distances between sun-earth	J m^{-2} s^{-1}
SCP	Scattering coefficient of leaves for PAR	-
SINB	Sine of solar elevation	-
SINLD	Intermediate variable in calculating solar declination	-
SLA	Specific leaf area	ha leaf kg^{-1} leaf
SLOPE	Tangent of the relation between saturated vapour pressure and temperature	mbar °C^{-1}
SQV	Intermediate variable in calculation of reflection coefficient	-
SVP	Saturated vapour pressure	mbar
TADRW	Total above-ground dry matter	kg DM ha^{-1}
TAEVAP	Cumulative actual soil evaporation	mm

TAINTC	Total amount of rainfall intercepted by the canopy	mm
TAR	Transpiration / assimilation ratio	kg H_2O kg^{-1} CO_2
TATRAN	Total amount of water transpired by the crop	mm
TBASE	Base temperature for juvenile leaf area growth	°C
TDRAIN	Total drainage	mm
TDRW	Total biomass	kg DM ha^{-1}
TDTGA	Total gross CO_2 assimilation of the crop	kg CO_2 ha^{-1} ground
TEFF	Factor accounting for effect of temperature on maintenance respiration	-
TEVAPD	Cumulative potential soil evaporation due to drying power of the air	mm
TEVAPR	Cumulative potential soil evaporation due to radiation	mm
TIME	Daynumber start simulation	d
TKL1-3	Thickness of the soil layers	mm
TKLT	Sum of thickness of the soil layers	mm
TLAI	Total leaf area index (including dead leaves)	ha leaf ha^{-1} ground
TMAXT	Table daily maximum temperature as function of day of the year	°C, d
TMINT	Table daily minimum temperature as function of day of the year	°C, d
TOTASS	Subroutine to calculate gross CO_2 assimilation of the crop	-
TPENM	Cumulative potential evapotranspiration	mm
TPEVAP	Cumulative potential soil evaporation	mm
TPTRAN	Cumulative actual soil evaporation	mm
TRAIN	Total precipitation	mm
TRANSC	Characteristic potential transpiration rate (see Table 2.2)	mm d^{-1}
TRANSL	Translocation rate of stem dry matter to storage organs	kg DM ha^{-1} d^{-1}
TRC	Transpiration coefficient	kg H_2O kg^{-1} DM
TREF	Reference temperature	°C
TRNOFF	Total runoff	mm
TRRM	Potential rate of water uptake per mm effective rooted depth	mm^{-1}
TRWL1-3	Rate of transpiration	mm d^{-1}
TSTORE	Total surface storage due to waterlogging	mm
VAPHTB	Table of daily vapour pressure as function of day of the year	kPa, d
VISD	Absorbed direct component of direct flux per unit leaf area (at depth LAIC)	J m^{-2} leaf s^{-1}
VISDF	Absorbed total direct flux per unit leaf area (at depth LAIC)	J m^{-2} leaf s^{-1}
VISPP	Absorbed light flux by leaves perpendicular on direct beam	J m^{-2} leaf s^{-1}
VISSHD	Total absorbed flux for shaded leaves per unit leaf area (at depth LAIC)	J m^{-2} leaf s^{-1}
VISSUN	Total absorbed flux for sunlit leaves in one of three Gauss point classes	J m^{-2} leaf s^{-1}
VIST	Absorbed total direct flux per unit leaf area (at depth LAIC)	J m^{-2} leaf s^{-1}
WCAD1-3	Volumetric water content in each soil layer at air dry	cm^3 H_2O cm^{-3} soil
WCCR	Critical volumetric water content	cm^3 H_2O cm^{-3} soil
WCFC	Volumetric water content at field capacity	cm^3 H_2O cm^{-3} soil
WCFC1-3	Volumetric water content at field capacity in each soil layer	cm^3 H_2O cm^{-3} soil
WCL	Volumetric water content in soil layers (θ)	cm^3 H_2O cm^{-3} soil
WCL1-3	Volumetric water content in each soil layer	cm^3 H_2O cm^{-3} soil
WCLI1-3	Initial value of Volumetric water content in each soil layer	cm^3 H_2O cm^{-3} soil
WCST	Volumetric water content at saturation	cm^3 H_2O cm^{-3} soil
WCST1-3	Volumetric water content at saturation in each soil layer	cm^3 H_2O cm^{-3} soil
WCUM	Total amount of water in the soil profile	mm
WCUMI	Initial total amount of water in the soil profile	mm
WCWET1-3	Volumetric water content where water logging begins	cm^3 H_2O cm^{-3} soil
WCWP	Volumetric water content at wilting point	cm^3 H_2O cm^{-3} soil
WCWP1-3	Volumetric water content at wilting point in each soil layer	cm^3 H_2O cm^{-3} soil
WDF	Wind function	mm d^{-1} $mbar^{-1}$
WDS	Wind speed	m s^{-1}

WGAUSS	Array containing weights to be assigned to Gauss points	-
WL1I	Initial moisture content in compartment 1	cm^3 H_2O cm^{-3} soil
WL2I	Initial moisture content in compartment 2	cm^3 H_2O cm^{-3} soil
WL3I	Initial moisture content in compartment 3	cm^3 H_2O cm^{-3} soil
WL1-3	Amount of water in soil compartments	mm
WLFL1-8	Infiltration and drainage rates for the several soil layers	mm d^{-1}
WLV	Dry weight of the leaves (green + dead)	kg ha^{-1}
WLVD	Dry weight of dead leaves	kg ha^{-1}
WLVG	Dry weight of green leaves	kg ha^{-1}
WLVI	Initial dry weight of the leaves	kg ha^{-1}
WRT	Dry weight of the roots	kg ha^{-1}
WRTI	Initial dry weight of the roots	kg ha^{-1}
WSE1-3	Factor accounting for effect of uptake availability of soil water	-
WSERT	Auxiliary variable to calculate root extension	-
WSO	Dry weight of storage organs	kg ha^{-1}
WSRT	Function to decide whether root extension growth continues or ceases	-
WST	Dry weight of the stems	kg ha^{-1}
WSTB	Table of wind speed as function of day of the year	m s^{-1}, d
XGAUSS	Array containing Gauss points	-
ZRT	Rooted depth	mm
ZRT1-3	Thickness of rooted layer	mm
ZRTI	Initial value for rooted depth	mm
ZRTM	Maximum value for rooted depth	mm
ZRTMC	Maximum value for rooted depth as crop characteristic	mm
ZRTMS	Maximum value for rooted depth as soil characteristic	mm