SUCROS97: Simulation of crop growth for potential and water-limited production situations

As applied to spring wheat

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Preface

This report describes the new 1997 versions of the models SUCROS1 and SUCROS2, which are improved and slightly modified versions of the models as they were described in our earlier report of 1992.
The units of the variables were streamlined into g m^{-2} for dry matter variables and to mm for water balance variables. The leaf assimilation rates were first expressed on a second basis, but integrated into daily values, so that daily growth rate and daily transpiration rates are expressed in g m^{-2} d^{-1} and in mm d^{-1}, respectively.
The unit of air humidity was altered from mbar to kPa.

Over the past five years we were pointed to several errors and bugs in the 1992 version. We gratefully acknowledge such contributions of all our colleagues, but we would like to mention specifically Daniel van Kraalingen and Willem Stol who were most helpful in this respect.

The model SUCROS1 is for potential growth situations, whereas SUCROS2 is for water-limited situations. The results of SUCROS2 become identical to those of SUCROS1 when there is enough water to prevent any water shortage, and not so much as to cause water logging.
The modelling of the soil water balance is done by the ‘tipping bucket’ approach, with a daily time interval of integration. The soil depth was extended to 2 m, so that the number of soil layers had to be increased from three to four.

We added the major photosynthesis subroutine (MOMASSP) for the calculation of the current rate of canopy photosynthesis, as separately embedded within an FST program. Using this model it is possible to study the diurnal course of canopy photosynthesis as affected by leaf properties, LAI and environmental conditions. Although SUCROS does not provide this intra-diurnal time course, this model will show the underlying dynamics which is integrated within SUCROS by using Gaussian integration over the day.

The models and the Fortran Simulation Translator (FST) are available upon request. Information about distribution and costs can be obtained from:
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Abstract

Two versions of the simulation model for crop growth SUCROS (Simple and Universal CROp growth Simulator) are described, one for potential production (SUCROS1) 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, and carbohydrate allocation is modified in favour of the roots.

Key words: Simulation model, systems analysis, photosynthesis, water stress

Table of Contents

1. Crop growth model for potential production (SUCROS1)

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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). Most of the process descriptions included in SUCROS1 are explained in Goudriaan & van Laar (1994).

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 yields measured at a given site or region to total seasonal rainfall (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. In addition, these empirical, descriptive models give little insight into 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, and it can be reduced by pests and diseases. Therefore, 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), Spitters *et al.* (1986) and Goudriaan & van Laar (1994). A submodel (MOMASSP.FST) that generates the diurnal course of gross assimilation for a specific set of conditions is included for separate study (Appendix I).

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.

Figure 1.1 Relational diagram of SUCROS1. Boxes are state variables, valves are rate variables, circles are intermediate variables. Solid lines are flows of material, dotted lines are flows of information. Source: ORYZA1 (SUCROS1 as applied for rice), Kropff et al., 1994.

SUCROS1 requires as input physiological properties of the crop 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. A relational diagram is given in Figure 1.1.

SUCROS1 is written in FST, the FORTRAN Simulation Translator, a program developed by Rappoldt & van Kraalingen (1996). The model can be executed on VAX computers, IBM PC-AT's, or compatibles and Apple-Macintosh computers.

FST requires, before the program starts, a definition of the call for subroutines that are used in the program. All variables in the subroutine-call have to be defined as input or output variables. Following the definition of the subroutine-calls the program starts with the `TITLE` of the program.

```
DEFINE_CALL GLA   (INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT, ...
                   INPUT,INPUT,     OUTPUT)
DEFINE_CALL SUBEAI(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,OUTPUT)
DEFINE_CALL TOTASS(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,    ...
                   INPUT,INPUT,    OUTPUT,OUTPUT,OUTPUT)

TITLE Crop growth for potential production (SUCROS1)
*     Spring wheat, Version September 1997 (SUCROS1_97 V1.0)
```

1.2. Initial conditions

```
INITIAL
*   INCON ZERO       = 0.
    PARAMETER DOYEM  = 90.
    INCON WLVI       = 0.5; WSTI = 0.3; WRTI = 0.8
    INCON WLVDI      = 0. ; WSOI = 0. ; ILAI = 0.012
    INCON IDVS       = 0. ; IEAI = 0.

* Initialization of TNASS: total CO2 equivalents initially available
      TNASSI = (WLVI*CFLV + WSTI*CFST + WRTI*CFRT) * 44./12.
```

Usually, the model SUCROS1 starts at the moment of crop emergence (DOYEM), the number 90 representing the day of the year.

The initial amounts of dry matter in leaves (WLVI, g DM m^{-2}), stems (WSTI, g DM m^{-2}), and roots (WRTI, g DM m^{-2}) are set to their values at emergence; in this case ILAI=0.012 and SLA=0.022, so that WLVI becomes ca 0.5 g m^{-2}, from the partitioning tables the values of WSTI and WRTI can be found. Dead leaves (WLVDI, g DM m^{-2}) and storage organs (WSOI, g DM m^{-2}) at emergence are zero. The initial value for the leaf area index (ILAI, m^2 m^{-2}) has been set at 0.012, assuming a plant density of 210 plants m^{-2} and a leaf area per plant at emergence of 5.7×10^{-5} m^2 $plant^{-1}$. ILAI has a large effect on further growth. The initial values for development stage (IDVS, -) and ear area index (IEAI, m^2 m^{-2}) are set to zero.

FST requires a variable as initial condition for an integral. If this integral starts at zero (e.g. summation of temperature) the variable ZERO is used.

1.3. Crop development

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

This part is described in more detail in Chapter 5 in Goudriaan & van Laar (1994). 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 (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 (pre-anthesis, DVRV), and from flowering till maturity (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).

Phenological development starts at seedling emergence. The factor EMERG equals 0 before emergence and 1 after emergence. For explanation of the INSW function see Appendix II.

1.4. Leaf CO_2 assimilation

```
      AMAX       = AMX * AMDVS * AMTMP * EMERG
      AMDVS      = AFGEN(AMDVST, DVS)
      AMTMP      = AFGEN(AMTMPT, DDTMP)
PARAMETER AMX    = 1.11E-3
* 1.11 mg 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  = -10.,0.,0.,0.,10.,1.,25.,1.,35.,0.,50.,0.
```

This part is described in more detail in Chapter 8 in Goudriaan & van Laar (1994). 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, g CO_2 m^{-2} s^{-1}). The temperature effect (AMTMP) is a function of the average temperature during daytime (DDTMP, ˚C) as given in the function AMTMPT.

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 1.11 mg CO_2 m^{-2} s^{-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.

1.5. Daily gross CO_2 assimilation

```
     CALL TOTASS(DAY,LATT,DTR,SCP,AMAX,EFF,KDF,TAI,  ...
                 DAYL,DTGA,DS0)
PARAMETER EFF    = 12.5E-6
* 12.5 microgram CO2/J  = 0.45 (kg CO2/ha/h)/(J/m2/s)
PARAMETER KDF    = 0.60
PARAMETER SCP    = 0.20
PARAMETER LATT   = 52.
```

This part is described in more detail in Chapter 6 in Goudriaan & van Laar (1994). Daily gross crop CO_2 assimilation (DTGA, g CO_2 m^{-2} 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 Subroutines 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 literature.

Detailed discussions are also 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 instantaneous assimilation rates over the canopy and over the day (see also Appendix II).

The only site characteristic required for the calculation of potential production is the latitude (LATT). In the given example, a latitude of 52˚ N for The Netherlands was used.

1.6. Carbohydrate production

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

This part is described in more detail in Chapter 4 in Goudriaan & van Laar (1994). In the leaves, the absorbed CO_2 is reduced to carbohydrates (CH_2O) using the energy supplied by the absorbed light. For each g of CO_2 absorbed, 30/44 g of CH_2O is formed, the numerical values representing the molecular weights of CH_2O and CO_2, respectively.

1.7. Maintenance respiration

```
      MAINT      = MAINTS * TEFF * MNDVS * EMERG
      MAINTS     = MAINLV*WLVG + MAINST*WST + MAINRT*WRT + MAINSO*WSO
      MNDVS      = WLVG / NOTNUL(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
```

This part is described in more detail in Chapter 4 in Goudriaan & van Laar (1994). 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 storage organs, i.e. grains, tubers etc.) 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).

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, and dying of leaves proceed simultaneously. The NOTNUL function prevents division by zero (see Appendix II).

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      = AFGEN(FSOTB, DVS)
FUNCTION FSOTB = 0.00,0.00, 0.95,0.00, 1.05,1.00, 2.50,0.00

      ERRSH    = ABS(FLV + FST + FSO - 1.)
FINISH ERRSH   > 1.E-6
```

This part is described in more detail in Chapter 5 in Goudriaan & van Laar (1994). The primary assimilates in excess of the maintenance costs are available for conversion into structural 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), followed by distribution of the shoot fraction among leaves (FLV), stems (FST) and storage organs (FSO). To avoid errors in the partitioning tables the variable ERRSH is introduced.

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

* The following values are calculated without
* the costs of nitrate reduction:
PARAMETER ASRQRT = 1.444; ASRQLV = 1.463
PARAMETER ASRQST = 1.513; ASRQSO = 1.415
PARAMETER FRTRL  = 0.20 ; CONVL  = 0.947
```

This part is described in more detail in Chapters 4 and 5 in Goudriaan & van Laar (1994). The overall value of assimilate requirement for conversion of carbohydrates into dry matter (ASRQ, g CH_2O g^{-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 dry 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 g CH_2O g^{-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 g CH_2O g^{-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 (g dry matter m^{-2} 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, g dry matter m^{-2} 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 (CONVL), 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

```
      TAI        = 0.5 * EAI + LAI
      LAI        = INTGRL(ILAI, RLAI)
      RLAI       = GLAI - DLAI
      CALL GLA(TIME, DOYEM, DTEFF, DVS,           ...
               RGRL, DELT, SLA  , LAI, GLV,      GLAI)
PARAMETER RGRL   = 0.009
PARAMETER SLA    = 0.022
```

This part is described in more detail in Chapter 5 in Goudriaan & van Laar (1994). The area of green leaves is the major determinant for light absorption and CO_2 assimilation of the crop, but in wheat half of the Ear Area Index (EAI) also contributes. The Leaf Area Index (LAI, m^2 m^{-2}) follows from the balance between growth rate (GLAI, m^2 m^{-2} d^{-1}), and senescence rate (DLAI, m^2 m^{-2} d^{-1}).

GLAI is calculated, depending on the phenological development stage, in the Subroutine GLA. Before seedling emergence (TIME < DOYEM), GLA equals zero. 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 suggests 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
```

where LAI(t) is the current leaf area, RGRL is the relative growth rate of leaf area per degree-day ((˚Cd)$^{-1}$), 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`, $m^2\ g^{-1}$).

```
      EAI         = INTGRL(IEAI, REAI)
      CALL SUBEAI(DELT,DVS,EAR,TADRW,RDRDV,EAI,  REAI)
PARAMETER EAR     = 0.63E-3
```

The ear area index (`EAI`, m^2 ears (2 × one-sided projection) m^{-2}) is set to zero for `DVS < 0.8`, and is calculated in the Subroutine `SUBEAI`. At `DVS = 0.8`, `EAI` is set to a fixed proportion, the Ear Area Ratio (`EAR`, m^2 ear g^{-1} dry matter) of the total above-ground dry matter (`TADRW`, $g\ m^{-2}$). Till `DVS = 1.3`, `EAI` remains at this value, and decreases subsequently.

```
      DLAI        = LAI * RDR
      RDR         = MAX(RDRDV, RDRSH)
      RDRDV       = INSW(DVS-1.0, 0., DVR/(MAX(0.1, 2.-DVS))*FRDR)
      RDRSH       = LIMIT(0., 0.03, 0.03 * (LAI-LAICR) / LAICR)
PARAMETER LAICR   = 4.0 ; FRDR = 1.
```

The senescence rate of `LAI` (`DLAI`, $m^2\ m^{-2}\ d^{-1}$) 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 increases linearly with increasing `LAI` till a maximum value of 0.03 at `LAI = 8` (the meaning of the `LIMIT` function in combination with `LAICR = 4.`, see Appendix II).

`RDRDV` equals zero for `DVS < 1` (pre-anthesis stage) and subsequently increases with `DVS`. The parameter `FRDR` determines the rate at which `RDR` increases. For `FRDR = 1.`, `LAI` decreases linearly with `DVS`.

```
      DLV         = WLVG * DLAI/NOTNUL(LAI)
```

The death rate of leaves (`DLV`, $g\ m^{-2}\ d^{-1}$) is defined as the relative senescence rate of `LAI` times the weight of the green leaves (`WLVG`), the `NOTNUL` function prevents division by zero.

1.11. Dry matter production

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

Dry weights of the various plant organs (roots (`WRT`, $g\ m^{-2}$), green leaves (`WLVG`, $g\ m^{-2}$), dead leaves (`WLVD`, $g\ m^{-2}$), stems (`WST`, $g\ m^{-2}$), storage organs (`WSO`, $g\ m^{-2}$)) are obtained through integration of the respective growth rates.

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

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

```
HI          = WSO / NOTNUL(TADRW)
```

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

1.12. Weather data

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

This part is described in more detail in Chapter 3 and Appendix 5 in Goudriaan & van Laar (1994). 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, DAY)
DTMIN       = AFGEN(TMINT, DAY)
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 approximate formula (see also Chapter 3 in Goudrian & van Laar, 1994). Weather data are read from tables with 365 data pairs each. The independent variable is the current day number of the year (DAY).

```
      DTEFF       = MAX(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 - 80.

```
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
```

When weather data are read from the AB/TPE standard weather files, the following specifications are given (the 'weather' variable names are reserved names in FST, see Rappoldt & van Kraalingen, 1996):

```
WEATHER WTRDIR='C:\SYS\WEATHER\', CNTR='NLD', ISTN=1, IYEAR=1990
* Reading weather data from the weather file:
* RDD    Daily global radiation            J/m2/d
* TMMN   Daily minimum temperature         degree C
* TMMX   Daily maximum temperature         degree C
* LAT    Latitude of the site              degree
* DOY    Daynumber of year                 d
```

Behind the WEATHER keyword, assignments should be written for the directory of the weather data files (WTRDIR='directory'), the country code (CNTR='country code'), the station number within the country (ISTN=number) and the year to which the weather data pertain (IYEAR=year).
The following adaptations have to be made:

```
DTR         = RDD
DTMAX       = TMMX
DTMIN       = TMMN
```

NOTE: From the weather file the latitude (LAT) and day of year (DOY) are generated, so the variables LATT and DAY have to be taken out of the model. Replace DAY by DOY and LATT by LAT (see call for TOTASS).

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 – CONVL) that occurs during remobilization of stem carbohydrates into glucose.
In practice, the two terms CHKIN and CHKFL should never differ by more than a fraction [10^{-6}]. A larger relative deviation (mostly of the order of a few per cent) will be a sure signal of omission of a term somewhere in the program (CHKDIF), and the simulation will stop.

```
CHKIN       = WLV*CFLV + WST*CFST + ...
              WRT*CFRT + WSO*CFSO
CHKFL       = TNASS * (12./44.)
TNASS       = INTGRL(TNASSI, RTNASS)
RTNASS      = ((GPHOT - MAINT)*44./30.) -  ...
                              (GRT*CO2RT + GLV*CO2LV +  ...
                      (GST+TRANSL)*CO2ST + GSO*CO2SO +  ...
                      (1.-CONVL)* 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     = (CHKIN-CHKFL)/NOTNUL(CHKIN)

FINISH CHKDIF > 0.001
PARAM CFLV=0.459; CFST=0.494; CFRT=0.467; CFSO=0.471
```

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

1.14. Run control

```
       DAY        = 1. + AMOD(TIME-1., 365.)
```

(If weather data are read from the AB/TPE standard weather files this statement should be omitted.) 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 TIMER statement (STTIME).

```
FINISH DVS       > 2.
```

The simulation stops when the crop is mature, i.e. at development stage 2.

```
TIMER STTIME     = 80., FINTIM = 300., DELT = 1., PRDEL = 5.
TRANSLATION_GENERAL DRIVER='EUDRIV'
```

Simulation is executed with time steps of one day (DELT = 1.), with rectilinear integration of the rates (DRIVER='EUDRIV'). Output is produced every fifth day (PRDEL = 5.). To make sure that the simulation does not continue endlessly due to a mistak (or error) in model formulation, the finish time (FINTIM) is set about 50 days later than the expected maturation date.

```
PRINT DAY,DTR,DVS,TDRW,TADRW,WLVG,WLVD,WLV,WST,...
      WSO,WRT,LAI,EAI,HI,GPHOT,DAYL, ...
      DS0,TRANSL,CHKIN,CHKFL,CHKDIF,ERRSH,MAINT
```

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

END	completes the specifications of the model.
STOP	hereafter the subroutines are invoked.

```
   (SUBROUTINES)
```

1.15. Subroutines

Subroutines are invoked following the STOP statement.

```
*___________________________________________________________________________
* Subroutine GLA
* computes daily increase in leaf area index (LAI, m^2 leaf m^-2 ground d^-1)
*___________________________________________________________________________
*___________________________________________________________________________
* Subroutine SUBEAI
* calculates ear area index (EAI)
*___________________________________________________________________________
*___________________________________________________________________________
* Subroutine ASTRO
* computes daylength and daily extra-terrestrial radiation from day number and latitude
*___________________________________________________________________________
*___________________________________________________________________________
* Subroutine TOTASS
* computes daily total gross CO2 assimilation rates (DTGA, g CO2 m^-2 d^-1)
*___________________________________________________________________________
*___________________________________________________________________________
* Subroutine ASSIM
* calculates instantaneous assimilation rates (FGROS, g CO2 m^-2 s^-1)
*___________________________________________________________________________
```

The structure of the model:

1.16. Listing of the model SUCROS1

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 (here applied to spring wheat) under water-limited conditions by including water balances of crop and soil in the SUCROS1 model (see Figure 2.1). 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, effects of temporary water shortage and 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 only allows for effects of water stress that are mediated through a) photosynthesis and b) altered root/shoot partitioning. Other, possibly important, effects remain to be included such as increased leaf senescence and abscission, changes in harvest index and suppressed tillering.

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

In Sections 2.2-2.22 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 texts, the acronyms are explained and the units of all variables and data are treated. 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

Figure 2.1. Relational diagram of a system, where water is limiting crop growth at least part of the growing season.

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 Sections 2.2-2.12, only differences between SUCROS2 and SUCROS1 will be discussed.

FST requires, before the program starts, a definition of the call for subroutines that are used in the program. All variables in the subroutine-call have to be defined as input or output variables. In addition to SUCROS1 the subroutines `SUBGRT` and `SUBFR` are needed in SUCROS2.

```
DEFINE_CALL GLA   (INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
                   INPUT,          OUTPUT)
DEFINE_CALL SUBEAI(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,  OUTPUT)
DEFINE_CALL TOTASS(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
                   OUTPUT,OUTPUT,OUTPUT)
DEFINE_CALL SUBGRT(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
                   INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,  OUTPUT)
DEFINE_CALL SUBFR (INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,  OUTPUT)

TITLE Crop growth for water-limited production (SUCROS2)
*     Spring wheat, Version September 1997     (SUCROS2_97 V1.0)
```

2.2. Initial conditions

```
INITIAL
INCON ZERO        = 0.
PARAMETER DOYEM   = 90.
INCON WLVI        = 0.5;   WSTI = 0.3; WRTI = 0.8
INCON WLVDI       = 0. ;   WSOI = 0. ; ILAI = 0.012
INCON IDVS        = 0. ;   IEAI = 0.

INCON ZRTI        = 5.
      WL1I        = WCLI1 * TKL1
      WL2I        = WCLI2 * TKL2
      WL3I        = WCLI3 * TKL3
      WL4I        = WCLI4 * TKL4
PARAM WCLI1       = 0.2;  WCLI2 = 0.2;  WCLI3 = 0.2;  WCLI4 = 0.2
PARAM TKL1        = 200.; TKL2  = 400.; TKL3  = 600.; TKL4  = 800.
      TKLT        = TKL1 + TKL2 + TKL3 + TKL4
      WCUMI       = WL1I + WL2I + WL3I + WL4I

INCON IDSLR       = 1.
PARAM MDRATE      = 50.

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

* Initialization of TNASS: total CO2 equivalents initially available
```

```
      TNASSI=(WLVI*CFLV + WSTI*CFST + WRTI*CFRT) * 44./12.
```

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, WCLI3 and WCLI4 are the initial moisture contents (cm^3 cm^{-3}) in the four soil layers distinguished in this model (Section 2.14). Model results are rather sensitive to these initial values because they define the available 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, TKL3 and TKL4) is 2000 mm (Subsection 2.14.1), the amount of stored water (WCUMI) is 400 mm. When all layers are at wilting point (Sections 2.14 and 2.18) the profile contains 150 mm of water. Hence, at the start of the simulation, the profile contains 250 mm (400-150) crop available water.

The model takes for the maximum rooted depth (ZRTM) the minimum of the values set by soil properties (ZRTMS, mm), crop characteristics (ZRTMC, mm), or total soil depth defined in the model (TKLT, mm), see also Subsection 2.15.3.

2.3. Crop development

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

For explanation see page 3.

2.4. Leaf CO_2 assimilation

```
      AMAX       = AMX * AMDVS * AMTMP * EMERG
      AMDVS      = AFGEN(AMDVST, DVS)
      AMTMP      = AFGEN(AMTMPT, DDTMP)
PARAMETER AMX    = 1.11E-3
* 1.11 milligram 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  = -10.,0., 0.,0., 10.,1., 25.,1., 35.,0., 50.,0.
```

For explanation see page 4.

2.5. Daily gross CO_2 assimilation

```
     CALL TOTASS(DOY,LAT,DTR,SCP,AMAX,EFF,KDF,TAI,  ...
                 DAYL,DTGA,DS0)
PARAMETER EFF    = 12.5E-6
```

```
* 12.5 microgram CO2/J  = 0.45 (kg CO2/ha/h)/(J/m2/s)
PARAMETER KDF    = 0.60
PARAMETER SCP    = 0.20
*PARAMETER LATT   = 52.
```

For explanation see page 4.

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.

For more explanation see page 5.

2.7. Maintenance respiration

```
      MAINT      = MAINTS * TEFF * MNDVS * EMERG
      MAINTS     = MAINLV*WLVG + MAINST*WST + MAINRT*WRT + MAINSO*WSO
      MNDVS      = WLVG / NOTNUL(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
* Maintenance parameters are expressed in g glucose per g dry matter per day
```

For explanation see page 5.

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        = AFGEN(FSOTB, 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
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
FUNCTION FSOTB   = 0.00,0.00, 0.95,0.00, 1.05,1.00, 2.50, 1.00
```

```
       ERRSH  = ABS(FLV + FST + FSO - 1.)
FINISH ERRSH  > 1.E-6
```

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).

For more explanation see page 6.

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

* The following values are calculated without
* the costs of nitrate reduction:
PARAMETER ASRQRT = 1.444; ASRQLV = 1.463
PARAMETER ASRQST = 1.513; ASRQSO = 1.415
PARAMETER FRTRL  = 0.20 ; CONVL  = 0.947
```

For explanation see page 6.

2.10. Leaf and ear development

```
      TAI        = 0.5 * EAI + LAI
      LAI        = INTGRL(ILAI, RLAI)
      RLAI       = GLAI - DLAI
      CALL GLA(TIME, DOYEM, DTEFF, DVS,            ...
               RGRL, DELT, SLA  , LAI, GLV,      GLAI)
PARAMETER RGRL   = 0.009
PARAMETER SLA    = 0.022

      EAI        = INTGRL(IEAI, REAI)
      CALL SUBEAI(DELT,DVS,EAR,TADRW,RDRDV,EAI,  REAI)
PARAMETER EAR    = 0.63E-3

      DLAI       = LAI * RDR
      RDR        = MAX(RDRDV, RDRSH)
      RDRDV      = INSW(DVS-1.0, 0., DVR/(MAX(0.1, 2.-DVS))*FRDR)
      RDRSH      = LIMIT(0., 0.03, 0.03 * (LAI-LAICR) / LAICR)
```

```
PARAMETER LAICR  = 4.0 ; FRDR = 1.

      DLV        = WLVG * DLAI/NOTNUL(LAI)
```

For explanation see pages 7 and 8.

2.11. Dry matter production

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

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

      HI         = WSO / NOTNUL(TADRW)
```

For explanation see page 8.

2.12. Weather data

```
WEATHER WTRDIR='C:\SYS\WEATHER\';CNTR='NLD';ISTN=1;IYEAR=1990
* Reading weather data from the weather file:
* RDD    Daily global radiation              J/m2/d
* TMMN   Daily minimum temperature           degree C
* TMMX   Daily maximum temperature           degree C
* VP     Vapour pressure                     kPa
* WN     Wind speed                          m/s
* RAIN   Precipitation                       mm/d
* LAT    Latitude of the site                degree
* DOY    Daynumber of year = TIME            d

      DTR        = RDD

      DAVTMP     = 0.5 * (TMMX + TMMN)
      DDTMP      = TMMX - 0.25 * (TMMX-TMMN)
      DTEFF      = MAX(0., DAVTMP-TBASE)
PARAMETER TBASE  = 0.

      AVP        = VP
      WDS        = WN
      RRAIN      = RAIN

      TRAIN      = INTGRL(ZERO, RRAIN)
```

In addition to the variables explained in SUCROS1 (see page 9), actual vapour pressure (AVP, kPa; daily averaged), wind speed (WDS, m s^{-1}) and rainfall (RAIN, mm) are read from the AB/TPE standard weather file NLD1.990. Actual vapour pressure is read in kPa (1 mbar =100 Pa). Total rainfall (TRAIN) is computed to be included in the output and in the water balance check (Subsection 2.14).

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.

The principal driving force for evapotranspiration is the gradient of vapour pressure from the evaporating surface to the surrounding air. The vapour pressure at the evaporating surface is assumed to be equal to the saturated vapour pressure at the prevailing temperature of that surface. The vapour pressure in the air is a meteorological variable. The rate of evapotranspiration depends also on the diffusion resistance between the evaporating surface and the air, which 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. Evapotranspiration 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 evapotranspiration 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 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 evapotranspiration.

Net radiation is the balance between incoming (short-wave) radiation from the sun, corrected for reflection and outgoing (long-wave) radiation. Heat supplied by moving air (advection) is another source of energy, but this is usually negligible, except in situations where the vegetation is surrounded by extensive bare areas (oasis). Only 1% 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 evapotranspiration 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 H_2O 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         = 0.611 * EXP(17.4 * DAVTMP / (DAVTMP + 239.))
PARAMETER LHVAP  = 2.4E6
PARAMETER PSYCH  = 0.067
```

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 (kPa $˚C^{-1}$) is the tangent of the relation between saturated vapour pressure (kPa) and temperature (˚C) and PSYCH (0.067 kPa $˚C^{-1}$ 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 its surface color and 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*10.)
      FCLEAR      = 0.1+0.9*CLEAR
      CLEAR       = LIMIT(0., 1., ((DTR/DS0)-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 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/DS0 using the Ångström formula:

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

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, kPa (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
```

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

2.13.5. Drying power term

```
WDF      = 2.63 * (1.0 + 0.54 * WDS) * PSYCH
DRYP     = (SVP-AVP) * WDF
EVAPD    = DRYP/(SLOPE+PSYCH)
```

The numerical values in the equation for DRYP (mm d^{-1} kPa $°C^{-1}$) are not unitless and, therefore, depend on the units 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 kPa. 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(ZERO, PENMAN)
TEVAPR     = INTGRL(ZERO, EVAPR)
TEVAPD     = INTGRL(ZERO, EVAPD)
```

Cumulative potential evapotranspiration since the start of the simulation (TPENM, mm) is computed as well as the cumulative values for the 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 on 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

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 four layers, called soil compartments. Thickness and physical characteristics of each layer are inputs to the model. The upper layer (TKL1) is set at 200 mm thick, the second (TKL2) at 400 mm, the third (TKL3) at 600 mm, and the fourth (TKL4) at 800 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 assumed equal to soil porosity, though some ‘entrapped’ air may occupy a small part of the pore space. ‘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 10 kPa 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 1600 kPa 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 varies strongly among soil types.

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      = MIN(RRAIN, 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 (RRAIN) is higher, hence the use of the MIN function (Appendix II).

2.14.3. Runoff

```
      RNOFF      = MAX(0.,  0.15*(RRAIN-AINTC-10.),     ...
                            RRAIN-AINTC-(WCST1*TKL1-WL1)/(2.*DELT))
```

Not all the water that reaches the surface infiltrates into the soil, especially not during heavy rain. Runoff from a field can be upto 20% of precipitation, and even higher on unfavourable surfaces (Stroosnijder & Koné, 1982) or with large and intense showers. Runoff may be reduced by proper soil management or specific anti-erosion measures such as terracing or ridging. 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      = RRAIN-AINTC-RNOFF
```

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

2.14.5. Redistribution

```
      WLFL2      = MAX(0., MIN(WL1-WCFC1*TKL1,                    ...
                           WCST2*TKL2-WL2)/(2.*DELT)
      WLFL3      = MAX(0., MIN(WL2-WCFC2*TKL2,                    ...
                           WCST3*TKL3-WL3)/(2.*DELT)
      WLFL4      = MAX(0., MIN(WL3-WCFC3*TKL3,                    ...
                           WCST4*TKL4-WL4)/(2.*DELT)
      WLFL5      = MAX(0., MIN((WL4-WCFC4*TKL4)/(2.*DELT),MDRATE))
PARAMETER WCFC1  = 0.23; WCFC2 = 0.23; WCFC3 = 0.23; WCFC4 = 0.23
PARAMETER WCST1  = 0.40; WCST2 = 0.40; WCST3 = 0.40; WCST4 = 0.40
```

Redistribution of water in the soil can be simulated by using the Richards equation, but the problem is then the small time coefficient, especially near water saturation. In SUCROS2, this problem is circumvented by applying the ‘tipping bucket’ approach, with a time step of one day. For optimal numerical stability, a drainage coefficient of 0.5 is used. Which means that each day half the surplus water in excess of field capacity is drained to the adjacent lower layer, i.e. WLFL2, WLFL3, WLFL4, WLFL5 (mm d^{-1}, positive in downward direction).

2.14.6. External drainage

```
DRAIN       = WLFL5
```

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 the soil compartments above field capacity causing buildup of a perched water table. Drainage is limited by the maximum drainage rate of the subsoil (MDRATE, 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).
Water that cannot drain, fills up the soil layers till saturation. This occurs first in the deepest layer simulating the formation of a perched groundwater table. If still more excess water is to be stored in the soil profile overlying compartments are successively filled up till saturation as well. If the whole soil profile is saturated, water flows over the surface. This parametric way to account for waterlogged conditions will not always be satisfactory. Mechanistic (this parametric method is also dynamic) simulation of waterlogging can be done with a model named SAWAH (ten Berge *et al*., 1992) when the transport characteristics of the soil are known.

2.14.7. Evaporation and transpiration

The rate of water extraction due to evaporation (EVSW1-4, mm d^{-1}) and transpiration (TRWL1-4, mm d^{-1}) for each of the four layers is calculated later in the model (Sections 2.17 and 2.16, respectively).

2.14.8. Calculation of soil water content

```
RWL1        = WLFL1-WLFL2-EVSW1-TRWL1
RWL2        = WLFL2-WLFL3-EVSW2-TRWL2
RWL3        = WLFL3-WLFL4-EVSW3-TRWL3
RWL4        = WLFL4-WLFL5-EVSW4-TRWL4

WL1         = INTGRL(WL1I,RWL1)
WL2         = INTGRL(WL2I,RWL2)
WL3         = INTGRL(WL3I,RWL3)
WL4         = INTGRL(WL4I,RWL4)
WCL1        = WL1/TKL1
WCL2        = WL2/TKL2
WCL3        = WL3/TKL3
WCL4        = WL4/TKL4
RWCL1       = (WCL1-WCWP1)/(WCFC1-WCWP1)
RWCL2       = (WCL2-WCWP2)/(WCFC2-WCWP2)
RWCL3       = (WCL3-WCWP3)/(WCFC3-WCWP3)
RWCL4       = (WCL4-WCWP4)/(WCFC4-WCWP4)
```

First, the amount of water (WL1-4, 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.
Finally the ‘relative amount’ of crop available water in each of the compartments (RWCL1-4, -) is calculated (*S* in Subsection 2.18.1). These values are used in the calculation of actual transpiration (Subsection 2.16.3).

2.14.9. Output variables

```
TDRAIN     = INTGRL(ZERO, DRAIN)
TAINTC     = INTGRL(ZERO, AINTC)
TRNOFF     = INTGRL(ZERO, RNOFF)
```

A number of output variables are computed. Total drainage since the start of the simulation (TDRAIN, mm), total interception (TAINTC, mm) and total runoff (TRNOFF, mm). These variables are also used in the calculation of the water balance of the system.

2.14.10. Checking the balances

```
WCUM       = WL1+WL2+WL3+WL4
CHECK      = TRAIN+WCUMI-TAINTC-TRNOFF-TDRAIN-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 Subsections 2.16.5 and 2.17.5, respectively.

2.15. Rooted depth

2.15.1. Introduction

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

The rooted depth (ZRT, mm) is defined as the maximum 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 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, i.e. rooted depth at emergence (ZRTI, mm), defined in the initial section of the model.

2.15.2. Elongation rate of roots

```
      EZRT       = EZRTC * WSERT * AMTMP
* Temperature effect included, same as for AMAX (AMTMP)

     CALL SUBGRT (ZRT,ZRTM,DVS,TKL1,TKL2,TKL3,TKL4,WCL1,WCL2,WCL3,WCL4, ...
```

```
                  WCWP1,WCWP2,WCWP3,WCWP4,  WSERT)
PARAMETER EZRTC  = 12.
```

The length of fibrous roots can vary enormously without much relation to root weight. Hence, rooted depth is calculated independently of the growth of the root mass. Rooted depth (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 function value of WSERT.

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

Roots grow to a certain maximum depth (ZRTM, see also Section 2.2) 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 among 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 17 - 80 g m^{-2} 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 * ...
                    MIN(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 intercepted 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 high. 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  = -.50,0., -.05,0., 0.,.15, .15,.6, ...
                     .3,.8, .5,1., 2.,1.
      ERLB       = ZRT1*AFGEN(EDPTFT, RWCL1) +...
                   ZRT2*AFGEN(EDPTFT, RWCL2) +...
                   ZRT3*AFGEN(EDPTFT, RWCL3) +...
                   ZRT4*AFGEN(EDPTFT, RWCL4)
      TRRM       = PTRANS/NOTNUL(ERLB)
      TRWL1      = TRRM*WSE1*ZRT1*AFGEN(EDPTFT, RWCL1)
      TRWL2      = TRRM*WSE2*ZRT2*AFGEN(EDPTFT, RWCL2)
      TRWL3      = TRRM*WSE3*ZRT3*AFGEN(EDPTFT, RWCL3)
      TRWL4      = TRRM*WSE4*ZRT4*AFGEN(EDPTFT, RWCL4)
      ZRT1       = LIMIT(0.,TKL1,ZRT)
      ZRT2       = LIMIT(0.,TKL2,ZRT-TKL1)
      ZRT3       = LIMIT(0.,TKL3,ZRT-TKL1-TKL2)
      ZRT4       = LIMIT(0.,TKL4,ZRT-TKL1-TKL2-TKL3)

      ATRANS     = TRWL1+TRWL2+TRWL3+TRWL4
```

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 under field conditions, 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`, mm mm^{-1} d^{-1}) per millimeter of effective rooted depth is calculated by dividing the potential transpiration rate of the canopy (`PTRANS`) by the cumulative effective root length.

The uptake per compartment (`TRWL1-4`) 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 (`WSE1-4`), and by the effective root length per soil compartment. Total water uptake (`ATRANS`) is the sum of water withdrawn from the individual soil compartments.

The multiplication factors for moisture uptake due to low soil moisture contents (between 1 and 0) for the individual soil compartments (`WSE1-4`) are discussed in Subsection 2.18.1.

2.16.4. Output variables

```
TPTRAN     = INTGRL(ZERO, PTRANS)
TATRAN     = INTGRL(ZERO, 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*LAI) * (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(IDSLR, RDSLR)
RDSLR      = INSW(RRAIN-0.5, 1., -(DSLR-1.)/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), the value of IDSLR has a minimum of 1. and is reset to 1. when it rains (Stroosnijder, 1982). Days with less than 0.5 mm of rain are not taken into account.

2.17.3. Actual evaporation

```
      AEVAP       = INSW(RRAIN-0.5, EVSD, EVSH)
      EVSH        = MIN(PEVAP, (WL1-WCAD1*TKL1)/DELT+WLFL1)
PARAMETER WCAD1   = 0.025; WCAD2 = 0.025; WCAD3 = 0.025; WCAD4 = 0.025
```

In calculating 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, and calculated as:

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

The evaporation rate decreases as the top soil 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 below 0.5 mm is too small to trigger the resetting of days since the last rain and is added to evaporation. This small amount of rainfall is assumed to evaporate without soil wetting.

2.17.4. Extraction of ‘evaporation water’ from soil layers

```
      FEVL1       = MAX(WL1-WCAD1*TKL1, 0.1)*EXP(-EES*(0.5*TKL1))
      FEVL2       = MAX(WL2-WCAD2*TKL2, 0.1)*EXP(-EES*(TKL1+...
                    (0.5*TKL2)))
      FEVL3       = MAX(WL3-WCAD3*TKL3, 0.1)*EXP(-EES*(TKL1+TKL2+...
                    (0.5*TKL3)))
      FEVL4       = MAX(WL4-WCAD4*TKL4, 0.1)*EXP(-EES*(TKL1+TKL2+TKL3+...
                    (0.5*TKL4)))
PARAMETER EES     = 0.002
```

Partitioning parameters (FEVL1-4) are computed for the four 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^{-2} mm^{-1} for heavy (clay) soils and 3×10^{-2} mm^{-1} for light (sandy) soils.

```
      FEVLT       = FEVL1+FEVL2+FEVL3+FEVL4
```

```
EVSW1      = AEVAP*(FEVL1/FEVLT)
EVSW2      = AEVAP*(FEVL2/FEVLT)
EVSW3      = AEVAP*(FEVL3/FEVLT)
EVSW4      = AEVAP*(FEVL4/FEVLT)
```

Finally, the contribution from the individual layers (EVSW1-4, 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(ZERO, PEVAP)
TAEVAP     = INTGRL(ZERO, 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 2.2, 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 (Subroutine SUBFR), 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):

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

Table 2.2. Characteristic potential transpiration rates (see text for explanation 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

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 $T_{S=0.5}$.

Implementation in the model:

```
      P           = TRANSC/(TRANSC+PTRANS)
PARAMETER TRANSC = 9.
      CALL SUBFR (WCL1,WCFC1,P,WCWP1,WCWET1,WCST1, WSE1)
      CALL SUBFR (WCL2,WCFC2,P,WCWP2,WCWET2,WCST2, WSE2)
      CALL SUBFR (WCL3,WCFC3,P,WCWP3,WCWET3,WCST3, WSE3)
      CALL SUBFR (WCL4,WCFC4,P,WCWP4,WCWET4,WCST4, WSE4)

PARAMETER WCWET1 = 0.35; WCWET2 = 0.35; WCWET3 = 0.35; WCWET4 = 0.35
PARAMETER WCWP1  = 0.075;WCWP2  = 0.075;WCWP3  = 0.075; WCWP4 = 0.075
```

The effect of availability of soil water on uptake in a compartment is presented by a factor (WSE1-4), with a value between 0.0 and 1.0. Figure 2.2 schematically shows the relation between this stress factor and soil water content.

These WSE-factors are computed in the Subroutine SUBFR. 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). In this subroutine, the critical water content (WCCR) is first calculated on the basis of the critical transpiration rate and P.

Water stress factors for the individual layers (WSE1-4) are used to compute total water uptake in Section 2.16. This leads to the actual transpiration (ATRANS).

2.18.2. Effect on CO_2 assimilation

```
PCEW       = ATRANS/NOTNUL(PTRANS)
```

There is a significant influence of water stress 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, g CO_2 m^{-2} ground d^{-1}) is calculated (see Section 2.6) this is multiplied by PCEW.

2.18.3. Effect on carbohydrate partitioning

```
CPEW       = MIN(1., 0.5+ATRANS/NOTNUL(PTRANS))
```

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 response of root biomass 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 have gone 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.

Figure 2.2. 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.

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), see Section 2.8.

2.19. Water use efficiency

```
      TDTGA      = INTGRL(ZERO, DTGA)
      TAR        = TATRAN*1.E3/NOTNUL(TDTGA)
*      TRC        = TATRAN*1.E3/NOTNUL(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 the large variation in evaporative demand and the inclusion of the soil evaporation. Hence, this variable 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, g DM m^{-2}). 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). 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. Carbon balance check

```
      CHKIN      = WLV * CFLV + WST * CFST + ...
                     WRT * CFRT + WSO * CFSO
      CHKFL      = TNASS * (12./44.)
      TNASS      = INTGRL(TNASSI, RTNASS)
      RTNASS     = ((GPHOT - MAINT)*44./30.) -  ...
                                  (GRT*CO2RT + GLV*CO2LV +  ...
                          (GST+TRANSL)*CO2ST + GSO*CO2SO +  ...
```

```
                         (1.-CONVL)* 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     = (CHKIN-CHKFL)/NOTNUL(CHKIN)

PARAM CFLV=0.459; CFST=0.494; CFRT=0.467; CFSO=0.471
```

2.21. Run control

```
*      DAY        = 1. + AMOD(TIME-1., 365.)

FINISH DVS       > 2.
TIMER STTIME     = 80.; FINTIM = 300.; DELT = 1.; PRDEL = 5.
TRANSLATION_GENERAL DRIVER='EUDRIV'

PRINT DOY,DVS,DAYL,TDRW,TADRW,WLVG,WLVD,WLV,WST,...
      WSO,WRT,LAI,EAI,HI,WL1,WL2,WL3,WL4,...
      TPENM,TEVAPR,TEVAPD,TRAIN,TAINTC,TRNOFF,TDRAIN,...
      TPTRAN,TATRAN,TPEVAP,TAEVAP,CHECK,TAR,EVAPR
```

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 RES.DAT at every print interval (PRDEL).

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

   SUBROUTINES
```

2.22. Subroutines

SUCROS2 is SUCROS1, extended for water-limited conditions. There are two additional subroutines (SUBFR is used to compute water stress factors for each soil layer and SUBGRT to decide whether root extension growth continues or ceases), and the main program in FST is extended with a section on water relations.

2.23. Listing of SUCROS2

References

Baier, W. & G.W. Robertson, 1967.
Estimating yield components of wheat from calculated soil moisture. Canadian Journal of Plant Science 47: 617-630.

Berge, H.F.M. ten, 1989.
Heat and water transfer in bare topsoil and lower atmosphere. Simulation Monographs 33, Pudoc, Wageningen, 200 p.

Berge, H.F.M. ten, D.M. Jansen, K. Rappoldt & W. Stol, 1992.
The soil water balance module SAWAH: description and users guide. Simulation Reports CABO-TT no 22, Centre for Agrobiological Research and Department of Theoretical Production Ecology, Wageningen Agricultural University, 78 p.

Bresler, E., 1991.
Soil spatial variability. In: Eds J. Hanks & J.T. Ritchie, Modeling plant and soil systems. ASA/CSSA/SSSA Publishers, Madison (WI), Agronomy Monograph 31, 145-180.

Brouwer, R., 1962.
Some aspects of the equilibrium between overground and undergroud plant parts. Jaarboek IBS 1963: 31-39.

Brunt, D., 1932.
Notes on radiation in the atmosphere. I. Quarterly Journal of the Royal Meteorological Society 58: 349-420.

Denmead, O.T. & R.H. Shaw, 1962.
Availability of soil water to plants as affected by soil moisture conditions and meteorological conditions. Agronomy Journal 54: 385-389.

Doorenbos, J. & W.O. Pruitt, 1977.
Guidelines for predicting crop water requirements. FAO Irrigation and Drainage paper No. 24, F.A.O., Rome, 144 p.

Doorenbos, J. & A.H. Kassam, 1979.
Yield response to water. FAO Irrigation and Drainage paper No. 33, F.A.O., Rome, 193 p.

Doorenbos, J. & A.H. Kassam, C. Bentvelder & G. Uittenbogaard, 1978.
Yield response to water.U.N. Economic Commission West Asia, Rome.

Driessen, P.M., 1986.
The water balance of the soil. In: Eds H. van Keulen & J. Wolf, Modelling of agricultural production: weather, soils and crops. Simulation Monographs, Pudoc, Wageningen, 76-116.

Dwyer, L.M. & D.W. Stewart, 1986.
Effect of leaf age and position on net photosynthetic rates in maize (*Zea mays* L.). Agricultural and Forest Meteorology 37: 29-46.

Feddes, R.A., 1987.
Crop factors in relation to Makkink reference crop evapotranspiration. In: Ed. J.C. Hooghart, Evaporation and weather. Proceedings and Information no. 39, TNO Committee on Hydrological Research, The Hague, 33-46.

Feddes, R.A., P.J. Kowalik & H. Zaradny, 1978.
Simulation of field water use and crop yield. Simulation Monographs, Pudoc, Wageningen, 195 p.

Frère, M. & G.F. Popov, 1979.
Agrometeorological crop monitoring and forecasting. Plant Production and Protection Paper 17, FAO, Rome, 64 p.

Gollan, T., J.B. Passioura & R. Maas, 1986.
Soil water status affects the stomatal conductance of fully turgid wheat and sunflower leaves. Autralian Journal of Plant Physiology 13: 459-464.
Goudriaan, J., 1986.
A simple and fast numerical method for the computation of daily totals of crop photosynthesis. Agricultural and Forest Meteorology 38: 251-255.
Goudriaan, J. & H.H. van Laar, 1978.
Relations between leaf resistance, CO_2-concentration and CO_2-assimilation in maize, beans, lalang grass and sunflower. Photosynthetica 12(3): 241-249.
Goudriaan, J. & H.H. van Laar, 1994.
Modelling potential crop growth processes. Textbook with exercises. Kluwer Academic Publishers, Dordrecht, The Netherlands, 274 pp.
IBM, 1975.
Continuous system modeling program III (CSMP III), Program Reference Manual. IBM SH19-7001-3. Technical Publication Department, White Plains, USA, 206 p.
Jackson, M.B. & M.C. Drew, 1984.
Effects of flooding on growth and metabolism of herbaceous plants. In: Ed. T.T. Kozlowski, Flooding and plant growth. Academic Press, London, 47-128.
Jansen, D.M. & P. Gosseye, 1986.
Simulation of growth of millet (*Pennisetum americanum*) as influenced by water stress. Simulation Reports CABO-TT no. 10, Centre for Agrobiological Research and Department of Theoretical Production Ecology, Wageningen Agricultural University, 108 p.
Jansen, D.M., R.T. Dierkx, H.H. van Laar & M.J. Alagos, 1988. PCSMP on IBM PC-AT's or PC-XT's and compatibles. Simulation Reports CABO-TT no. 15, Centre for Agrobiological Research and Department of Theoretical Production Ecology, Wageningen Agricultural University, 64 p.
Kraalingen, D.W.G. van, 1991.
The FSE system for crop simulation. Simulation Reports CABO-TT no. 23, Centre for Agrobiological Research and Department of Theoretical Production Ecology, Wageningen Agricultural University, 77 p.
Keulen, H. van, 1975.
Simulation of water use and herbage growth in arid regions. Simulation Monographs, Pudoc, Wageningen, 176 p.
Keulen, H. van & H.H. van Laar, 1982.
The relation between water use and crop production. In: Eds H. van Keulen & J. Wolf, Modelling of agricultural production: weather, soils and crops. Simulation Monographs, Pudoc, Wageningen, 117-129.
Keulen, H. van & J. Wolf (Eds), 1986.
Modelling of agricultural production: weather, soils and crops. Simulation Monographs, Pudoc, Wageningen, 470 p.
Keulen, H. van & N.G. Seligman, 1987.
Simulation of water use, nitrogen nutrition and growth of a spring wheat crop. Simulation Monographs, Pudoc, Wageningen, 310 p.
Keulen, H. van, F.W.T. Penning de Vries & E.M. Drees, 1982.
A summary model for crop growth. In: Eds F.W.T. Penning de Vries & H.H. van Laar, Simulation of plant growth and crop production. Simulation Monographs, Pudoc, Wageningen, 87-97.
Kropff, M.J., H.H. van Laar & R.B. Matthews (Eds), 1994.
ORYZA1; An ecophysiological model for irrigated rice production. SARP Research Proceedings, AB-DLO, WAU-TPE, Wageningen and IRRI, Philippines, 110 pp.

Lawlor, D.W., 1973.
Growth and water absorption of wheat with part of the roots at different water potentials. New Phytologist 72: 297-305.
Le Houérou & C.H. Hoste, 1977.
Rangeland production and annual rainfall relations in the Mediterrean Basin and in the African Sahelo-Sudanian zone. Journal of Range Management 30: 181-189.
Lomas, J. & Y. Shashoua, 1974.
The dependence of wheat yields and grain weight in a semi-arid region on rainfall and the number of hot dry days. Israeli Journal of Agricultural Research 23: 113-121.
Monteith, J.L., 1965.
Evaporation and environment. Proc. Symp. Society of Experimental Biology 19: 205-234.
Penman, H.L., 1948.
Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society A193, 120-145.
Penman, H.L., 1956.
Evaporation: an introductory survey. Netherlands Journal of Agricultural Science 4: 9-29.
Penning de Vries, F.W.T. & H.H. van Laar (Eds), 1982.
Simulation of plant growth and crop production. Simulation Monographs, Pudoc, Wageningen, 308 p.
Penning de Vries, F.W.T., D.M. Jansen, H.F.M. ten Berge & A. Bakema, 1989.
Simulation of ecophysiological processes of growth of several annual crops. Simulation Monographs 29, Pudoc, Wageningen, 271 p.
Rappoldt, C. & D.W.G. van Kraalingen, 1996.
The Fortran Simulation Translator, FST version 2.0. Introduction and Reference Manual. Quantitative Approaches in Systems Analysis No. 5, June 1996. DLO-Research Institute for Agrobiology and Soil Fertility and C.T. de Wit Graduate School for Production Ecology, Wageningen, The Netherlands, 178 pp.
Rawson, H.M., J.H. Hindmarsh, R.A. Fisher & Y.M. Stockman, 1983.
Changes in leaf photosynthesis with plant ontogeny and relationships with yield per ear in wheat cultivars and 120 progeny. Australian Journal of Plant Physiology 10: 503-514.
Schulze, E.D., 1986.
Carbon dioxide and water vapor exchange in response to drought in the atmosphere and in the soil. Annual Review of Plant Physiology 37: 247-274.
Singh, B. & G. Sceicz, 1979.
The effect of intercepted rainfall on the water balance of a hardwood forest. Water Resources Research 15: 131-138.
Spiertz, J.H.J. & J. Ellen, 1978.
Effects of nitrogen on crop development and grain growth of winter wheat in relation to assimilation and utilisation of assimilates and nutrients. Netherlands Journal of Agricultural Sciences 26: 210-231.
Spitters, C.J.T., 1986.
Separating the diffuse and direct component of global radiation and its implications for modeling canopy photosynthesis. II. Calculations of canopy photosynthesis. Agricultural and Forest Meteorology 38: 231-242.
Spitters, C.J.T., H.A.J.M. Toussaint & J. Goudriaan, 1986.
Separating the diffuse and direct component of global radiation and its implications for modeling canopy photosynthesis. I. Components of incoming radiation. Agricultural and Forest Meteorology 38: 217-229.

Spitters, C.J.T., H. van Keulen & D.W.G. van Kraalingen, 1989.

A simple and universal crop growth simulator: SUCROS87. In: Eds R. Rabbinge, S.A. Ward & H.H. van Laar, Simulation and systems management in crop protection. Simulation Monographs 32, Pudoc, Wageningen, 147-181.
Stroosnijder, L., 1982.
Simulation of the soil water balance. In: Eds F.W.T. Penning de Vries & H.H. van Laar, Simulation of plant growth and crop production. Simulation Monographs, Pudoc, Wageningen, 175-193.
Stroosnijder, L., 1987.
Soil evaporation: test of a practical approach under semi-arid conditions. Netherlands Journal of Agricultural Science 35: 417-426.
Stroosnijder, L. & D. Koné, 1982.
Le bilan d’eau du sol. In: Eds F.W.T. Penning de Vries & M.A. Djitèye, La productivité des paturâges sahéliens. Une étude des sols, des végétations et de l'exploitation de cette resource naturelle. Pudoc, Wageningen, 133-165.
Swinbank, W.C., 1963.
Longwave radiation from clear skies. Quarterly Journal of the Royal Meteorological Society 89: 339-348.
Tanner, C.B. & T.R. Sinclair, 1982.
Efficient water use in crop production: Research or re-search. In: Eds H.M. Taylor, W.R. Jordan & T.R. Sinclair, Limitations of efficient water use in crop production. American Society of Agronomy Monograph, ASA Monographs Inc., Madison, Wisconsin, 1-27.
Taylor, H.M. & B. Klepper, 1978.
The role of rooting characteristics in the supply of water to plants. Advances in Agronomy 30: 99-128.
Teare, I.D. & M.M. Peet, 1983.
Crop-water relations. Wiley, New York, 547 p.
Veihmeyer, F.J. & A.H. Hendrickson, 1931.
The moisture equivalent as a measure of the field capacity of soils. Soil Science 32: 181-193.
Vos, J. & J. Groenwold, 1983.
Estimation of root densities by observation tubes and endoscope. Plant and Soil 74: 295-300.
Wit, C.T. de, 1958.
Transpiration and crop yields. Verslagen van Landbouwkundige Onderzoekingen (Agricultural Research Reports) 64.6, Pudoc, Wageningen, 88 p.

Appendix I: MOMASSP

In SUCROS, daily canopy assimilation rate is found by Gaussian integration over the day. This method, which is computationally very efficient, obscures however the underlying within-day dynamics of the canopy assimilation rate. To see this dynamics and to study the photosynthesis-light response curve of the canopy as a whole a separate FST program is here presented which uses the modules of SUCROS, but specifically applied on the time scale of the within-day dynamics.
This means that the canopy variables such as leaf area index (LAI) are input parameters, and do not grow. Also, the leaf photosynthesis properties such as AMAX are treated as input parameters. In reality they might not be constant due to temperature and/or water stress. To see these kind of effects, the model presented here should be extended.
The daily time course of incoming radiation is handled as in SUCROS: solar height determines the radiation level, using a daily constant transmissivity of the atmosphere.

The computational accuracy of the equations for radiation distribution over the canopy is checked by the variable BALANS. This variable is calculated as the difference between the net fluxes above and below the canopy and the independently calculated sum of PAR absorption by the individual leaves (PARABS).

```
DEFINE_CALL RADMOM(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
                   OUTPUT,OUTPUT,OUTPUT)
DEFINE_CALL ASSMOM(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
                   OUTPUT,OUTPUT,OUTPUT,OUTPUT,OUTPUT)

TITLE Time course of canopy assimilation rate within a day
*     MOMASSP V1.0, Version September 1997

INITIAL
PARAM PI    = 3.141592654
PARAM LATT  = 52.
PARAM AMAX  = 1000.; EFF   = 12.
PARAM DAY   =  1.00; ATMTR = 0.5
PARAM LAI   =    5.; KDF   = 0.7; SCP = 0.2

      RAD   = PI/180.

*-----declination of the sun as function of daynumber (DAY)
      DEC   = -ASIN(SIN(23.45*RAD)*COS(2.*PI*(DAY+10.)/365.))

*-----SINLD, COSLD and AOB are intermediate variables
      SINLD = SIN(RAD*LATT)*SIN(DEC)
      COSLD = COS(RAD*LATT)*COS(DEC)
      AOB   = SINLD/COSLD

*-----daylength (DAYL) and photoperiodic daylength (DAYLP)
      DAYL  = 12.0*(1.+2.*ASIN(AOB)/PI)
```

```
*-----run control
TIMER STTIME = 0.; FINTIM = 24.; DELT = 1.; PRDEL = 1.
TRANSLATION_GENERAL DRIVER='EUDRIV'
PRINT LAI, FGROS, BALANS, PARINC, REFL, SOIL, PARABS

DYNAMIC
      HOUR   = TIME
      CALL RADMOM (HOUR, DAY,   DAYL, SINLD, COSLD, ATMTR,          ...
                   SINB, PARDR, PARDF)
      CALL ASSMOM (SCP,  AMAX,  EFF,  KDF, LAI, SINB, PARDR, PARDF, ...
                   REFL, SOIL,  PARABS, FGROS, BALANS)
      PARINC = PARDF+PARDR
END

PARAM LAI = 1.
END
PARAM LAI = 0.1
END
STOP

*----------------------------------------------------------------------*
*  Subroutine RADMOM:                                                  *
*  This is a modified RADIAT Subroutine                                *
*  Fraction diffuse is calculated according to momentane values as     *
*  described by                                                        *
*  Spitters, C.J.T., H.A.J.M. Toussaint & J. Goudriaan, 1986,          *
*    Separating the diffuse and direct component of global radiation   *
*    and its implications for modeling canopy photosynthesis. Part I.  *
*    Components of incoming radiation.                                 *
*    Agric. and Forest Meteorology 38, 217-229.                        *
*                                                                      *
*  Computation of diffuse and direct amount of photosynthetically      *
*  active radiation (PAR) from average global radiation (AVRAD),       *
*  DAY of the year and HOUR of the day.                                *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                   units  class *
*  ----   ---- -------                                   -----  ----- *
*  HOUR    R4  Selected hour during the day                 h      T  *
*  DAY     R4  Day number (January 1 = 1)                   d      T  *
*  DAYL    R4  Daylength                                    h      I  *
*  SINDL   R4  Seasonal offset of sine of solar height      -      I  *
*  COSLD   R4  Amplitude of sine of solar height            -      I  *
*  ATMTR   R4  Atmospheric transmission coefficient         -      I  *
*  SINB    R4  Sine of solar elevation                      -      O  *
*  PARDR   R4  Instantaneous direct flux of incoming PAR   J/m2/s   O  *
*  PARDF   R4  Instantaneous diffuse flux of incoming PAR  J/m2/s   O  *
*----------------------------------------------------------------------*

      SUBROUTINE RADMOM (HOUR,DAY,DAYL,SINLD,COSLD,ATMTR,
```

```
     $                   SINB,PARDR,PARDF)
      IMPLICIT REAL (A-Z)
      PARAMETER (PI=3.141592654)

*-----sine of solar elevation (SINB), integral of SINB (DSINB)
      AOB    = SINLD/COSLD
      SINB   = MAX(0.,SINLD+COSLD*COS(2.*PI*(HOUR+12.)/24.))
      DSINB  = 3600.*(DAYL*SINLD+24.*COSLD*SQRT(1.-AOB*AOB)/PI)
      SC     = 1370.*(1.+0.033*COS(2.*PI*DAY/365.))
      AVRAD  = ATMTR*SC*SINB

*-----diffuse light fraction (FRDF) from atmospheric transmission (ATMTR)
      FRDF   = 1.47-1.66*ATMTR
      IF (ATMTR.LE.0.35.AND.ATMTR.GT.0.22) FRDF=1.-6.4*(ATMTR-0.22)**2
      IF (ATMTR.LE.0.22)                   FRDF=1.
      FRDF   = MAX(FRDF,0.15+0.85*(1.-EXP(-0.1/MAX(0.01,SINB))))

*-----diffuse PAR (PARDF) and direct PAR (PARDR)
      PAR    = 0.5*AVRAD
      PARDF  = MIN(PAR,SINB*FRDF*ATMTR*0.5*SC)
      PARDR  = PAR-PARDF

      RETURN
      END


*----------------------------------------------------------------------*
*  Subroutine ASSMOM                                                   *
*  Performs a Gaussian integration over depth of canopy by             *
*  selecting five different LAI's and computing assimilation at        *
*  these LAI levels. The integrated variable is FGROS.                 *
*  Calculation of the BALANS of PAR                                    *
*                                                                      *
*  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   microg CO2/     *
*                                                        m2 leaf/s  I  *
*  EFF     R4  Initial light cobversion factor         microg CO2/J I  *
*  KDF     R4  Extinction coefficient for leaves             -      I  *
*  LAI     R4  Leaf area index                             m2/m2    I  *
*  SINB    R4  Sine of solar elevation                       -      I  *
*  PARDR   R4  Instantaneous direct flux of incomng PAR   J/m2/s    I  *
*  PARDF   R4  Instantaneous diffuse flux of incoming PAR J/m2/s    I  *
*  REFL    R4  Reflected flux of PAR by the crop          J/m2/s    O  *
*  SOIL    R4  Flux of PAR absorbed by the soil surface   J/m2/s    O  *
*  PARABS  R4  Total PAR absorbed by the leaves           J/m2/s    O  *
*  FGROS   R4  Instantaneous assimilation rate of   microg CO2/m2/s O  *
```

```
*              whole canopy                                        *
*  BALANS  R4  Difference between PARABS and net flux at  J/m2/s    O  *
*              canopy boundaries                                   *
*------------------------------------------------------------------------*

      SUBROUTINE ASSMOM(SCP, AMAX, EFF, KDF, LAI, SINB, PARDR, PARDF,
     $                  REFL,SOIL,PARABS,FGROS,BALANS)
      IMPLICIT REAL(A-Z)
      REAL XGAUSS(5), WGAUSS(5)
      INTEGER I1, I2, IGAUSS


*-----Gauss weights for five point Gauss
      DATA XGAUSS /0.0469101,0.2307534,0.5000  ,0.7692465,0.9530899/
      DATA WGAUSS /0.1184635,0.2393144,0.284444,0.2393144,0.1184635/
      DATA IGAUSS /5/

*-----reflection of horizontal and spherical leaf angle distribution
      SQV    = SQRT(1.-SCP)
      REFH   = (1.-SQV)/(1.+SQV)
      REFS   = REFH*2./(1.+1.6*SINB)

*-----extinction coefficient for direct radiation and total direct flux
      CLUSTF = KDF / (0.8*SQV)
      KBL    = (0.5/MAX(0.01,SINB)) * CLUSTF
      KDRT   = KBL * SQV

*-----selection of depth of canopy, canopy assimilation is set to zero
      FGROS  = 0.
      IABS   = 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 / MAX(0.01,SINB)
         FGRSUN = 0.
         IABSUN = 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)
            IABSUN = IABSUN + VISSUN*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
      IABSL  = FSLLA * IABSUN+(1.-FSLLA)*VISSHD

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

      FGROS  = FGROS*LAI
      PARABS = IABS *LAI
      REFL   = REFS *PARDR + REFH*PARDF
      SOIL   = (1.-REFS)*PARDR*EXP(-KDRT*LAI) +
     $         (1.-REFH)*PARDF*EXP(-KDF *LAI)
      PARINC = PARDF+PARDR
      BALANS = PARINC-REFL-SOIL-PARABS
      RETURN
      END
```

Appendix II: FST and FORTRAN intrinsic functions

List of FST intrinsic functions with explanation. The input arguments K and L denote an integer constant, variable or expression. Array arguments are written as A or B. The symbol F means an FST interpolation function and all other input arguments are real constants, variables or expressions.
Taken from Rappoldt & van Kraalingen (1996).

FST function	Mathematical notation or Graph
`Y = AFGEN(F,X)` Linear interpolation between (x,y) function points. Y - Result of interpolation, estimated F(X) F - Table of (x,y) values specified with FUNCTION statement X - Value of independent variable	
`Y = ARIMPR(A,B,K,L)` Returns the improduct of a vector A and a vector B calculated over the subscript range K,...,L. Y - Returned improduct A - Array variable seen as vector B - Array variable seen as vector K - Start of subscript range L - End of subscript range with L≥K	$y = \sum_{i=K}^{L} A_i B_i$
`Y = ARLENG(A,K,L)` Returns the length of the vector with elements A(K),...., A(L) in (L-K+1)-dimensional space. Y - Returned length A - Array variable seen as vector K - Start of subscript range L - End of subscript range with L≥K	$y = \sqrt{\sum_{i=K}^{L} A_i^2}$
`Y = ARMAXI(A,K,L)` Returns the maximum value among the array elements A(K),...., A(L). Y - Resulting number A - Array variable K - Start of subscript range L - End of subscript range with L≥K	$y = \max_{i=K}^{L} A_i$
`Y = ARMEAN(A,K,L)` Returns the arithmetic mean of the array elements A(K),...., A(L). Y - Maximum value A - Array variable	$y = \frac{\sum_{i=K}^{L} A_i}{L-K+1}$

K - Start of subscript range L - End of subscript range with L≥K	

`Y = ARMINI(A,K,L)` Returns the minimum value among the array elements A(K),...., A(L). Y - Resulting number A - Array variable K - Start of subscript range L - End of subscript range with L≥K	$y = \min_{i=K}^{L} A_i$
`Y = ARSMPS(A,K,L,D)` Simpson's integral of a function over L-K closed intervals (x_K,x_{K+1}), (x_{K+1},x_{K+2}),...(x_{L-1},x_L). At the L-K+1 points the function takes the values A(K),...., A(L). All intervals have equal width D. Y - Approximate integral A - Array containing function values K - Start of subscript range L - End of subscript range with L>K D - Interval width	$y = D\sum_{i=K}^{L} w_i A_i$ in with the coefficients w_i follow - trapezoidal rule for - extended 1/n^3 rule for - alternative extended Simpson's rule for n≥8
`Y = ARSTDV(A,K,L)` Returns the standard deviation of the array elements A(K),...., A(L) seen as a sample. Y - Returned standard deviation A - Array variable K - Start of subscript range L - End of subscript range with L>K	$y = \sqrt{\dfrac{\sum_{i=K}^{L}\left(A_i - \overline{A}\right)^2}{L-K}}$
`Y = ARSUMM(A,K,L)` Returns the sum of the array elements A(K),...., A(L). Y - Resulting sum A - Array variable K - Start of subscript range L - End of subscript range with L≥K	$y = \sum_{i=K}^{L} A_i$
`Y = CSPLIN(F,X)` Natural cubic splines interpolation between (x,y) function points according to Press *et al*. (1989). Y - Result of interpolation, estimated F(X) F - Table of (x,y) values specified with FUNCTION statement X - Value of independent variable	
`Y = ELEMNT(A,K)` Returns value of the K-th element of array A after verifying its existence by comparing K with the declared array bounds. Y - Returned element value A - Array variable K - Subscript	$y = A_K$

`Y = FCNSW(X,Y1,Y2,Y3)` Input switch. Y is set equal to Y1, Y2 or Y3 depending on the value of X. Y - Returned as either Y1, Y2 or Y3 X - Control variable Y1 - Returned value of Y if X<0 Y2 - Returned value of Y if X=0 Y3 - Returned value of Y if X>0	$\begin{cases} y=y_1, & x<0 \\ y=y_2, & x=0 \\ y=y_3, & x>0 \end{cases}$
`Y = INTGRL(YI,YR)` Integration command in the form of a function call. The algorithm of the numerical integration depends on the selected translation mode and driver. Y - State variable YI - Initial value of Y, must be a variable YR- Rate of change, must be a variable	$y(t) = y(0) + \int_0^t \frac{dy(t)}{dt}\,dt$
`Y = INSW(X,Y1,Y2)` Input switch. Y is set equal to Y1 or Y2 depending on the value of X. Y - Returned as either Y1 or Y2 X - Control variable Y1 - Returned value of Y if X<0 Y2 - Returned value of Y if X≥0	$\begin{cases} y=y_1, & x<0 \\ y=y_2, & x\geq 0 \end{cases}$
`Y = LIMIT(XL,XH,X)` Y is equal to X but limited between XL and XH Y - Returned as X bounded on [XL,XH] XL - Lower bound of X XH- Upper bound of X	$\begin{cases} y=x\ , & x_l\leq x\leq x_h \\ y=x_l\ , & x<x_l \\ y=x_h, & x>x_h \end{cases}$
`Y = NOTNUL(X)` Y is equal to X but 1.0 in case of X=0.0. Note that X is evaluated without any tolerance interval. Y - Returned result X - Checked for being zero	$\begin{cases} y=x\ , & x\neq 0 \\ y=1, & x=0 \end{cases}$
`Y = REAAND(X1,X2)` Returns 1.0 if both input values are positive, otherwise Y=0.0.	y=1, x_1,x_2 > 0 y=0, x_1Š0 or x_2Š0
`Y = REANOR(X1,X2)` Returns 1.0 if both input values are less than or equal to zero, otherwise Y=0.0.	y=1, x_1,x_2 Š 0 y=0, $x_1>0$ or $x_2>0$
`Y = RGNORM(M,SD)` Random number Generator which returns numbers with an univariate normal distribution. Y - Returned random number M - Mean of the normal distribution SD- Standard deviation of the distribution	
`Y = RGUNIF(YL,YH)` Random number Generator which returns numbers with a uniform distribution on (YL,YH). Y - Returned random number YL - Lower bound of interval YH - Upper bound of interval	

List of Fortran intrinsic functions with explanation. The input arguments I and J denote an integer constant, variable or expression. The input arguments X, X1, X2, ... are real constants, variables or expressions. Taken from Rappoldt & van Kraalingen (1996).

Fortran function	Explanation	Mathematical notation	Restrictions
`ABS(X)`	absolute value of *x*	$\|x\|$	
`INT(X)`	the integer part of x, result is integer	int(x)	
`AINT(X)`	the integer part of x, converted to real	int(x)	
`NINT(X)`	the nearest integer, result is integer	int(x)	
`ANINT(X)`	the nearest integer converted to real	int(x)	
`MAX(X1, X2,...,Xn)`	maximum value among the real arguments	max(x_1, x_2,. .,x_n)	$n \geq 2$
`AMAX(X1, X2,...,Xn)`	maximum value among the real arguments	max(x_1, x_2,. .,x_n)	$n \geq 2$
`MIN(X1,X2,...,Xn)`	minimum value among the real arguments	min(x_1, x_2,. . ,x_n)	$n \geq 2$
`AMIN(X1,X2,...,Xn)`	minimum value among the real arguments	min(x_1, x_2,. . ,x_n)	$n \geq 2$
`MOD(I,J)`	remainder of i/j with sine of i, result is integer	i mod j	$j \neq 0$
`AMOD(X,Y)`	remainder of x/y with sign of x, result is real	x mod y	$y \neq 0$
`COS(X)`	cosine of x, x in radians	cos(x)	
`COSH(X)`	hyperbolic cosine of x	cosh(x)	
`ACOS(X)`	arccosine of x in range [0,π]	arccos(x)	$-1 \leq x \leq 1$
`EXP(X)`	exponential function	e^x	
`LOG(X)`	natural logarithm of x	e log x	$x > 0$
`ALOG(X)`	natural logarithm of x	e log x	$x > 0$
`LOG10(X)`	base 10 logarithm of x	10log$x$	$x > 0$
`ALOG10(X)`	base 10 logarithm of x	10log$x$	$x > 0$
`REAL(I)`	the real number nearest to integer I		
`SQRT(X)`	square root of x	$\sqrt{x}$	$x \geq 0$
`SIN(X)`	sine of x, x in radians	sin(x)	
`SINH(X)`	hyperbolic sine of x	sinh(x)	
`ASIN(X)`	arc sin of x in range [–π/2, π/2]	arcsin(x)	$-1 \leq x \leq 1$
`TAN(X)`	tangent of x, x in radians	tan(x)	x mod $\pi/2 \neq \pi/4$
`TANH(X)`	hyperbolic tangent of x	tanh(x)	
`ATAN(X)`	arc tangent of x in range [–π/2, π/2]	arctan(x)	
`ATAN2(X,Y)`	arc tangent of x/y in range [–π/2, π/2]	arctan(x/y)	

Appendix III: Definition of abbreviations

Name	Description	Units
A	Parameter in the Ångstrom 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	g CO_2 m^{-2} leaf s^{-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	g CO_2 m^{-2} leaf s^{-1}
AOB	Intermediate variable	-
ASIN	Arcsine function (intrinsic FORTRAN function)	-
ASRQ	Assimilate (CH_2O) requirement for dry matter prod.	g CH_2O g^{-1} DM
ASRQLV	Assimilate requirement for leaf dry matter production	g CH_2O g^{-1} DM leaf
ASRQRT	Assimilate requirement for root dry matter production	g CH_2O g^{-1} DM root
ASRQSO	Assimilate requirement for storage organ dry matter production	g CH_2O g^{-1} DM stor. organs
ASRQST	Assimilate requirement for stem dry matter production	g CH_2O g^{-1} DM stem
ASSIM	FORTRAN subroutine to calculate FGROS	-
ASTRO	FORTRAN subroutine to compute e.g. daylength	-
ATMTR	Atmospheric transmission coefficient	-
ATRANS	Total actual transpiration rate of the canopy	mm d^{-1}
AVP	Actual vapour pressure	kPa
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	g C g^{-1} DM
CFRT	Mass fraction carbon in the roots	g C g^{-1} DM
CFSO	Mass fraction carbon in the storage organs	g C g^{-1} DM
CFST	Mass fraction carbon in the stems	g C g^{-1} DM
CHECK	Variable to check the water balance (should be zero)	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	g C m^{-2}
CHKFL	Sum of integrated carbon fluxes into and out of the crop	g C m^{-2}
CLUSTF	Cluster factor	-
CLEAR	Penman's original clearness factor	-
CONVL	Conversion factor for remobilization of stem carbohydrates into glucose	-
COS	Cosine function (intrinsic FORTRAN function)	-
COSLD	Intermediate variable in calculating solar height	-
CO2LV	CO_2 production factor for growth of leaves	g CO_2 g^{-1} DM
CO2RT	CO_2 production factor for growth of roots	g CO_2 g^{-1} DM
CO2SO	CO_2 production factor for growth of storage organs	g CO_2 g^{-1} DM
CO2ST	CO_2 production factor for growth of stems	g CO_2 g^{-1} DM
CPEW	Factor accounting for effect of water stress on DM partitioning	-
CROPF	Crop factor for crop water requirement	-
DAVTMP	Daily average temperature	˚C
DAY	Day number since 1 January (day of year)	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	m^2 m^{-2} d^{-1}
DLV	Death rate of leaves	g leaf m^{-2} d^{-1}
DOY	Day number since 1 January (day of year) (from AB/TPE weather system)	d
DOYEM	Day of year of crop emergence	d

DPAR	Daily photosynthetic active radiation	J m^{-2} d^{-1}
DRAIN	Drainage rate below the root zone	mm d-1
DRYP	Drying power term in Penman equation	mm d^{-1} kPa °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	g CO_2 m^{-2} ground d^{-1}
DTGAS	Total gross CO_2 assimilation of the crop	g CO_2 m^{-2} ground s^{-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 post-anthesis phase as function of temperature	d^{-1}, °C
DVRVT	Table of DVR in pre-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/weight ratio	m^2 ear g^{-1} DM TADRW
EDPTFT	Table to read the root activity coefficient	-
EES	Soil-specific extinction coefficient	mm^{-1}
EFF	Initial light conversion factor for individual leaves	g CO_2 / J
EMERG	Parameter to indicate emergence	-
ERLB	Cumulative effective root length	mm
ERRSH	Check in partitioning tables (total should be 1.)	-
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}
EVSW1-4	Rate of evaporation	mm d^{-1}
EZRT	Rate of root elogation	mm d^{-1}
EZRTC	Constant for root elongation	mm d^{-1}
FCLEAR	Sky clearness function in calculation of net long-wave radiation	-
FEVL1-4	Distribution factors for soil water extraction over compartments	-
FEVLT	Sum of FEVL	-
FGL	CO_2 assimilation rate at one depth in the canopy	g CO_2 m^{-2} leaf s^{-1}
FGROS	Instantaneous canopy CO_2 assimilation	g CO_2 m^{-2} ground s^{-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	g CO_2 m^{-2} leaf s^{-1}
FGRSUN	CO_2 assimilation rate at one depth in the canopy for sunlit leaves	g CO_2 m^{-2} leaf s^{-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	-
FRDR	Parameter to determine rate of increase in RDR	-
FRT	Fraction total dry matter allocated to roots	-
FRTRL	Fraction stem weight eventually translocated to storage organs	-
FSH	Fraction total dry matter allocated to shoots	-
FSHP	Fraction 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	-, -
FVAP	Vapour pressure effect on RWLN (Brunt equation)	-
GLA	FORTRAN subroutine to calculate GLAI	-
GLAI	Net growth rate of leaf area index	m^2 leaf m^{-2} ground d^{-1}
GLV	Dry matter growth rate of leaves	g DM m^{-2} ground d^{-1}
GPHOT	Daily total gross CH_2O assimilation of the crop	g CH_2O m^{-2} ground d^{-1}
GRT	Dry matter growth rate of roots	g DM m^{-2} ground d^{-1}
GSO	Dry matter growth rate of storage organs	g DM m^{-2} ground d^{-1}

GST	Dry matter growth rate of stems	g DM m^{-2} ground d^{-1}
GTW	Gross growth rate of crop dry matter, including translocation	g DM m^{-2} ground d^{-1}
HI	Harvest index	g stor. organs g^{-1} TADRW
HOUR	Selected hour during the day	h
I1	Do-loop counter	-
I2	Do-loop counter	-
IEAI	Initial ear area index	m^2 ear m^{-2} ground
IDSLR	Initial of DSLR	d
IDVS	Initial development stage	-
IGAUSS	Do-loop counter	-
ILAI	Initial leaf area index	m^2 leaf m^{-2} ground
INTC	Interception capacity of precipitation of 1 layer of leaves	mm d^{-1}
KBL	Extinction coefficient for direct component of direct PAR flux	m^2 ground m^{-2} leaf
KDF	Extinction coefficient for leaves	m^2 ground ha^{-1} leaf
KDRT	Extinction coefficient for total direct PAR flux	m^2 ground ha^{-1} leaf
LAI	Leaf area index	m^2 leaf m^{-2} ground
LAIC	Leaf area index above selected height in canopy	m^2 leaf m^{-2} ground
LAICR	Critical leaf area index beyond which death to self-shading occurs	m^2 leaf m^{-2} ground
LAITB	Table of LAI as function of day of the year	m^2 leaf m^{-2} ground, d
LAT	Latitude of the weather station (from AB/TPE weather system)	degrees
LATT	Latitude of the weather station	degrees
LONG	Longitude of weather station (from AB/TPE weather system)	degrees
LHVAP	Latent heat of evaporation of water	J kg^{-1} H_2O
MAINLV	Maintenance respiration coefficient of leaves	g CH_2O g^{-1} DM d^{-1}
MAINRT	Maintenance respiration coefficient of roots	g CH_2O g^{-1} DM d^{-1}
MAINSO	Maintenance respiration coefficient of storage organs	g CH_2O g^{-1} DM d^{-1}
MAINST	Maintenance respiration coefficient of stems	g CH_2O g^{-1} DM d^{-1}
MAINT	Maintenance respiration rate of the crop	g CH_2O m^{-2} d^{-1}
MAINTS	Maintenance respiration rate of the crop at reference temperature	g CH_2O m^{-2} d^{-1}
MDRATE	Maximum drainage rate of the subsoil	mm d^{-1}
MNDVS	Factor accounting for effect of DVS on maintenance respiration	-
NRAD	Net radiation	J m^{-2} d^{-1}
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}
PCEW	Factor that accounts for reduced photosynthesis due to water stress	-
PENMAN	Penman reference value for potential evaporation	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	Psychromatic instrument constant	kPa $^{\circ}C^{-1}$
PTRANS	Potential transpiration rate derived from Penman evaporation	mm d^{-1}
Q10	Factor accounting for increase in maintenance respiration with a 10 ˚C rise temperature	-
RAD	Factor to convert degrees to radians	radians $degree^{-1}$
RAIN	Daily precipitation (from AB/TPE weather system)	mm d^{-1}
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	Growth rate ear area index	m^2 m^{-2} d^{-1}
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	$(^{\circ}C\ d)^{-1}$

RLWN	Net long-wave radiation	$J\ m^{-2}\ d^{-1}$
RNOFF	Runoff	$mm\ d^{-1}$
RRAIN	Daily precipitation	$mm\ d^{-1}$
RWL1-4	Rate of increase for WL1-4	$mm\ d^{-1}$
RWCL1-4	Relative available 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	m^2 leaf g^{-1} leaf
SLOPE	Tangent of the relationship between saturated vapour pressure and temperature	kPa $^{\circ}C^{-1}$
STTIME	Time start simulation	d
SQV	Intermediate variable in calc. of reflection coefficient	-
SUBEAI	FORTRAN subroutine to compute REAI	-
SUBFR	FORTRAN subroutine to compute WSE	-
SUBGRT	FORTRAN subroutine to compute WSERT	-
SVP	Saturated vapour pressure	kPa
TADRW	Total above-ground dry matter	g DM m^{-2}
TAEVAP	Cumulative actual soil evaporation	mm
TAINTC	Total amount of rainfall intercepted by the canopy	mm
TAI	Total area index	$m^2\ m^{-2}$ ground
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	$^{\circ}C$
TDRAIN	Total drainage	mm
TDRW	Total biomass	g DM m^{-2}
TDTGA	Total gross CO_2 assimilation of the crop	g CO_2 m^{-2} 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
TKL1-4	Thickness of the soil layers	mm
TKLT	Sum of thickness of the soil layers	mm
TMAXT	Table daily max. temp. as function of day of the year	$^{\circ}C$, d
TMINT	Table daily min. temp. as function of day of the year	$^{\circ}C$, d
TMMX	Daily maximum temperature (from AB/TPE weather system)	$^{\circ}C$
TMMN	Daily minimum temperature (from AB/TPE weather system)	$^{\circ}C$
TNASS	Total net CO_2 assimilation	g CO_2 m^{-2}
TNASSI	Initial value of TNASS	g CO_2 m^{-2}
TOTASS	FORTRAN subroutine to calculate the gross CO_2 assimilation of the crop	-
TPENM	Cumulative potential evapotranspiration	mm
TPEVAP	Cumulative potential ecaporation	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	g DM $m^{-2}\ d^{-1}$
TRC	Transpiration coefficient	kg H_2O kg^{-1} DM
TREF	Reference temperature	$^{\circ}C$
TRNOFF	Total runoff	mm
TRRM	Potential rate of water uptake per mm effective rooted depth	d^{-1}
TRWL1-4	Rate of transpiration	$mm\ d^{-1}$
TSTORE	Total surface storage due to waterlogging	mm
VISD	Absorbed direct component of direct flux per unit leaf area (at depth LAIC)	$J\ m^{-2}$ leaf s^{-1}
VISDF	Absorbed diffuse 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 ´g	Absorbed total direct flux per unit leaf area (at depth LAIC)	$J\ m^{-2}$ leaf s^{-1}
VP	Actual vapour pressure (from AB/TPE weather system)	kPa

WCAD1-4	Volumetric water content in each soil layer at dry air	cm^3 H_2O cm^{-3} soil
WCCR	Critical volumetric water content	cm^3 H_2O cm^{-3} soil
WCFC1-4	Volumetric water content at field capacity in each soil layer	cm^3 H_2O cm^{-3} soil
WCL1-4	Volumetric water content in each soil layer	cm^3 H_2O cm^{-3} soil
WCLI1-4	Initial values for WCL1-4	cm^3 H_2O cm^{-3} soil
WCUM	Total amount of water in the soil profile	mm
WCUMI	Initial value for WCUM	mm
WCWET1-4	Volumetric water content where water logging begins	cm^3 H_2O cm^{-3} soil
WCWP1-4	Volumetric water content at wilting point in each soil layer	cm^3 H_2O cm^{-3} soil
WDF	Wind function	mm d^{-1} $°C^{-1}$
WDS	Wind speed	m s^{-1}
WGAUSS	Array containing weights to be assigned to Gauss points	-
WL1-4	Amount of water in soil compartments	mm
WL1I-WL4I	Initial amounts for WL1-4	mm
WLFL1-4	Infiltration and drainage rates for the soil layer	mm d^{-1}
WLV	Dry weight of the leaves (green + dead)	g m^{-2}
WLVD	Dry weight of dead leaves	g m^{-2}
WLVDI	Initial value for WLVD	g m^{-2}
WLVG	Dry weight of green leaves	g m^{-2}
WLVI	Initial dry weight of the leaves	g m^{-2}
WN	Wind speed (from AB/TPE weather system)	m s^{-1}
WRT	Dry weight of the roots	g m^{-2}
WRTI	Initial dry weight of the roots	g m^{-2}
WSE1-4	Factor accounting for effect of uptake availability of soil water	-
WSERT	Auxiliary variable to calculate root extension	-
WSO	Dry weight of storage organs	g m^{-2}
WSOI	Initial value for WSO	g m^{-2}
WST	Dry weight of the stems	g m^{-2}
WSTI	Initial value for WST	g m^{-2}
XGAUSS	Array containing Gauss points	-
ZERO	Initial value of zero in an integration	-
ZRT	Rooted depth	mm
ZRT1-4	Thickness of rooted layer	mm
ZRTI	Initial value for ZRT	mm
ZTRM	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