Simulation of Maize Growth under Conservation Farming in Tropical Environments

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Preface

This book reflects a study that started in 1987 during the development of a course 'Simulation of Potential Crop Production' for an MSc-programme in soil and water management at Brawijaya University, Malang, East Java, Indonesia. The model was adapted in a later stage to tropical highland conditions at the ICRAF Research Station, Machakos, Kenya. It may serve students and researchers from various disciplines, e.g. soil physics, surface hydrology, soil and water conservation and rainfed agriculture, with a keen interest in the quantification of the field soil water balance in tropical environments and the effect of conservation farming on crop production.

Part 1 of this book deals with potential production, i.e. crop growth under ample supply of water and nutrients in a pest, disease and weed free environment. Production is then determined by the prevalent temperature and radiation as well as by crop characteristics. Maize is taken as the reference crop in the model, given its importance in tropical environments. Hence, the model is named MAIZE1.

The model is described in an unusual way. The explanatory text follows as closely as possible the computer listing of the model, i.e. each chapter starts with a number of lines that was copied from the listing. In the subsequent explanation it is then possible to justify the special and complicated terminology, so typical for computer modelling, and to emphasize the dimensions of all variables and data. Another special feature is the fact that parameter and function values are defined directly after the line where they are used for the first time. This method highlights the places where the model needs input from the user. In this way it will be emphasized that the accuracy of the model depends on the availability and quality of the input data, next to the correct understanding and description of the processes involved. The way MAIZE1 is presented here is different from the modular structure of present day models where separate data blocks for soil; crop and climate are added at the end of the main program. Both special features serve an educational goal and are the result of many years of experience with training students in this field.

Once modelling of the potential production is sufficiently understood the reader is invited to proceed with Part 2 of this book. Here, maize production under rainfed or water-limited conditions is modelled by including the crop water balance as well as the soil water balance into the model. The extended model is named MAIZE2, which can be used to explore a variety of aspects of rainfed agriculture, e.g. the effect of soil and water conservation interventions, like conservation farming. Environmental conditions are assumed to be still optimal for other growth determining factors than water, i.e. ample nutrients as well as a pest, disease and weed free environment. MAIZE2 is based on earlier versions documented by Stroosnijder (1982), Penning de Vries et al. (1989), Van Keulen et al. (1992) and Van Kraalingen (1996). In the description of MAIZE2 (Chapters 2.1-2.13), only the additions to MAIZE1 will be discussed. These additions comprehend computations, formulae, parameters an their subsequent values.

The models are written in the simulation language FST (version 2.0; Rappoldt & Van Kraalingen, 1996). The FST software was developed at the DLO Research Institute for Agrobiology and Soil Fertility (AB-DLO) and at Wageningen Agricultural University, Department of Environmental Sciences, Theoretical Production Ecology Group (TPE-WAU).

Copies of the FST software are available from H.E. de Ruiter, Bornsesteeg 47, NL-6708 PD Wageningen, The Netherlands (E-mail: hennie.deruiter@staff.tpe.wau.nl, phone: +31 (0)317 475.770, fax: +31 (0)317 484.892,). Besides the FST program a FORTRAN-77 compiler is needed. FST versions as well as FORTRAN versions of the MAIZE1 and MAIZE2 models, the necessary subroutines as well as two supplementary weather files can be downloaded from the internet site http://www.slm.wau.nl/eswc/. Alternatively, the user can connect to the home page of the Wageningen Agricultural University (http://www.wau.nl), click on Corporate, next on Departments, subsequently on Environmental Sciences, thereafter on Erosion and Soil & Water Conservation Group and look finally for the link to download software.

Although this model focuses on maize production in the semi-arid tropics, the readers are encouraged to adapt the model to any crop and environment of their personal interest. The authors are interested in remarks about this book, in suggestions for improvement as well as in experiences with adapted versions for other crops and environments. Please communicate these to the principal authors' address.

Leo Stroosnijder and Paul Kiepe
Ouagadougou, August 1998

Abstract

This book is written for students and researchers with a keen interest in the quantification of the field soil water balance in tropical environments and the effect of conservation farming on crop production. Part 1 of this book deals with the potential production, i.e. crop growth under ample supply of water and nutrients in a pest, disease and weed free environment. Part 2 deals with crop production under rainfed or water-limited conditions by including the crop water balance as well as the soil water balance. Both models use maize as example. The way the MAIZE models are presented differs from the modular structure of present day models, where separate data blocks for soil, crop and climate are added at the end of a main program. Here, the explanatory text follows as closely as possible the computer listing of the model. Each chapter starts with a number of lines that was copied from the listing. Subsequently, the terminology is justified and the input data and dimensions of variables are explained. Another special feature is the fact that parameter and function values are defined directly after the line where they are used for the first time. This method highlights the places where the model needs input from the user. In this way it is stressed that the accuracy of the model depends on the availability and quality of the input data, next to the correct understanding and description of the processes involved. The third part of this book contains a number of applications.

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3 Some applications of the MAIZE1 and MAIZE2 models

1 Modelling the potential maize production in a tropical environment

1.1 Introduction

The conceptual basis for the MAIZE model is the simple and universal crop growth simulator, named SUCROS87 (Spitters et al., 1989). The most recent version (SUCROS92) was described by Goudriaan et al. (1992). Although the SUCROS model does include parameters for a maize crop, it has been tested for temperate climatic conditions only. Contrastingly, the MAIZE model was specifically designed for a tropical environment. The first version of the MAIZE model was adapted for tropical lowland climatic conditions and originally validated with an experiment in Jatikerto, East Java, Indonesia from December 1987 until March 1988. This revised version (ver. 98.08) was extended to include tropical highlands and was subsequently validated in Machakos, Kenya, from October 1991 until March 1992.

Crop growth is often described by empirical models, consisting of a number of regression equations. Sporadically, environmental variables, like radiation and rainfall, are incorporated in the regression equations. This type of models can generate accurate yield predictions, especially when the parameters were estimated on extensive sets of experimental data. The predictions are restricted to the same environment on which the regression was based. These empirical, descriptive models give, however, little insight in the causes of the observed variation in yield.

MAIZE1 is a mechanistic model that explains maize growth on the basis of the underlying processes, such as CO_2 assimilation and respiration, and how these processes are influenced by environmental conditions. The predictive ability of mechanistic models does not always live up to the 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 mechanistic models. Their primary aim is to improve insight in the studied system by integrating the present knowledge quantitativaly in terms of a simulation model. By studying the behaviour of the model, a better insight in the real system is gained.

MAIZE1 simulates the potential growth of a maize 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 tropical weather conditions.

MAIZE1 simulates dry matter accumulation of a crop as a function of global radiation, 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 radiation 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 single leaves, the daily rate of gross CO_2 assimilation of the crop is calculated. This rate is not calculated in the main part of the model, but through a number 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).

Part of the carbohydrates (CH_2O) produced is used to maintain the present biomass. The remaining carbohydrates are either converted into structural dry matter (plant organs) or stored as reserves which are later used for grain development. In the process of conversion, part of the weight is lost as growth respiration. The dry matter produced is partitioned among the various plant organs, using partitioning factors introduced as a function of the phenological development stage of the crop. The dry weights of the plant organs are obtained by integration over time.

MAIZE1 requires a site description and crop characteristics as input data. The site is characterized by its altitude (ELEV in m a.m.s.l.), geographical latitude (LAT in degrees) and by daily values of minimum and maximum temperature (TMMN and TMMX in °C) and global radiation (RDD in J m^{-2} d^{-1}). The values are obtained from the weather files, located in a special directory. The construction of the weather files is documented by Van Kraalingen et al. (1991). An example of a weather file can be found in Chapter 1.18 and a comprehensive description of the crop characteristics is found in the model.

```
TITLE MAIZE1.FST (ver. 98.08) - simulates the potential maize production
TITLE in a tropical environment.

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DECLARATIONS

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

The model starts with the current TITLE of the model, the name of the authors who developed the model and the declaration of the subroutines that will be used by the model to perform specific computations. The TITLE will appear as heading on top of the output file.

```
MODEL
  INITIAL
  INCON ZERO       = 0.
*       Location   = Machakos, Kenya
```

It is convenient to write down the geographical location of the model parameters, in case of multi-location testing.

1.2 Initial conditions

```
*       Genotype   = Katumani Composite B
        LAII       = NPL * LAO
        NPL        = 3.7
  PARAMETER LAO    = 1.58E-3
```

The MAIZE1 model starts its daily computation at the moment of planting. The leaf area index at this moment (LAII, m^2 m^{-2}) is calculated as the product of plant density (NPL, plants m^{-2}) and leaf area per plant at emergence (LA0, m^2 $plant^{-1}$). In the example above plant density NPL = 3.7 plants m^{-1} since the planting scheme was 0.3 m x 0.9 m and LA0 was measured at 1.58×10^{-3} m^2 $plant^{-1}$.

```
INCON WLVI        = 0.; WSTI = 0.; WRTI = 0.
      TNASSI      = (WLVI*CFLV+WSTI*CFST+WRTI*CFRT)*44./12.
```

In the example above the initial dry matter of leaves (WLVI, kg DM ha^{-1}), stem (WSTI, kg DM ha^{-1}) and roots (WRTI, kg DM ha^{-1}) are required. They can be conveniently set to 0. The model is not very sensitive to these values. The total initial net carbon assimilation (TNASSI, kg CO_2 ha^{-1}) can also be set to zero.

1.3 Crop development

```
DYNAMIC
      DVS         = INTGRL(ZERO,DVR)
      DVR         = INSW(DVS-1.,DVRV,DVRR) * EMERG
      EMERG       = INSW(TIME-DAYEM,0.,1.)
      DVRV        = 0.029*(1.-EXP(-0.212*(DDTMP-12.)))
      DVRR        = 0.003744 + 0.000491*DDTMP
```

The pattern of dry matter distribution over the various plant organs is closely related to the phenological development stage of the crop. For many annual crops, the development stage (DVS) can be expressed conveniently in a dimensionless variable, having a value of 0 at seedling emergence, 1 at flowering (tasseling) 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 of emergence until flowering (the vegetative phase, DVRV) and the rate from flowering until maturity (the reproductive or grain filling phase, 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 the average daytime temperature (DDTMP, °C). The values used above to calculate DVRV and DVRR are derived from Lenga and Keating (1990).

Under tropical conditions the temperature is relatively constant and temperature sensitivity of DVR can, therefore, be omitted. In the above example the emergence phase (EMERG, -) takes 6 days, the vegetative phase 40 days and the reproductive phase 69 days. The day of emergence is set by the period between sowing and the length of the emergence phase (EMPER, d; see Chapter 1.15). If the relationship between the temperature and the development rate is not known, the vegetative and the reproductive phases can be replaced by parameters (e.g. PARAMETER DVRV = 0.0250; DVRR = 0.0145).

1.4 Leaf CO_2 assimilation

```
      AMAX        = AMX * AMDVS
      AMDVS       = AFGEN(AMDVT,DVS)
```

```
PARAMETER AMX      = 70.
FUNCTION AMDVT     = 0.0,1.0, 1.2,0.9, 1.6,0.5, 2.0,0.2, 2.5,0.2
```

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). With respect to the photosynthetic pathway, three groups of species can be identified: C_3, C_4 and CAM-species. In C_4-species, like maize, the slope at low light intensity is not affected by temperature because photorespiration is suppressed in the C_4-pathway. The temperature effect (AMTMP) is a function of the average temperature during daytime as given in the function AMTMT. For tropical conditions with average daytime temperatures between 20 and 30 °C, there is no temperature effect on AMX; the factor AMTPM can then be omitted.

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 70 (kg CO_2 ha^{-1} h^{-1}) for C_4-species is, in general, a reasonable estimate.

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

1.5 Daily gross CO_2 assimilation

```
        CALL TOTASS(DOY,LAT,RDD,SCP,AMAX,EFF,KDF,LAI, DAYL,DTGA,DSO)
PARAMETER EFF      = 0.45; KDF = 0.65; SCP = 0.20
```

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

The computation is performed in the subroutine TOTASS. This routine makes use of a number of other subroutines like ASTRO and ASSIM. The MAIZE models can be applied without a thorough understanding of these subroutines. The three parameters EFF, KDF and SCP need to be specified and are derived from literature. Detailed discussions are given by Spitters et al. (1986) about the calculation of the diffuse and direct radiation fluxes above the canopy, by Spitters (1986) for the calculation of the assimilation rates from these fluxes, and by Goudriaan (1986) about the Gaussian integration method used to calculate assimilation rates over the canopy and over the day. The only site characteristic required for the calculation of the potential production is the latitude, which value is obtained from the weather file.

1.6 Carbohydrate production

```
        GPHOT         = DTGA * RDFRL * 30./44.
        RDFRL         = LIMIT(0.,1.,(RESLMX-RESL)/(RESLMX-FEEDB*RESLMX))
        RESL          =  (WRES/ASRQCB)/(NOTNUL(WST))

  PARAMETER RESLMX = 0.1
  PARAMETER FEEDB  = 0.2
```

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

A non-structural carbohydrate content in the stem (WRES, kg CH_2O ha^{-1}) arises when the rate of conversion of assimilates into structural biomass (plant organs) is smaller than the assimilation rate. The storage capacity of the plant for carbohydrate reserves is limited and when the maximum capacity is approached the leaf photosynthesis (GPHOT, kg CO_2 ha^{-1} d^{-1}) is reduced by a feedback mechanism (RDFRL, -; obtained from Barnett and Pearce, 1983). In the model, a maximum content (RESLMX, -) of fractions of reserves in the stems (RESL, -) is defined at 10% of the weight of the stems (WST, kg DM ha^{-1}). The fraction of reserves is calculated as the ratio of the carbohydrate content in the stem and the assimilate requirement for cob dry matter production (ASRQCB, kg CH_2O kg^{-1} DM) to take the conversion of CH_2O to DM into account, divided by the weight of the stems. The model starts to reduce the rate of gross crop assimilation (DTGA, kg CO_2 ha^{-1} d^{-1}) when 20% (FEEDB, -) of this content is approached. This feedback mechanism occurs in the development phase where growth of stems and leaves is limited and the cobs have not attained their potential growth capacity.

1.7 Maintenance

```
        MAINT         = MAINTS * TEFF * MNDVS
        MAINTS        = MAINLV*WLV+MAINST*WST+MAINRT*WRT+MAINCB*...
                         (WCH+WGRAIN)
        MNDVS         = WLVG/(NOTNUL(WLV))
        TEFF          = Q10**((DAVTMP-TREF)/10.)
  PARAMETER MAINLV = 0.03; MAINST=0.015; MAINRT=0.015; MAINCB=0.01
  PARAMETER TREF   = 35.
  CONSTANT Q10     = 2.
```

Part of the carbohydrates that is formed is respired to provide energy for maintaining the existing biostructures. Fixed coefficients (for a plant species dependent reference temperature) are used to calculate the maintenance requirements of the various organs (leaves, stems, roots, chaff and grains) of the crop. Higher temperatures accelerate the turnover rates in plant tissue and hence increase the costs of maintenance (TEFF, -). A lower temperature reduces maintenance. An increase in temperature of 10 °C, increases maintenance respiration by a factor 2 (Q10, -; obtained from Penning de Vries and Van Laar, 1982). For tropical species the reference temperature (TREF, °C) is 35 °C.

When the crop ages its metabolic activity decreases and hence its maintenance requirements. Therefore, maintenance respiration is assumed to be proportional to the fraction of the accumulated leaf weight that is still green (WLVG, kg DM ha^{-1}) with respect to the total weight of leaves (WLV, kg DM ha^{-1}). This reduction factor, MNDVS (-), is also applied to the maintenance respiration of the other organs as it is assumed that die back of stem tissue and roots proceeds simultaneously to die back of leaves.

1.8 Dry matter partitioning

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

```
         FSH         = AFGEN(FSHTB,DVS)
         FRT         = 1. - FSH
FUNCTION FSHTB       = 0.,0.4, 0.5,0.5, 0.8,0.6, 1.,0.8, 1.1,1., 2.5,1.
```

Dry matter is first partitioned between shoots (FSH) and roots (FRT). The distribution is depicted in Fig. 1.1.

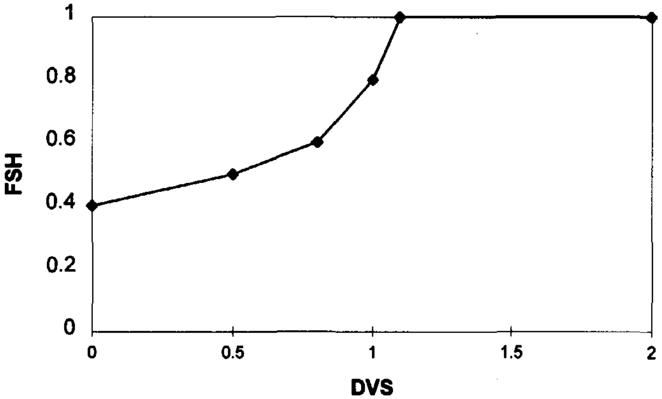

Fig. 1.1 *Factors that determine the dry matter distribution to the shoot (FSH) and to the root (FRT=1 - FSH) as a function of the development stage (DVS).*

```
         FLV         = AFGEN(FLVTB,DVS)
         FSC         = 1. - FLV
FUNCTION FLVTB       = 0.,1., 0.4,1., 1.2,0., 2.5,0.
```

In the second step, the shoot fraction is divided between leaves (FLV) and stems + cob (FSC).

```
        FST          = AFGEN(FSTTB,DVS)
        FCB          = 1. - FST
   FUNCTION FSTTB    = 0.,1., 0.9,1., 1.3,0.1, 2.5,0.1
```

In the third step the stem + cob fraction is partitioned between stem (FST) and cob (FCB). The distribution is depicted in Fig. 1.2.

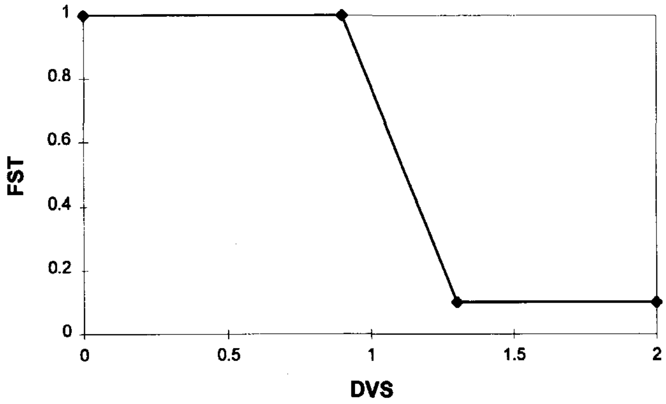

Fig. 1.2 *Factors that determine the dry matter distribution to the stem (FST) and to the cob (FCOB=1-FST) as a function of the development stage (DVS).*

Finally, the cob fraction is distributed over chaff (FCH) and reserves (FRES) from which the grains are formed. Reserves are formed because during the vegetative phase and in the early phase of kernel growth, not all primary assimilates are converted into structural plant material.

```
        FCH          = AFGEN(FCHTB,DVS)
        FRES         = 1.- FCH
   FUNCTION FCHTB    = 0.,1., 1.,1., 1.2,0.5, 1.4,0.1, 2.5,0.1
```

Reserves in the form of non-structural carbohydrates (starch, fructans, mono and di-saccharides) are accumulated, especially in the stem but also in the leaves. Together with the current assimilates at later development stages, these temporary reserves form the carbohydrate 'source' available for grain growth.

1.9 Growth of organs and reserves

The growth rates of the various plant organs (kg DM ha^{-1} d^{-1}) and the reserves (kg CH_2O ha^{-1} d^{-1}) are obtained by multiplying the overall growth rate by the fraction allocated to the various organs. The overall value of assimilate requirement for conversion of carbohydrates into dry matter (ASRQ, kg CH_2O kg^{-1} DM) for the crop as a whole is calculated as the weighted mean of the ASQR's for different plant organs.

```
ASRQ        = FSH*(ASRQLV*FLV+ASRQST*FST+ASRQCB*FCB)+ASRQRT*FRT

TRANSL      = INSW(DVS-1.,0.,WST*DVR*FRTRL)
GTW         = (GPHOT - MAINT+CONVF*TRANSL*CFST*30./12.)/ASRQ
GRT         = FRT * GTW
GLV         = FLV  * FSH * GTW
GST         = FST  * FSH * GTW - TRANSL
GCB         = FCB  * FSH * GTW
GCH         = FCH  * FCB * FSC  * FSH * GTW / ASRQCB
GRES        = FRES * FCB * FSC  * FSH * GTW / ASRQCB
```

Once the partitioning over the various plant organs is known the conversion of carbohydrates into dry matter can be computed. The assimilates required to produce a unit weight of a certain plant organ can be calculated from its chemical composition and the assimilate requirements of the various chemical compounds. Typical values for roots (ASRQRT), leaves (ASRQLV) and stem (ASRQST) are: 1.444, 1.463 and 1.513 kg CH_2O kg^{-1} DM respectively.

```
PARAMETER ASRQRT = 1.444; ASRQLV=1.463; ASRQST=1.513; ASRQCB=1.491
```

Storage organs (grains, tubers, etc.) vary too much in composition among species to give one general value for their assimilate requirement. For maize cobs the value (ASRQCB) is 1.491 kg CH_2O kg^{-1} DM. The growth rates of the various plant organs (kg DM ha^{-1} d^{-1}) are obtained by multiplying the overall growth rate by the fractions allocated to the various organs.

After anthesis, about 20% of the stem weight, assumed to consist of reserve carbohydrates (Spiertz & Ellen, 1978), is eventually translocated to the storage organs. The translocation rate (TRANSL, kg DM ha^{-1} d^{-1}) is introduced as a loss term in the rate of growth of the stem (GST), and added to 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.

```
PARAMETER CONVF  = 0.947; FRTRL  = 0.20
```

In addition a small conversion loss occurs when stem reserves are remobilized presumably from starch to glucose (the multiplication factor CONVF for conversion was obtained from Penning de Vries et al., 1989, p. 61). The rate of translocation depends directly on the 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 Development of grains

The actual growth rate of the grains (GGR, kg DM ha^{-1} d^{-1}) takes either the value of the sink-determined growth rate (GRSINK) or that of the source-determined growth rate (GRSOUR), whichever is the smallest.

```
       GGR          = MAX(0.,MIN(GRSINK,GRSOUR))

       GRSINK       = NGRAIN * 0.01 * PGRI * GRDVS * GRTMP
       GRDVS        = AFGEN(GRDVST,DVS)
       GRTMP        = AFGEN(GRTMPT,DAVTMP)
FUNCTION GRDVST     = 0.,0., 1.0,0., 1.1,0.25, 1.3,0.35, 1.4,1.,...
                      1.5,1., 1.6,0.35, 1.8,0.25, 2.0,0., 2.5,0.
FUNCTION GRTMPT     = 0.,0., 10.,0., 16.,1., 34.,4.
```

The potential rate of grain growth (sink-determined), GRSINK (kg DM ha^{-1} d^{-1}) is the product of the number of grains (NGRAIN in m^{-2}) and the potential growth rate of the individual grains (GRDVS * PGRI, mg DM $grain^{-1}$ d^{-1}). The temperature effect (GRTMP) is a function of the daily average temperature (DAVTMP).

Dry matter accumulation in the grains, and hence in the cobs, proceeds according to an S-shape curve in which three phases can be distinguished. First, the lag phase in which cell division takes place and growth is about exponential. Second, the linear phase with an approximate growth rate. Third, the maturation phase with a gradual decline in the growth rate. From the data the growth rate of the cobs can be computed and the result shows that the linear phase for maize is very short. This bell-shaped course of the potential growth rate is approximated by the function GRDVS as presented in Fig. 1.3.

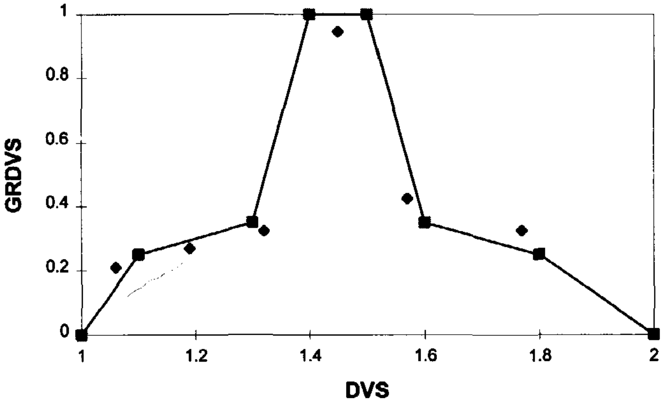

Fig. 1.3 *The potential growth rate of maize grains is regulated by a factor (GRDVS) as a function of the development stage (DVS). The approximated factor (■) is calibrated with field measurements (◆).*

The factor 0.01 converts the dimension of NGRAIN and PGRI into the one for GGR.

```
       NGRAIN       = INTGRL(ZERO,GNGRN)
       GNGRN        = MAX(0.,(NGA * NPL + NGB * TADRW) * ...
                      INSW(DVS-1., 0., 1.) * INSW(-NGRAIN, 0., 1.))
PARAMETER NGA       = -50.; NGB = 0.5
```

The number of grains (NGRAIN in m^{-2}) is computed as an integral of the increase in the number of grains (GNGRN in m^{-2}). GNGRN can often be estimated satisfactorily on the basis of the amount of above-ground biomass (TADRW, kg DM ha^{-1}) at anthesis (Stapper & Arkin, 1980; Spiertz & Van Keulen, 1980).

```
        PGRI          = PKRWT / (0.364 * GFD16)
  PARAMETER PKRWT     = 260.; GFD16 = 50.
```

The average potential growth rate of the grains may be obtained from the final dry weight of grains under potential conditions (PKRWT in mg DM $grain^{-1}$ = 260 (Muchow, 1989)) and the grain fill duration (GFD16 in d). For maize this growth rate is about 165 kg DM ha^{-1} d^{-1}. However, due to the bell-shape course of the growth, the potential growth rate is about three times higher (at GRDVS = 1) than the average rate.

```
        WRES          = INTGRL(ZERO,GWRES)
        GWRES         = GRES - DRES
        DRES          = (GGR * ASRQCB) - GRES
```

The size of the source of carbohydrates (kg CO_2 ha^{-1} d^{-1}) is calculated from the current CO_2 assimilation completed by the pool of reserves and is obtained as the integral (GWRES in kg CH_2O ha^{-1} d^{-1}) of the rates of replenishment (GRES) and depletion (DRES) of the reserves. The latter is the actual growth rate (GGR, kg DM ha^{-1} d^{-1}) times ASRQCB (the assimilate requirement for grain production) minus the growth of the reserves in the current time step.

```
        GRSOUR        = (GRES + WRES) / ASRQCB / TC
  PARAMETER TC        = 1.5
```

The rate of grain growth that could be sustained by the available carbohydrates (source-determined), GRSOUR, is determined by the growth of the reserves in the current time step, GRES, and by the stored reserves, WRES. However, not all reserves can be mobilized at once. This is reflected by the introduction of a time constant (TC, d) for the translocation of the carbohydrate reserves.

1.11 Leaf development

```
        LAI           = INSW(TIME-DAYEM,0.,TLAI)
        TLAI          = INTGRL(LAII,GLAI)
        GLAI          = INSW(LAI-1.0,GLAJ,GLAM)
        GLAJ          = EMERG*LAII*RGRL*DTEFAE*EXP(RGRL*TSUMAE)
  PARAMETER RGRL      = 0.025
```

The area of green leaves is the major determant for light absorption and photosynthesis of the crop. Under optimum conditions, light intensity and temperature are the environmental factors influencing the rate of leaf area expansion. During the early stages of crop growth, temperature is the overriding factor. 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 < 1.

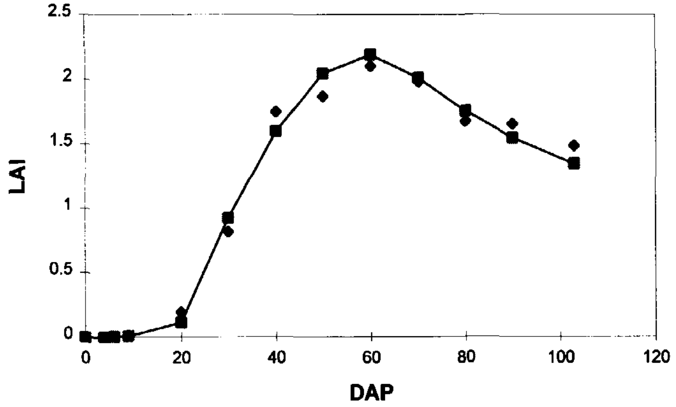

Fig. 1.4 *The simulated (■) and measured (◆) leaf area index (LAI in m^2 m^{-2}) as a function of the number of days after planting (DAP).*

Exponential leaf area development is described by: LAI = LAII * EXP (RGRL * DTEFAE * TIME) so that the daily increase in leaf area during juvenile growth (GLAJ) is obtained by differentiation: GLAJ = EMERG*LAII * RGRL* DTEFAE * EXP (RGRL * DTEFAE * TIME) in which EMERG is a factor to trigger leaf growth at emergence, LAII is the leaf area at emergence, RGRL is the relative growth rate of leaf area per degree day ($^oC^{-1}$ d^{-1}), TIME is the time after planting (d) and DTEFAE is the daily effective temperature after emergence (^oC). The product (DTEFAE * TIME) can be replaced by TSUMAE. The development of leaf area index (LAI) of maize was calibrated for Machakos (Fig. 1.4).

```
      GLAM            = SLA * (GLV - DLV)
   PARAMETER SLA      = 0.0014
```

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. For later stages (LAI > 1.) the model calculates the growth of leaf area during mature plant growth (GLAM) by multiplying the simulated increase in leaf weight by the specific leaf area of new leaves (SLA, ha kg^{-1}).

```
      DLV             = WLVG * INSW (DVS-C1, 0.0, OLVDF)
      OLVDF           = INSW (DVS-C2, RDR, 0.0)
   PARAMETER C1       = 0.4; C2 = 2.; RDR = 0.024
```

To account for leaf senescence, a constant relative death rate of leaves (RDR, d^{-1}) is defined as a die-back factor (OLVDF), which is operative from a certain point (C1) in the crop's development (DVS) until another point (C2).

1.12 Dry matter production

```
      WRT             = INTGRL(WRTI,GRT)
```

```
WLVG        = INTGRL(WLVI,GWLVG)
GWLVG       = GLV-DLV
WLVD        = INTGRL(ZERO,DLV)
WST         = INTGRL(WSTI,GST)
WCB         = INTGRL(ZERO,GCB)
WCH         = INTGRL(ZERO,GCH)
WGRAIN      = INTGRL(ZERO,GGR)
```

Dry weights of the various plant organs, like the weight of roots (WRT, kg DM ha^{-1}), green leaves (WLVG, kg DM ha^{-1}), dead leaves (WLVD, kg DM ha^{-1}), stems (WST, kg DM ha^{-1}), cobs (WCB, kg DM ha^{-1}), chaff (WCH, kg DM ha^{-1}) and grains (WGRAIN, kg DM ha^{-1}) is obtained through integration of the respective growth rates.

```
WLV         = WLVG + WLVD
TADRW       = WLV + WST + WCH + WGRAIN + WRES
TDRW        = TADRW + WRT
```

Some totals of dry matter production are calculated to be included in the output, like the weight of leaves (WLV, kg DM ha^{-1}), total above-ground biomass (TADRW, kg DM ha^{-1}) and total biomass (TDRW, kg DM ha^{-1}).

```
HI          = WGRAIN/TADRW
```

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

1.13 Weather functions

```
DAVTMP      = (TMMN+TMMX)/2.
DDTMP       = 1.12*DAVTMP
```

Average daily temperature (DAVTMP, °C) is calculated by dividing the sum of the daily maximum temperature (TMMX, °C) and the daily minimum temperature (TMMN, °C) by 2. The values for TMMX and TMMN are obtained from the weather file. For daytime temperature (DDTMP, °C) an approximation is used.

```
      DTEFF        = MAX(0.,DAVTMP-TBASE)
      DTEFAE       = EMERG * DTEFF
      TSUMAE       = INTGRL(ZERO,DTEFAE)
PARAMETER TBASE    = 10.
```

Since many growth processes are temperature dependent above a certain threshold temperature, a daily effective (DTEFAE) and a cumulative effective temperature after emergence (TSUMAE) are calculated. The threshold temperature for tropical maize is 10 °C.

1.14 Carbon balance check

The carbon balance check (CHKCRB, kg C ha^{-1}) compares the amount of carbon present in all organs in any point of time, with the integral (TNASS) of net carbon assimilation rate (GNASS, kg CO_2 ha^{-1}). 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, CO2ST and CO2CB, all in kg CO_2 kg^{-1} DM) and, in addition, the loss (a fraction 1-CONVF) that occurs during remobilization of stem starch to glucose.

In practice, the two terms CHKIN and CHKCFL should never differ more than by a fraction 1.E-6. A larger deviation will be a sure signal of omission of a term somewhere in the program. The simulation will subsequently stop.

```
      CHKIN       = (WLV-WLVI)*CFLV+(WST-WSTI)*CFST+(WRT-WRTI)*...
                    CFRT+WCB*CFCB
      CHKCFL      = TNASS * (12./44.)
      TNASS       = INTGRL(TNASSI,GNASS)
      GNASS       = ((GPHOT-MAINT)*44./30.)-(GRT*CO2RT+GLV*CO2LV+...
                    (GST+TRANSL)*CO2ST+GCB*CO2CB+(1.-CONVF)*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)
      CO2CB       = 44./12.*(ASRQCB*12./30.-CFCB)

      CHKCRB      = (CHKIN-CHKCFL)/(NOTNUL(CHKIN))

PARAMETER CFLV=0.459; CFST=0.494; CFRT=0.467; CFCB=0.491
```

The parameters CFLV, CFST, CFRT and CFCB (all in kg C kg^{-1} DM) represent the C-contents of leaves, stems, roots and cobs, respectively.

1.15 Run control

```
          DAYEM  = STTIME + EMPER
PARAMETER EMPER  = 6.
          DAE    = MAX(0.,TIME-DAYEM)
          DAP    = TIME - STTIME
```

The day of emergence (DAYEM) was six days after planting, the length of the emergency phase (EMPER, d). The number of days after emergence (DAE, d) is subsequently calculated. The number of days after planting (DAP, d) can be calculted and used as a reference in the output file. It equals the number of days since the start of the simulation.

```
FINISH CHKCRB     > 1.E-6
FINISH DVS        > 2.
```

The simulation is stopped either by the carbon balance check, when carbon is mysteriously generated by or disappearing from the system (FINISH CHKCRB > 1.E-6), or when the maize crop is mature (FINISH DVS > 2).

```
TIMER STTIME      = 302.; FINTIM = 500.; DELT=1.; PRDEL=1.

TRANSLATION_FSE
```

In this example the computation starts at day 302 (STTIME), which corresponds with 28 October in 1992, the day the maize was planted. Simulation is executed in time steps of one day (DELT) with rectilinear integration of the growth rates (TRANSLATION_FSE). Output is produced every day (PRDEL) or any other period if required. To prevent that the simulation will not continue endlessly, a final simulation time is set at a predefined limit, more than 50 days later then the expected maturation date (FINTIM).

```
WEATHER WTRDIR='C:\SYS\WEATHER\';CNTR='KENYA';ISTN=2;IYEAR=1992
```

Detailed information on the weather files are found in this line. Here the location of the directory that contains the weather files (WTRDIR='C:\SYS\WEATHER\'), the country code (CNTR='KENYA'), the number of the meteorological station (ISTN=2) and the year when the simulation starts (IYEAR=1992) are declared. After day 365, or in case of a leap year like 1992 after day 366, FST automatically proceeds with the following year if the simulation is not yet finished.

```
PRINT DVS,DAE,TDRW,WGRAIN
```

In this line any desired variable, which is calculated, can be specified. Values are printed every PRDEL in the output file.

```
END
```

The specifications of the model are now completed. Subroutines are invoked between the END and the STOP statement.

```
STOP
```

The simulation run is terminated by STOP.

```
ENDJOB
```

The job is terminated by ENDJOB. This statement has to start in the first column.

1.16 Listing of the MAIZE1 model

```
TITLE MAIZE1.FST (ver 98.08)- simulates the potential maize production
TITLE in a tropical environment.

*              © Leo Stroosnijder and Paul Kiepe

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*             Department of Environmental Sciences
*           Erosion and Soil & Water Conservation Group
*      Nieuwe Kanaal 11, 6709 PA Wageningen, The Netherlands
*            E-mail: leo.stroosnijder@users.tct.wau.nl

* 1.1 Declarations

DECLARATIONS
  DEFINE_CALL TOTASS (INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
                      INPUT,INPUT,   OUTPUT,OUTPUT,OUTPUT)

MODEL
  INITIAL
  INCON ZERO        = 0.
*       Location    = Machakos, Kenya


* 1.2 Initial conditions

*       Genotype    = Katumani Composite B
        LAII        = NPL * LA0
        NPL         = 3.7
  PARAMETER LA0     = 1.58E-3
  INCON WLVI        = 0.; WSTI = 0.; WRTI = 0.
        TNASSI      = (WLVI*CFLV+WSTI*CFST+WRTI*CFRT)*44./12.


* 1.3 Crop development

  DYNAMIC
        DVS         = INTGRL(ZERO,DVR)
        DVR         = INSW(DVS-1.,DVRV,DVRR) * EMERG
        EMERG       = INSW(TIME-DAYEM,0.,1.)
        DVRV        = 0.029*(1.-EXP(-0.212*(DDTMP-12.)))
        DVRR        = 0.003744 + 0.000491*DDTMP


* 1.4 Leaf CO2 assimilation

        AMAX        = AMX * AMDVS
        AMDVS       = AFGEN(AMDVT,DVS)
  PARAMETER AMX     = 70.
  FUNCTION AMDVT    = 0.0,1.0, 1.2,0.9, 1.6,0.5, 2.0,0.2, 2.5,0.2


* 1.5 Daily gross CO2 assimilation

     CALL TOTASS(DOY,LAT,RDD,SCP,AMAX,EFF,KDF,LAI,  DAYL,DTGA,DS0)
  PARAMETER EFF     = 0.45; KDF = 0.65; SCP = 0.20
```

```
* 1.6 Carbohydrate production

      GPHOT        = DTGA * RDFRL * 30./44.
      RDFRL        = LIMIT(0.,1.,(RESLMX-RESL)/(RESLMX-FEEDB*RESLMX))
      RESL         = (WRES/ASRQCB) / (NOTNUL(WST))
PARAMETER RESLMX = 0.1; FEEDB  = 0.2


* 1.7 Maintenance

      MAINT        = MAINTS * TEFF * MNDVS
      MAINTS       = MAINLV*WLV+MAINST*WST+MAINRT*WRT+MAINCB*...
                     (WCH+WGRAIN)
      MNDVS        = WLVG/(NOTNUL(WLV))
      TEFF         = Q10**((DAVTMP-TREF)/10.)
PARAMETER MAINLV = 0.03; MAINST=0.015; MAINRT=0.015; MAINCB=0.01
PARAMETER TREF   = 35.
CONSTANT Q10     = 2.


* 1.8 Dry matter partitioning

      FSH          = AFGEN(FSHTB,DVS)
      FRT          = 1. - FSH
FUNCTION FSHTB   = 0.,0.4, 0.5,0.5, 0.8,0.6, 1.,0.8, 1.1,1., 2.5,1.

      FLV          = AFGEN(FLVTB,DVS)
      FSC          = 1. - FLV
FUNCTION FLVTB   = 0.,1., 0.4,1., 1.2,0., 2.5,0.

      FST          = AFGEN(FSTTB,DVS)
      FCB          = 1. - FST
FUNCTION FSTTB   = 0.,1., 0.9,1., 1.3,0.1, 2.5,0.1

      FCH          = AFGEN(FCHTB,DVS)
      FRES         = 1.- FCH
FUNCTION FCHTB   = 0.,1., 1.,1., 1.2,0.5, 1.4,0.1, 2.5,0.1


* 1.9 Growth of organs and reserves

      ASRQ         = FSH*(ASRQLV*FLV+ASRQST*FST+ASRQCB*FCB)+ASRQRT*FRT

      TRANSL       = INSW(DVS-1.,0.,WST*DVR*FRTRL)
      GTW          = (GPHOT-MAINT+CONVF*TRANSL*CFST*30./12.)/ASRQ
      GRT          = FRT * GTW
      GLV          = FLV  * FSH * GTW
      GST          = FST  * FSH * GTW - TRANSL
      GCB          = FCB  * FSH * GTW
      GCH          = FCH  * FCB * FSC  * FSH * GTW / ASRQCB
      GRES         = FRES * FCB * FSC  * FSH * GTW / ASRQCB

PARAMETER ASRQRT = 1.444; ASRQLV=1.463; ASRQST=1.513; ASRQCB=1.491
PARAMETER CONVF  = 0.947; FRTRL  = 0.20
```

```
* 1.10 Development of grains

        GGR           = MAX(0.,MIN(GRSINK,GRSOUR))

        GRSINK        = NGRAIN * 0.01 * PGRI * GRDVS * GRTMP
        GRDVS         = AFGEN(GRDVST,DVS)
        GRTMP         = AFGEN(GRTMPT,DAVTMP)
  FUNCTION GRDVST     = 0.,0., 1.0,0., 1.1,0.25, 1.3,0.35, 1.4,1.,...
                        1.5,1., 1.6,0.35, 1.8,0.25, 2.0,0., 2.5,0.
  FUNCTION GRTMPT     = 0.,0., 10.,0., 16.,1., 34.,4.

        NGRAIN        = INTGRL(ZERO,GNGRN)
        GNGRN         = MAX(0.,(NGA * NPL + NGB * TADRW) * ...
                        INSW(DVS-1., 0., 1.) * INSW(-NGRAIN, 0., 1.))
  PARAMETER NGA       = -50.; NGB = 0.5
        PGRI          = PKRWT / (0.364 * GFD16)
  PARAMETER PKRWT     = 260.; GFD16 = 50.

        WRES          = INTGRL(ZERO,GWRES)
        GWRES         = GRES - DRES
        DRES          = (GGR * ASRQCB) - GRES

        GRSOUR        = (GRES + WRES) / ASRQCB / TC
  PARAMETER TC        = 1.5


* 1.11 Leaf development

        LAI           = INSW(TIME-DAYEM,0.,TLAI)
        TLAI          = INTGRL(LAII,GLAI)
        GLAI          = INSW(LAI-1.0,GLAJ,GLAM)
        GLAJ          = EMERG*LAII*RGRL*DTEFAE*EXP(RGRL*TSUMAE)
  PARAMETER RGRL      = 0.025

        GLAM          = SLA * (GLV - DLV)
  PARAMETER SLA       = 0.0014

        DLV           = WLVG * INSW (DVS-C1, 0.0, OLVDF)
        OLVDF         = INSW (DVS-C2, RDR, 0.0)
  PARAMETER C1        = 0.4; C2 = 2.; RDR = 0.024


* 1.12 Dry matter production

        WRT           = INTGRL(WRTI,GRT)
        WLVG          = INTGRL(WLVI,GWLVG)
        GWLVG         = GLV-DLV
        WLVD          = INTGRL(ZERO,DLV)
        WST           = INTGRL(WSTI,GST)
        WCB           = INTGRL(ZERO,GCB)
        WCH           = INTGRL(ZERO,GCH)
        WGRAIN        = INTGRL(ZERO,GGR)

        WLV           = WLVG + WLVD
        TADRW         = WLV + WST + WCH + WGRAIN + WRES
        TDRW          = TADRW + WRT
```

```
* 1.13 Weather functions

        DAVTMP     = (TMMN+TMMX)/2.
        DDTMP      = 1.12*DAVTMP

        DTEFF      = MAX(0.,DAVTMP-TBASE)
        DTEFAE     = EMERG*DTEFF
        TSUMAE     = INTGRL(ZERO,DTEFAE)
  PARAMETER TBASE  = 10.


* 1.14 Carbon balance check

        CHKIN      = (WLV-WLVI)*CFLV+(WST-WSTI)*CFST+(WRT-WRTI)*...
                     CFRT+WCB*CFCB
        CHKCRB     = TNASS * (12./44.)
        TNASS      = INTGRL(TNASSI,GNASS)
        GNASS      = ((GPHOT-MAINT)*44./30.)-(GRT*CO2RT+GLV*CO2LV+...
                     (GST+TRANSL)*CO2ST+GCB*CO2CB+(1.-CONVF)*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)
        CO2CB      = 44./12.*(ASRQCB*12./30.-CFCB)

        CHKCFL     = (CHKIN-CHKCRB)/(NOTNUL(CHKIN))

  PARAMETER CFLV=0.459; CFST=0.494; CFRT=0.467; CFCB=0.491


* 1.15 Run control

        DAYEM      = STTIME + EMPER
  PARAMETER EMPER  = 6.
        DAE        = MAX(0.,TIME-DAYEM)
        DAP        = TIME - STTIME

  FINISH CHKCFL    > 1.E-6
  FINISH DVS       > 2.

  TIMER STTIME     = 302.; FINTIM = 500.; DELT=1.; PRDEL=1.

  WEATHER WTRDIR='C:\SYS\WEATHER\';CNTR='KENYA';ISTN=2;IYEAR=1992

  TRANSLATION_FSE

  PRINT DVS,DAE,TDRW,WGRAIN,DAYL,DS0

END
STOP
ENDJOB
```

1.17 Listing of MAIZE1 subroutines

```
*----------------------------------------------------------------------*
*  SUBROUTINE ASTRO                                                    *
*  Purpose: This subroutine calculates astronomic daylength,           *
*           diurnal radiation characteristics such as the daily        *
*           integral of sine of solar elevation and solar constant.    *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                  units  class *
*  ----   ---- -------                                  -----  ----- *
*  DOY     R4  Daynumber (Jan 1st = 1)                    -       T  *
*  LAT     R4  Latitude of the site                     degrees   I  *
*  SC      R4  Solar constant                           J m-2 s-1 O  *
*  DS0     R4  Daily extraterrestrial radiation         J m-2 d-1 O  *
*  SINLD   R4  Seasonal offset of sine of solar height    -       O  *
*  COSLD   R4  Amplitude of sine of solar height          -       O  *
*  DAYL    R4  Astronomic daylength (base = 0 degrees)    h       O  *
*  DSINB   R4  Daily total of sine of solar height        s       O  *
*  DSINBE  R4  Daily total of effective solar height      s       O  *
*                                                                      *
*  FATAL ERROR CHECKS (execution terminated, message)                  *
*  condition: LAT > 67, LAT < -67                                      *
*----------------------------------------------------------------------*

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

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

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

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

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

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

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

      DSINB  = 3600.*(DAYL*SINLD+24.*COSLD*SQRT (1.-AOB*AOB)/PI)
      DSINBE = 3600.*(DAYL*(SINLD+0.4*(SINLD*SINLD+COSLD*COSLD*0.5))+
     &         12.0*COSLD*(2.0+3.0*0.4*SINLD)*SQRT (1.-AOB*AOB)/PI)

*-----solar constant (SC) and daily extraterrestrial radiation (DS0)
      SC   = 1370.*(1.+0.033*COS (2.*PI*DOY/365.))
      DS0  = SC*DSINB
```

```
      RETURN
      END

*----------------------------------------------------------------------*
*  SUBROUTINE TOTASS                                                   *
*  Purpose: This subroutine calculates daily total gross               *
*           assimilation (DTGA) by performing a Gaussian integration   *
*           over time. At three different times of the day,            *
*           radiation is computed and used to determine assimilation   *
*           whereafter integration takes place.                        *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                    units  class *
*  ----   ---- -------                                    -----  ----- *
*  DOY     R4  Day number (January 1 = 1)                   -      T   *
*  LAT     R4  Latitude of the site                       degrees  I   *
*  DTR     R4  Daily total of global radiation            J/m2/d   I   *
*  SCP     R4  Scattering coefficient of leaves for visible            *
*              radiation (PAR)                              -      I   *
*  AMAX    R4  Assimilation rate at light saturation      kg CO2/  I   *
*                                                        ha leaf/h     *
*  EFF     R4  Initial light conversion factor           kg CO2/J/ I   *
*                                                        ha/h m2 s     *
*  KDF     R4  Extinction coefficient for diffuse light    -       I   *
*  LAI     R4  Leaf area index as used for photosynthesis  ha/ha   I   *
*              Note: This can involve stem, flower or                  *
*                    ear area index!!                                  *
*  DAYL    R4  Astronomic daylength (base = 0 degrees)       h       O   *
*  DTGA    R4  Daily total gross assimilation          kg CO2/ha/d O   *
*  DS0     R4  Daily extraterrestrial radiation           J/m2/s   O   *
*                                                                      *
*                                                                      *
*  SUBROUTINES and FUNCTIONS called : ASTRO, ASSIM                     *
*----------------------------------------------------------------------*

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

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

      PI   = 3.141592654

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

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

      DO 10 I1=1,IGAUSS

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

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

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


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

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

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

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

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

10    CONTINUE

      DTGA = DTGA * DAYL

      RETURN
      END

*----------------------------------------------------------------------*
*  SUBROUTINE ASSIM                                                    *
*  Purpose: This subroutine performs a Gaussian integration over       *
*           depth of canopy by selecting five different LAI's and      *
*           computing assimilation at these LAI levels. The            *
*           integrated variable is FGROS.                              *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                    units  class *
*  ----   ---- -------                                    -----  ----- *
*  SCP     R4  Scattering coefficient of leaves for visible            *
*              radiation (PAR)                              -       I  *
*  AMAX    R4  Assimilation rate at light saturation      kg CO2/   I  *
*                                                        ha leaf/h     *
*  EFF     R4  Initial light conversion factor           kg CO2/J/  I  *
*                                                        ha/h m2 s     *
*  KDF     R4  Extinction coefficient for diffuse light             I  *
*  LAI     R4  Leaf area index as used for photosynthesis  ha/ha    I  *
*              Note: This can involve stem, flower or                  *
*                    ear area index!!                                  *
*  SINB    R4  Sine of solar height                         -       I  *
*  PARDR   R4  Instantaneous flux of direct radiation (PAR) W/m2    I  *
*  PARDF   R4  Instantaneous flux of diffuse radiation(PAR) W/m2    I  *
```

```
*  FGROS   R4  Instantaneous assimilation rate of         kg CO2/    O  *
*              whole canopy                              ha soil/h      *
*                                                                       *
*-----------------------------------------------------------------------*

      SUBROUTINE ASSIM (SCP, AMAX, EFF, KDF, LAI, SINB, PARDR, PARDF,
     &                  FGROS)
      IMPLICIT REAL(A-Z)
      REAL XGAUSS(5), WGAUSS(5)
      INTEGER I1, I2, IGAUSS

*-----Gauss weights for five point Gauss
      DATA IGAUSS /5/
      DATA XGAUSS /0.0469101,0.2307534,0.5      ,0.7692465,0.9530899/
      DATA WGAUSS /0.1184635,0.2393144,0.2844444,0.2393144,0.1184635/

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

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

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

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

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

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

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

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

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

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

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

10      CONTINUE
        FGROS = FGROS * LAI

        RETURN
        END
```

1.18 Example of a weather file

```
*--------------------------------------------------------------------*
* STATION   : ICRAF RESEARCH STATION, MACHAKOS, KENYA
* LONG      : 37 14 E (= 37.23)
* LAT       : 1 33 S (= -1.55)
* ALT       : 1600 m
* YEAR      : 1993
*
* AUTHOR    : PAUL KIEPE
* COMMENTS  : NONE
* COLUMN    : DAILY VALUE
* 1         : STATION NUMBER
* 2         : YEAR
* 3         : DAY
* 4         : RADIATION               (kJ m-2 d-1)
* 5         : MINIMUM TEMPERATURE     (Centigrade)
* 6         : MAXIMUM TEMPERATURE     (Centigrade)
* 7         : ACTUAL VAPOUR PRESSURE  (kPa)
* 8         : MEAN WIND SPEED         (m s-1)
* 9         : RAINFALL                (mm d-1)
*--------------------------------------------------------------------*
   37.23  -1.55   1600.   0.00  0.00
   2 1993   1  17580.  13.8  22.8   1.710   3.3   4.1
   2 1993   2  16820.  14.2  23.1   1.720   2.6   4.8
   2 1993   3  16160.  14.6  23.9   1.680   2.3    .0
   2 1993   4  14180.  12.2  23.0   1.650   2.3    .0
   2 1993   5  18440.  14.1  23.4   1.660   2.8  11.0
   2 1993   6  10800.  15.9  23.1   1.750   3.3  33.2
   2 1993   7   9790.  15.5  22.2   1.750   3.0   9.0
   2 1993   8  10880.  14.7  22.3   1.640   1.9    .0
   2 1993   9  22670.  14.7  25.3   1.550   2.6   7.1
   2 1993  10  18260.  12.7  25.0   1.700   2.4    .0
   2 1993  11  21550.  14.3  25.0   1.760   3.9    .0
   2 1993  12  18280.  15.8  24.7   1.780   2.3  13.0
   2 1993  13  11380.  15.7  26.5   1.730   1.6  16.7
   2 1993  14  16220.  15.6  24.2   1.780   1.6   1.0
   2 1993  15  10250.  15.3  24.1   1.780   1.7  26.2
   2 1993  16  20330.  14.7  25.1   1.740   2.2    .0
   2 1993  17   8190.  15.2  23.0   1.760   1.7  24.8
   2 1993  18  16450.  14.5  25.8   1.790   1.5   2.2
   2 1993  19  13860.  14.3  26.0   1.750   1.5  47.4
   2 1993  20  19950.  14.0  26.2   1.640   1.6    .0
   2 1993  21  21980.  12.0  25.7   1.660   2.0    .0
   2 1993  22  19430.  15.5  24.7   1.800   2.5    .0
   2 1993  23  18190.  14.7  23.7   1.720   2.8   3.1
   2 1993  24  22390.  11.7  24.1   1.630   2.4    .0
   2 1993  25  23460.  12.9  25.9   1.640   2.4   5.8
   2 1993  26  15350.  15.8  23.0   1.800   2.5   1.5
   2 1993  27  11030.  15.7  23.1   1.790   3.1  12.7
   2 1993  28  19490.  14.2  23.7   1.560   2.6   1.9
   2 1993  29  13160.  14.4  22.5   1.710   2.1  45.7
   2 1993  30  19050.  15.1  24.0   1.660   3.1   1.4
   2 1993  31  19670.  13.2  24.3   1.630   2.7   3.0
   2 1993  32  21690.  14.5  23.5   1.700   3.1    .0
   2 1993  33  21820.  14.7  24.4   1.620   3.1    .0
   2 1993  34  22290.  11.2  25.3   1.540   2.4    .0
```

2	1993	35	24970.	10.9	25.2	1.540	2.0	.0
2	1993	36	25030.	12.1	27.3	1.510	1.8	.0
2	1993	37	22030.	14.2	27.0	1.740	2.2	.0
2	1993	38	18580.	16.1	26.5	2.210	2.4	22.7
2	1993	39	18190.	14.5	24.5	1.850	2.5	42.2
2	1993	40	12570.	14.1	22.4	1.750	1.9	.0
2	1993	41	17590.	13.7	23.1	1.740	2.0	26.7
2	1993	42	5680.	13.4	19.4	1.670	1.3	2.2
2	1993	43	22640.	11.6	25.1	1.570	2.4	.0
2	1993	44	16360.	15.8	25.0	1.820	2.4	5.6
2	1993	45	21190.	15.2	24.8	1.640	2.6	.0
2	1993	46	24600.	11.8	24.3	1.610	2.3	.0
2	1993	47	23480.	12.7	25.0	1.650	2.4	.0
2	1993	48	23730.	12.6	26.0	1.510	2.3	.0
2	1993	49	24060.	12.6	25.8	1.570	2.6	.0
2	1993	50	21580.	14.9	23.7	1.690	3.3	.0
2	1993	51	15130.	12.4	22.8	1.600	2.7	.0
2	1993	52	25610.	10.0	25.2	1.320	2.5	.0
2	1993	53	24050.	11.2	26.6	1.360	2.3	.0
2	1993	54	25360.	11.8	28.0	1.480	2.3	.0
2	1993	55	19760.	11.9	26.3	1.720	2.2	4.5
2	1993	56	24180.	14.1	26.0	1.740	2.5	.0
2	1993	57	23630.	13.6	25.9	1.570	2.4	.0
2	1993	58	24610.	13.2	27.1	1.760	2.3	.0
2	1993	59	22240.	13.8	26.2	2.270	2.9	.0
2	1993	60	14160.	15.8	19.1	1.330	1.7	.0
2	1993	61	22180.	15.1	18.6	1.550	1.5	.0
2	1993	62	23340.	14.0	18.6	1.620	1.3	.0
2	1993	63	20100.	15.3	18.6	1.590	1.4	.0
2	1993	64	22470.	15.0	18.1	1.600	1.3	.0
2	1993	65	22080.	15.8	19.2	1.670	1.5	.0
2	1993	66	23060.	14.3	19.3	1.640	1.7	.0
2	1993	67	20190.	15.7	20.0	1.770	1.7	.0
2	1993	68	23700.	15.5	19.3	1.380	1.8	.0
2	1993	69	22660.	14.7	18.9	1.590	1.7	.0
2	1993	70	17930.	15.6	19.5	1.420	1.7	.0
2	1993	71	13280.	16.1	20.6	1.280	1.6	22.8
2	1993	72	21920.	14.9	18.5	1.490	1.4	.0
2	1993	73	22250.	15.2	19.4	1.640	1.5	.0
2	1993	74	17860.	14.6	19.7	1.480	1.8	.0
2	1993	75	20160.	13.1	19.7	1.600	1.6	.0
2	1993	76	17370.	15.7	19.9	1.510	1.9	.0
2	1993	77	18160.	16.3	20.8	1.470	1.7	2.0
2	1993	78	21950.	16.9	20.2	1.640	2.2	.0
2	1993	79	20440.	17.7	26.1	1.580	2.8	.0
2	1993	80	22550.	14.0	27.8	1.590	2.2	.0
2	1993	81	24220.	14.1	28.8	1.620	2.7	2.5
2	1993	82	17090.	16.9	26.4	1.770	3.3	.0
2	1993	83	17940.	16.2	25.9	1.660	2.9	.0
2	1993	84	24820.	12.7	27.8	1.460	2.4	.0
2	1993	85	23140.	14.0	27.7	1.450	2.4	.0
2	1993	86	24420.	15.4	27.2	1.510	2.7	.0
2	1993	87	25150.	15.4	27.6	2.360	2.4	.0
2	1993	88	22720.	14.5	27.7	2.360	2.2	.0
2	1993	89	22050.	17.0	27.2	1.750	3.4	.0
2	1993	90	17010.	16.3	27.2	1.690	2.6	11.3
2	1993	91	13480.	16.4	25.8	1.640	3.9	0.2
2	1993	92	15650.	15.0	25.3	1.520	3.4	.0

```
2 1993  93  15750.  13.1  25.8   1.420   2.9    .0
2 1993  94  13810.  15.7  25.9   1.520   2.8    .0
2 1993  95  14470.  15.1  25.9   1.560   2.5    .0
2 1993  96  16260.  15.3  26.0   2.160   2.9    .0
2 1993  97  13380.  15.1  26.5   1.650   2.6    .0
2 1993  98  16050.  15.4  26.9   1.640   2.5    .0
2 1993  99  13530.  16.4  27.7   1.590   2.3    .0
2 1993 100  14330.  15.7  26.9   1.620   3.0    .0
2 1993 101  15710.  16.3  27.6   1.650   2.9    .0
2 1993 102  16560.  17.0  27.7   1.620   2.6    .0
2 1993 103  16300.  17.5  28.1   1.680   3.2    .0
2 1993 104  14780.  17.2  27.6   1.670   2.7   0.5
2 1993 105  15140.  16.5  27.5   1.680   2.7   7.0
2 1993 106  12320.  15.9  25.3   1.700   2.8  24.5
2 1993 107  12430.  15.8  23.7   1.650   3.1    .0
2 1993 108  14210.  16.3  24.6   1.670   3.3   2.0
2 1993 109  15900.  16.1  25.4   1.580   2.5    .0
2 1993 110  17360.  15.5  26.7   1.600   2.1    .0
2 1993 111  18990.  15.7  26.7   1.630   2.8    .0
2 1993 112  17030.  16.9  26.0   1.680   2.8    .0
2 1993 113  13880.  16.8  26.0   1.690   2.4    .0
2 1993 114  17440.  17.2  27.8   1.690   2.4    .0
2 1993 115  15190.  17.5  27.1   1.670   2.5    .0
2 1993 116  12740.  17.1  27.4   1.660   2.7    .0
2 1993 117  12940.  15.9  26.5   1.620   2.2    .0
2 1993 118  14830.  15.1  27.3   1.530   2.0    .0
2 1993 119  17980.  15.6  27.2   1.590   2.1    .0
2 1993 120  17460.  14.0  27.6   1.610   2.4    .0
2 1993 121  21010.  16.2  27.4   1.690   2.9    .0
2 1993 122  20030.  16.6  27.2   1.690   2.7    .0
2 1993 123  19290.  16.1  27.6   1.690   2.6    .0
2 1993 124  22120.  17.2  28.0   2.050   2.3    .0
2 1993 125  14890.  16.1  27.6   2.120   2.5    .0
2 1993 126  21440.  14.2  29.3   2.190   2.1    .0
2 1993 127  19000.  16.0  29.5   1.830   1.9    .0
2 1993 128  21690.  16.6  28.5   1.490   2.5    .0
2 1993 129  22240.  15.2  28.2   1.460   2.4    .0
2 1993 130  18230.  14.2  27.7   1.520   2.3    .0
2 1993 131  22200.  16.3  28.0   1.620   2.5    .0
2 1993 132  15490.  16.4  26.3   1.640   2.3    .0
2 1993 133  15090.  15.6  26.4   1.650   2.4    .0
2 1993 134  13910.  13.8  24.6   1.570   2.0    .0
2 1993 135  13340.  14.6  25.4   1.560   1.8   7.0
2 1993 136  16050.  15.8  25.4   1.660   2.1    .0
2 1993 137  19370.  15.4  26.3   1.640   1.8    .0
2 1993 138  20820.  13.1  26.6   1.430   2.4    .0
2 1993 139  21290.  12.5  26.8   1.400   2.4    .0
2 1993 140  16010.  11.2  25.8   2.100   2.4    .0
2 1993 141  13860.  15.1  25.5   1.670   1.9   4.4
2 1993 142  16580.  14.6  26.7   1.600   1.8    .0
2 1993 143  20950.  15.2  28.0   1.520   2.1    .0
2 1993 144  18960.  14.8  27.1   1.550   2.3    .0
2 1993 145  14760.  16.1  26.1   1.600   2.1    .0
2 1993 146  19510.  14.4  27.0   1.430   2.0    .0
2 1993 147  22270.  11.4  27.2   1.360   2.1    .0
2 1993 148  22130.  12.7  27.9   1.580   1.8    .0
2 1993 149  22290.  10.9  28.2   1.410   1.9    .0
2 1993 150  20840.  11.7  28.1   1.370   2.2    .0
```

2	1993	151	14330.	14.2	26.8	1.500	2.0	.0
2	1993	152	12610.	13.3	26.1	1.470	1.6	.0
2	1993	153	8680.	15.0	24.7	1.550	1.6	.0
2	1993	154	15060.	15.1	27.8	1.470	1.7	.0
2	1993	155	12240.	14.1	27.7	1.520	1.5	0.7
2	1993	156	13610.	16.1	25.2	1.720	1.9	.0
2	1993	157	11720.	14.5	25.3	1.500	1.6	.0
2	1993	158	13520.	11.1	26.1	1.320	1.4	.0
2	1993	159	13780.	13.7	26.8	1.310	1.6	.0
2	1993	160	16480.	13.7	27.3	1.380	1.9	.0
2	1993	161	12000.	14.7	25.0	1.480	1.8	1.6
2	1993	162	12120.	13.5	25.7	1.340	1.6	.0
2	1993	163	13020.	13.4	23.3	1.380	2.0	.0
2	1993	164	5120.	14.5	20.4	1.400	1.9	.0
2	1993	165	13790.	15.1	24.1	1.540	2.3	.0
2	1993	166	16810.	15.3	25.4	1.250	2.1	.0
2	1993	167	7680.	12.8	22.0	0.860	1.9	.0
2	1993	168	12190.	12.7	23.8	0.900	1.9	.0
2	1993	169	14510.	14.2	25.6	1.410	1.9	.0
2	1993	170	15560.	12.8	25.3	1.370	1.8	.0
2	1993	171	12320.	14.6	23.4	1.510	2.0	.0
2	1993	172	11680.	14.3	24.5	1.470	2.1	.0
2	1993	173	17210.	13.1	24.3	1.310	2.1	.0
2	1993	174	20140.	13.3	25.3	1.330	2.1	.0
2	1993	175	10720.	13.0	24.1	1.350	1.6	.0
2	1993	176	9850.	12.7	24.3	1.760	1.7	.0
2	1993	177	12660.	12.2	24.6	1.320	1.8	.0
2	1993	178	14060.	13.6	23.1	1.410	2.4	.0
2	1993	179	12530.	13.3	22.2	1.350	2.2	10.2
2	1993	180	8360.	13.7	21.2	1.470	1.7	.0
2	1993	181	8420.	13.2	21.1	1.400	1.5	.0
2	1993	182	10210.	13.3	22.5	1.300	1.6	.0
2	1993	183	6680.	9.3	18.8	1.230	1.3	.0
2	1993	184	14620.	11.5	23.9	1.150	1.9	.0
2	1993	185	12090.	7.3	22.7	1.100	1.5	.0
2	1993	186	21090.	7.3	25.5	1.090	1.9	.0
2	1993	187	10970.	9.0	22.7	1.220	2.0	.0
2	1993	188	10900.	12.8	22.1	1.450	1.6	.0
2	1993	189	14080.	8.7	24.7	1.420	1.8	.0
2	1993	190	6690.	13.9	19.8	1.500	2.1	.0
2	1993	191	13910.	13.9	24.0	1.540	2.1	.0
2	1993	192	4410.	13.8	18.4	1.480	2.0	.0
2	1993	193	7010.	11.9	21.2	1.360	1.6	.0
2	1993	194	6810.	12.5	21.8	1.370	1.4	.0
2	1993	195	10120.	13.3	23.3	1.580	1.9	.0
2	1993	196	6350.	13.3	20.0	1.720	1.7	.0
2	1993	197	6250.	13.2	20.2	1.720	1.7	.0
2	1993	198	7280.	12.2	20.4	1.690	1.6	.0
2	1993	199	9900.	13.0	23.3	1.820	1.9	.0
2	1993	200	9830.	13.1	21.5	1.850	2.2	.0
2	1993	201	5300.	13.0	19.2	1.680	2.0	.0
2	1993	202	9510.	13.0	23.0	1.800	2.2	.0
2	1993	203	11620.	12.4	22.7	1.790	1.8	.0
2	1993	204	19450.	9.8	26.5	1.950	1.9	.0
2	1993	205	15250.	10.1	24.3	1.760	1.8	.0
2	1993	206	15110.	10.0	24.0	1.690	1.9	.0
2	1993	207	18100.	6.5	23.6	1.720	1.9	.0
2	1993	208	20000.	7.5	25.2	1.870	2.1	.0

2	1993	209	21350.	8.1	26.0	1.930	2.0	.0
2	1993	210	20860.	8.1	27.2	1.980	2.2	.0
2	1993	211	13450.	13.2	25.7	1.960	2.3	.0
2	1993	212	17330.	12.2	24.5	1.900	2.3	.0
2	1993	213	15920.	12.3	24.0	1.870	2.1	.0
2	1993	214	17910.	12.4	26.5	2.000	2.1	.0
2	1993	215	17120.	13.4	25.7	2.010	2.0	.0
2	1993	216	9590.	10.9	21.7	1.640	1.6	.0
2	1993	217	9850.	12.7	24.3	1.760	1.7	.0
2	1993	218	12660.	12.2	24.6	1.320	1.8	.0
2	1993	219	10670.	12.6	20.6	1.720	1.9	.0
2	1993	220	8420.	13.9	23.0	1.860	1.9	.0
2	1993	221	12760.	13.0	24.1	1.870	1.9	.0
2	1993	222	14450.	11.7	26.0	1.960	1.7	.0
2	1993	223	18250.	10.1	25.0	1.880	1.8	.0
2	1993	224	19070.	12.2	26.2	2.010	2.0	.0
2	1993	225	20200.	10.6	25.1	1.900	2.4	.0
2	1993	226	8850.	13.2	21.8	1.790	2.4	.0
2	1993	227	8920.	11.8	21.0	1.750	2.1	.0
2	1993	228	12510.	11.6	23.7	1.770	2.1	.0
2	1993	229	12670.	13.3	24.0	1.800	2.4	.0
2	1993	230	13410.	12.6	24.6	1.810	2.1	.0
2	1993	231	13470.	13.4	24.8	1.840	2.3	.0
2	1993	232	11740.	13.3	23.8	1.820	2.3	.0
2	1993	233	14120.	13.6	25.0	1.940	2.1	.0
2	1993	234	17650.	10.5	26.0	1.860	1.9	.0
2	1993	235	21640.	9.6	27.0	1.970	2.3	.0
2	1993	236	16770.	9.9	26.2	1.910	2.3	.0
2	1993	237	10870.	11.4	24.4	1.760	2.0	.0
2	1993	238	18640.	13.1	24.8	1.830	2.2	1.3
2	1993	239	10900.	11.5	24.2	1.750	2.0	.0
2	1993	240	14760.	12.9	24.9	1.790	2.1	.0
2	1993	241	23930.	10.8	27.3	2.030	2.4	.0
2	1993	242	10830.	13.0	23.4	1.780	2.3	.0
2	1993	243	17130.	13.0	26.4	1.860	2.0	.0
2	1993	244	22790.	8.8	26.0	1.840	2.4	.0
2	1993	245	14810.	7.1	24.2	1.690	2.1	.0
2	1993	246	7820.	13.5	22.2	1.710	2.4	.0
2	1993	247	9870.	12.2	23.4	1.660	2.2	.0
2	1993	248	10290.	13.0	22.4	1.650	2.0	0.2
2	1993	249	21360.	12.5	24.3	1.680	2.7	.0
2	1993	250	18310.	12.8	26.7	1.450	2.3	.0
2	1993	251	21770.	11.1	26.8	1.400	2.5	.0
2	1993	252	20870.	13.4	26.9	1.990	2.1	.0
2	1993	253	24470.	8.6	28.2	1.500	2.4	.0
2	1993	254	24390.	9.2	28.0	1.610	2.3	.0
2	1993	255	23250.	12.6	28.0	1.620	2.3	.0
2	1993	256	23990.	12.3	28.9	1.530	2.6	.0
2	1993	257	24090.	14.4	29.0	1.550	2.9	.0
2	1993	258	26540.	11.1	31.2	1.360	2.6	.0
2	1993	259	24010.	11.7	31.3	1.420	2.1	.0
2	1993	260	17760.	15.3	28.7	1.730	2.7	.0
2	1993	261	23490.	15.0	28.4	1.580	3.1	.0
2	1993	262	22430.	12.7	29.9	1.390	2.6	.0
2	1993	263	19260.	11.8	29.0	1.500	2.7	.0
2	1993	264	22540.	12.8	28.9	1.560	3.0	.0
2	1993	265	22360.	14.6	27.9	1.480	3.0	.0
2	1993	266	20970.	15.9	30.3	2.870	3.3	.0

2	1993	267	24980.	13.7	28.7	2.430	2.5	.0
2	1993	268	25070.	11.7	28.5	2.350	2.6	.0
2	1993	269	22020.	12.9	29.3	2.340	2.3	.0
2	1993	270	24170.	9.0	31.4	2.480	2.2	.0
2	1993	271	19000.	15.9	27.4	2.570	3.1	.0
2	1993	272	19900.	11.8	28.9	1.980	2.0	.0
2	1993	273	23350.	11.4	27.9	1.980	2.3	.0
2	1993	274	20350.	13.9	27.3	2.230	2.4	.0
2	1993	275	22630.	13.2	29.0	2.410	3.0	.0
2	1993	276	24830.	15.0	28.3	2.410	3.2	.0
2	1993	277	17460.	14.3	26.5	2.150	2.8	.0
2	1993	278	22310.	14.5	28.7	2.380	2.8	.0
2	1993	279	23700.	13.0	29.0	1.730	2.4	.0
2	1993	280	15550.	14.3	28.6	1.570	2.5	.0
2	1993	281	17900.	14.9	27.4	1.600	2.4	0.5
2	1993	282	24980.	11.9	27.3	1.400	2.5	.0
2	1993	283	21070.	14.9	29.2	1.380	2.6	.0
2	1993	284	22560.	10.4	29.3	1.240	2.4	.0
2	1993	285	21890.	14.8	28.6	1.340	0.9	.0
2	1993	286	24550.	9.2	29.1	1.310	0.4	.0
2	1993	287	21370.	14.8	29.8	2.220	0.4	.0
2	1993	288	17930.	14.8	27.9	2.380	0.4	2.5
2	1993	289	20690.	13.7	27.5	2.040	0.4	.0
2	1993	290	24630.	14.7	28.8	1.680	0.4	.0
2	1993	291	25110.	14.0	27.1	1.630	0.4	.0
2	1993	292	20790.	14.2	27.2	1.650	0.4	.0
2	1993	293	15860.	14.9	26.2	1.650	0.4	.0
2	1993	294	22240.	13.2	26.4	1.660	0.4	.0
2	1993	295	21900.	14.6	26.3	1.880	0.4	.0
2	1993	296	19360.	14.3	26.7	1.820	0.4	.0
2	1993	297	19760.	15.4	27.4	1.700	0.4	.0
2	1993	298	14320.	12.5	31.8	1.710	0.4	.0
2	1993	299	24990.	13.0	27.9	1.690	0.4	.0
2	1993	300	15800.	15.9	26.7	1.680	0.4	.0
2	1993	301	23150.	14.0	29.5	1.600	0.4	.0
2	1993	302	19680.	16.6	27.7	1.660	0.4	.0
2	1993	303	19060.	16.4	27.3	1.650	0.4	.0
2	1993	304	14290.	15.8	25.3	1.790	0.4	5.5
2	1993	305	12640.	15.5	25.8	1.850	2.3	1.6
2	1993	306	21150.	14.2	27.6	1.910	2.3	12.6
2	1993	307	25310.	15.8	27.7	1.780	2.5	.0
2	1993	308	24120.	13.0	27.1	1.500	1.8	.0
2	1993	309	19050.	15.7	27.6	1.550	2.6	.0
2	1993	310	23770.	16.6	28.3	1.260	2.6	.0
2	1993	311	22420.	15.4	26.5	1.070	2.8	20.3
2	1993	312	16540.	15.5	25.3	1.680	2.2	22.6
2	1993	313	16040.	15.8	24.8	1.650	2.1	.0
2	1993	314	24940.	15.8	26.2	1.630	2.5	.0
2	1993	315	20870.	14.3	25.8	1.600	2.4	.0
2	1993	316	22500.	16.3	26.7	1.600	2.8	.0
2	1993	317	23760.	15.8	26.7	1.550	2.7	.0
2	1993	318	24110.	15.5	26.4	1.490	3.3	.0
2	1993	319	24000.	16.0	26.1	1.200	3.3	.0
2	1993	320	23400.	15.7	25.5	1.530	3.1	.0
2	1993	321	21560.	15.5	24.4	1.520	3.4	.0
2	1993	322	25430.	14.8	25.9	1.520	2.2	.0
2	1993	323	20070.	15.5	25.9	1.510	2.1	5.8
2	1993	324	15390.	15.4	23.5	1.660	2.4	8.4

```
2 1993 325  17080.  15.3  22.6   1.660   3.1   6.3
2 1993 326  19610.  15.4  23.8   1.690   3.6   4.2
2 1993 327  22710.  15.7  25.0   1.660   2.6   2.1
2 1993 328  18630.  16.0  24.6   1.660   2.5   8.2
2 1993 329  19130.  15.9  23.5   1.670   2.3  18.9
2 1993 330  16940.  15.1  23.0   1.710   2.3   9.7
2 1993 331  18270.  15.9  22.9   1.690   2.1   5.4
2 1993 332  17450.  15.7  23.8   1.760   2.5  11.5
2 1993 333  13210.  14.7  21.7   1.760   2.2   0.6
2 1993 334  13900.  14.4  24.5   1.660   2.6  21.0
2 1993 335  12660.  15.9  23.6   1.780   2.7   6.8
2 1993 336  18660.  15.1  24.1   1.750   2.1   1.3
2 1993 337  18840.  15.8  24.5   1.780   2.6    .0
2 1993 338  24220.  16.3  24.7   1.780   2.1    .0
2 1993 339  19360.  15.9  24.1   1.760   2.3  37.0
2 1993 340  22160.  15.3  24.4   1.720   1.3  15.0
2 1993 341  15390.  15.5  23.3   1.710   1.9    .0
2 1993 342  21200.  13.9  24.7   1.690   2.1    .0
2 1993 343  19950.  16.1  25.6   1.740   1.9    .0
2 1993 344  23300.  12.4  24.8   1.560   2.9    .0
2 1993 345  22550.  15.3  24.8   1.650   2.5    .0
2 1993 346  22010.  14.0  24.7   1.700   2.4    .0
2 1993 347  14350.  15.7  22.3   1.710   2.4    .0
2 1993 348  18770.  13.4  23.6   1.630   2.2    .0
2 1993 349  19480.  14.2  24.2   1.690   1.8    .0
2 1993 350  24980.  15.0  24.9   1.650   2.7    .0
2 1993 351  21220.  15.7  24.6   1.730   2.6    .0
2 1993 352  22190.  15.9  24.2   1.690   3.0    .0
2 1993 353  20150.  14.4  24.1   1.510   2.2    .0
2 1993 354  25920.  13.3  24.9   1.490   2.2    .0
2 1993 355  20260.  14.8  24.6   1.640   2.3    .0
2 1993 356  28700.  14.3  25.2   1.700   2.6    .0
2 1993 357  23430.  15.6  25.6   1.710   2.5    .0
2 1993 358  23450.  16.2  26.1   1.750   2.1    .0
2 1993 359  29560.  16.0  24.8   1.680   2.4  12.4
2 1993 360  24370.  16.1  24.1   1.600   2.6   1.5
2 1993 361  23110.  15.1  22.6   1.640   2.0   1.2
2 1993 362  28620.  13.6  25.3   1.600   2.4    .0
2 1993 363  28000.  14.7  25.0   1.580   2.8    .0
2 1993 364  21470.  13.8  24.0   1.520   1.7    .0
2 1993 365  23980.  13.9  24.5   1.560   1.9    .0
```

2 Modelling the water-limited maize production in a tropical environment

2.1 Introduction

Three meteorological parameters, i.e. rainfall (RAIN, mm d^{-1}), vapour pressure (VP, kPa) and average wind speed (WN, m s^{-1}), are added to the parameters that were already used in Part 1 of this report (MAIZE1), global radiation and minimum and maximum temperature. The three variables are also obtained from the weather file. These weather files are located in a special weather directory and the construction of the files is documented by Van Kraalingen et al. (1991). An example of a weather file is listed in Chapter 1.18.

```
TITLE MAIZE2.FST (ver. 98.08)- simulates the water-limited maize
TITLE production in tropical environments.

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*          E-mail: leo.stroosnijder@users.tct.wau.nl

DECLARATIONS

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,INPUT,...
                   OUTPUT)
DEFINE_CALL SUBFR (INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
                   OUTPUT)
```

The model starts with the current TITLE of the model, the name of the authors who developed the model and the declaration of the subroutines that will be used by the model to perform specific computations.

2.2 Initial conditions

```
MODEL
  INITIAL
  INCON ZERO       = 0.

*       Location   = Machakos, Kenya
        WL1I       = WCL1I * TKL1
        WL2I       = WCL2I * TKL2
        WL3I       = WCL3I * TKL3
        WL4I       = WCL4I * TKL4
        WCUMI      = WL1I + WL2I + WL3I + WL4I
  PARAMETER WCL1I  = 0.06; WCL2I = 0.17; WCL3I = 0.20; WCL4I = 0.19
  PARAMETER TKL1   = 100.; TKL2 = 200.; TKL3 = 800.; TKL4 = 400.
```

In addition to the crop and weather statements already explained in Part 1 of this book (MAIZE1), a number of functions, parameters and initial conditions are specified. Especially, water flow and soil characteristics will be added. The soil depth of the site is 1.5 m. It can be divided into four separate layers (Fig. 2.1) with a respective depth from top to bottom of 100 mm (TKL1), 200 mm (TKL2), 800 mm (TKL3) and 400 mm (TKL4).

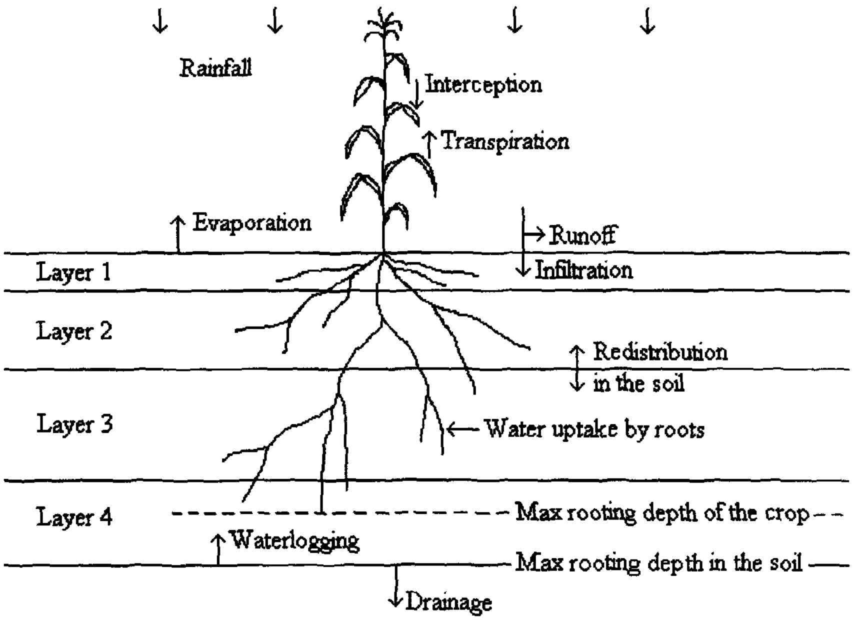

Fig. 2.1 *Schematic view of elements and processes of the soil water balance (adapted from Stroosnijder, 1982).*

A number of additional initial conditions are specified, like the initial water content (WCL1-4I, m^3 m^{-3}) of each soil layer. The initial amount of water in each layer (WL1-4I, mm) is found by multiplying the initial water content with the depth of its respective soil layer. The MAIZE2 model is quite sensitive to these initial values. Plants can grow for quite some time without rain, because they are thriving on water that is stored in the soil. The initial amount of stored water (WCUMI, mm) is the sum of the water present in each layer, in this particular example WCUMI = 276 mm. When all layers are at wilting point (c.f. Chapters 2.15 and 2.19) there is still 225 mm in the soil. Hence at the start of the simulation there is potentially 51 mm available for the crop.

```
*       Genotype       = Katumani Composite B
        LAII           = NPL * LAIO
        NPL            = 3.7
  PARAMETER LAIO       = 1.58E-3
  INCON ZRTI           = 58.
  INCON WLVI           = 0.; WSTI = 0.; WRTI = 0.
        TNASSI         = (WLVI*CFLV+WSTI*CFST+WRTI*CFRT)*44./12.
```

The initial rooted depth of the crop (ZRTI, mm) is added to the initial crop conditions. It will be used in Chapter 2.16.

2.3 Crop development

```
DYNAMIC
      DVS          = INTGRL(ZERO,DVR)
      DVR          = INSW(DVS-1.,DVRV,DVRR) * EMERG
      EMERG        = INSW(TIME-DAYEM,0.,1.)
      DVRV         = 0.029*(1.-EXP(-0.212*(DDTMP-12.)))
      DVRR         = 0.003744 + 0.000491*DDTMP
```

2.4 Leaf CO_2 assimilation

```
      AMAX         = AMX * AMDVS
      AMDVS        = AFGEN(AMDVT,DVS)
PARAMETER AMX      = 70.
FUNCTION AMDVT     = 0.0,1.0, 1.2,0.9, 1.6,0.5, 2.0,0.2, 2.5,0.2
```

2.5 Daily gross CO_2 assimilation

```
      CALL TOTASS (DOY,LAT,RDD,SCP,AMAX,EFF,KDF,LAI,  DAYL,DTGA,DS0)
PARAMETER EFF      = 0.45; KDF = 0.65; SCP = 0.20
```

2.6 Carbohydrate production

```
      GPHOT        = DTGA * RDFRL * PRODSF * 30./44.
      RDFRL        = LIMIT(0.,1.,(RESLMX-RESL)/(RESLMX-FEEDB*RESLMX))
      RESL         = (WRES/ASRQCB) / (NOTNUL(WST))
PARAMETER RESLMX = 0.1; FEEDB = 0.2
```

The production stress factor (PRODSF) reflects the effect of water stress on CO_2 assimilation. The daily value is calculated in Chapter 2.19.

2.7 Maintenance

```
      MAINT        = MAINTS * TEFF * MNDVS
      MAINTS       = MAINLV*WLV+MAINST*WST+MAINRT*WRT+MAINCB*...
                     (WCH+WGRAIN)
      MNDVS        = WLVG/(NOTNUL(WLV))
      TEFF         = Q10**((DAVTMP-TREF)/10.)
PARAMETER MAINLV = 0.03;  MAINST=0.015; MAINRT=0.015; MAINCB=0.01
PARAMETER TREF     = 35.
CONSTANT Q10       = 2.
```

2.8 Dry matter partitioning

```
      FSHP       = AFGEN(FSHTB,DVS)
      FSH        = (FSHP*PARTSF)/(1.+(PARTSF-1.)*FSHP)
      FRT        = 1. - FSH
FUNCTION FSHTB   = 0.,0.4, 0.5,0.5, 0.8,0.6, 1.,0.8, 1.1,1., 2.5,1.

      FLV        = AFGEN(FLVTB,DVS)
      FSC        = 1. - FLV
FUNCTION FLVTB   = 0.,1., 0.4,1., 1.2,0., 2.5,0.

      FST        = AFGEN(FSTTB, DVS)
      FCB        = 1. - FST
FUNCTION FSTTB   = 0.,1., 0.9,1., 1.3,0.1, 2.5,0.1

      FCH        = AFGEN(FCHTB,DVS)
      FRES       = 1.-FCH
FUNCTION FCHTB   = 0.,1., 1.,1., 1.2,0.5, 1.4,0.1, 2.5,0.1
```

The factor PARTSF reflects the effect of water stress on dry matter partitioning. The daily value is computed in Chapter 2.19.

2.9 Growth of organs and reserves

```
      ASRQ       = FSH*(ASRQLV*FLV+ASRQST*FST+ASRQCB*FCB)+ASRQRT*FRT

      TRANSL     = INSW(DVS-1.,0.,WST*DVR*FRTRL)
      GTW        = (GPHOT-MAINT+CONVF*TRANSL*CFST*30./12.)/ASRQ
      GRT        = FRT * GTW
      GLV        = FLV  * FSH * GTW
      GST        = FST  * FSH * GTW - TRANSL
      GCB        = FCB  * FSH * GTW
      GCH        = FCH  * FCB * FSC  * FSH * GTW / ASRQCB
      GRES       = FRES * FCB * FSC  * FSH * GTW / ASRQCB
PARAMETER ASRQRT = 1.444; ASRQLV=1.463; ASRQST=1.513; ASRQCB=1.491
PARAMETER CONVF  = 0.947; FRTRL  = 0.20
```

2.10 Development of grains

```
      GGR        = MAX(0.,MIN(GRSINK,GRSOUR))

      GRSINK     = NGRAIN * 0.01 * PGRI * GRDVS * GRTMP
      GRDVS      = AFGEN(GRDVST,DVS)
      GRTMP      = AFGEN(GRTMPT,DAVTMP)

FUNCTION GRDVST  = 0.,0., 1.0,0., 1.1,0.25, 1.3,0.35, 1.4,1.,...
                   1.5,1., 1.6,0.35, 1.8,0.25, 2.0,0., 2.5,0.
FUNCTION GRTMPT  = 0.,0., 10.,0., 16.,1., 34.,4.

      NGRAIN     = INTGRL(ZERO,GNGRN)
      GNGRN      = (NGA * NPL + NGB * TADRW) * ...
                   INSW(DVS-1., 0., 1.) * INSW(-NGRAIN, 0., 1.)
PARAMETER NGA    = -50.; NGB = 0.5
```

```
      PGRI          = PKRWT / (0.364 * GFD16)
PARAMETER PKRWT     = 260.; GFD16 = 50.

      WRES          = INTGRL(ZERO,GWRES)
      GWRES         = GRES - DRES
      DRES          = (GGR * ASRQCB) - GRES

      GRSOUR        = (GRES + WRES) / ASRQCB / TC
PARAMETER TC        = 1.5
```

2.11 Leaf development

```
      LAI           = INSW(TIME-DAYEM,0.,TLAI)
      TLAI          = INTGRL(LAII,GLAI)
      GLAI          = INSW(LAI-1.0,GLAJ,GLAM)
      GLAJ          = EMERG*LAII*RGRL*DTEFAE*EXP(RGRL*TSUMAE)
PARAMETER RGRL      = 0.025

      GLAM          = SLA * (GLV - DLV)
PARAMETER SLA       = 0.0014

      DLV           = WLVG * INSW (DVS-C1, 0.0, OLVDF)
      OLVDF         = INSW (DVS-C2, RDR, 0.0)
PARAMETER C1        = 0.4; C2 = 2.; RDR = 0.024
```

2.12 Dry matter production

```
      WRT           = INTGRL(WRTI,GRT)
      WLVG          = INTGRL(WLVI,GWLVG)
      GWLVG         = GLV-DLV
      WLVD          = INTGRL(ZERO,DLV)
      WST           = INTGRL(WSTI,GST)
      WCB           = INTGRL(ZERO,GCB)
      WCH           = INTGRL(ZERO,GCH)
      WGRAIN        = INTGRL(ZERO,GGR)

      WLV           = WLVG + WLVD
      TADRW         = WLV + WST + WCH + WGRAIN + WRES
      TDRW          = TADRW + WRT

      HI            = WGRAIN/NOTNUL(TADRW)
```

2.13 Weather functions

```
      DAVTMP        = (TMMN + TMMX)/2.
      DDTMP         = 1.12*DAVTMP

      DTEFF         = MAX(0.,DAVTMP-TBASE)
      DTEFAE        = EMERG*DTEFF
      TSUMAE        = INTGRL(ZERO,DTEFAE)
PARAMETER TBASE     = 10.

      TRAIN         = INTGRL(ZERO,RAIN)
```

Total rainfall (TRAIN, mm) is computed. It can be included in the output table.

2.14 Potential evapotranspiration

2.14.1 Introduction

Transpiration is the loss of water vapour by plants and evaporation is the loss of water vapour from the soil or from a free water surface. Evapotranspiration is a broader term that covers both transpiration and evaporation during the growth of a crop when the crop does not fully cover the soil surface. Strictly speaking, the transfer of liquid water into water vapour is called evaporation, irrespective whether this occurs at the soil surface or at the surface of leaves. Taking the fact into account that this is often a source of confusion, the term evapotranspiration will be used throughout this book.

The principle driving force for evaporation is the gradient of vapour pressure from the evaporating surface to the atmosphere. The vapour pressure at the evaporating surface is considered to be the saturated vapour pressure at the prevailing temperature of that surface. The vapour pressure of the air depends on the relative humidity of that air. The rate of vapour removal depends on the resistance that exists for this vapour flow. The resistance is strongly related to wind speed. These two environmental variables, air humidity and wind speed are, sometimes referred to as the `evaporative demand' or `drying power' of the air.

The problem with the concept described above is that the temperature of the evaporating surface can usually not be derived from standard meteorological observations. Evaporation of a 1 mm layer of water requires as much as 2.4 MJ m^{-2} of energy and can, therefore, be considered mainly as an energy balance process. Evaporation cools the evaporating surface, which reduces the vapour gradient. A power source is required to maintain a certain surface temperature and, hence, a certain vapour pressure gradient. Solar radiation supplies the bulk of this power. The net radiation received by the canopy or soil is the overriding environmental factor and driving force determining the evaporation rate.

The net radiation depends on the incoming (short wave) radiation from the sun as well as the radiation losses due to reflection and outgoing (long wave) radiation. Net thermal (long wave) radiation is mostly a negative term in the heat balance. Heat carried by moving air is another power source than radiation. Photosynthesis traps less than 5 to 8% of solar radiation and is not considered here and respiration yields an insignificant amount of energy. Evapotranspiration is, as a form of simplification, considered as a result from two factors: radiation and drying power.

Penman (1948) was the first who described evapotranspiration in physical and mathematical terms. He calculated evaporation from free water surfaces, bare soil and from a short-cut grass sward for 10-day periods. There is an ongoing discussion in the literature whether his formula is also applicable if daily values are used. If daily values are used, only 24-hour average values should be used. For large differences between day and night (e.g. in wind speed), Doorenbos and Kassam (1979) suggested the use of correction factors.

The calculated evapotranspiration is the potential evapotranspiration, 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, i.e. reflecting the relative loss of water to the atmosphere during crop growth. For the precise calculation of crop water use, so-called crop factors are used (e.g. Doorenbos & Pruitt, 1977; Feddes, 1987).

```
        PENMAN      = EVAPR + EVAPD
```

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

2.14.2 Radiation term:

```
        EVAPR       = (1./LHVAP) * (DELTA/(DELTA+PSYCH)) * NRAD
        DELTA       = 4.1586 * 1.E2 * 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 the net radiation (NRAD, J m^{-2} d^{-1}), the latent heat of evaporation (LHVAP, J kg^{-1}) and a weighing factor (DELTA/(DELTA+PSYCH)) in which DELTA (kPa $^{o}C^{-1}$) is the tangent of the relation between saturated vapour pressure (SVP, kPa) and temperature (^{o}C), while PSYCH (kPa $^{o}C^{-1}$) is the psychrometer constant (Monteith, 1965). Values for DELTA and SVP can be found in look-up tables (check for the correct units!), or parameterized equations can be used (Kiepe, 1995).

2.14.3 Net radiation

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

The net radiation depends on the incoming short wave radiation (measured value DTR, J m^{-2} d^{-1}) and the reflection or albedo value (ALB). The combined albedo for the soil and the canopy is composed of that for the soil (ALBS) and that for the canopy (0.25). The relative contributions of both albedos depend on the shading of the soil by the crop and is calculated on the basis of the leaf area index (LAI). An extinction coefficient (for short-wave radiation penetrating the crop) of 0.5 is used here. The soil's albedo depends on the surface colour and the moisture content. Albedo values for dry soil vary from 0.15 (clay) to 0.40 (dune sand). Here, an average value of 0.25 is used. The dependence on soil moisture is described in relation to the average water content of the topsoil layer (Ten Berge, 1989).

2.14.4 Net long-wave radiation

```
        RLWN        = FTEMP * FVAP * FCLEAR
        FTEMP       = BOLTZM * (DAVTMP+273.)**4
  CONSTANT BOLTZM   = 4.897E-3
        FVAP        = 0.56-0.25*SQRT(VP)
        FCLEAR      = 0.1+0.9*CLEAR
```

```
      CLEAR        = LIMIT(0.,1.,((RDD/DS0)-ANGSTA)/ANGSTB)
  PARAMETER ANGSTA = 0.25; ANGSTB = 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 (FTEMP), vapour pressure of the atmosphere (FVAP) and sky clearness (FCLEAR). Note that the parameters used in this function 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) contains the ratio 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 day of the year) and can be derived from Smithsonian tables. If n is not available, but DTR instead, the ratio n/N can be replaced by DTR/DS0, where DS0 is the extra-terrestrial radiation or Angot value. It is the amount of radiation that would reach the Earth's surface in the absence of an atmosphere. Its value depends on the location on Earth (latitude or LAT) and the day of the year (DOY). The indicative values for the empirical constants A (ANGSTA) and B (ANGSTB) in the Angstom formula:

$$n * N^{-1} = (DTR * DS0^{-1} - A) * B^{-1}$$

are obtained from Frere and Popov (1979), c.f. Table 2.1.

Table 2.1 *Indicative values for empirical constants in the Angstrom formula in relation to latitude and climate used by the FAO (Frere & 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

Values for DS0 can also be obtained from the Smithsonian Meteorological Table no. 132 (in cal cm^{-2} d^{-1}) or from Van Keulen and Wolf (1986; Table 14, in J m^{-2} d^{-1}). In the MAIZE model the value for DS0 is calculated in subroutine TOTASS (Chapter 2.5).

The actual vapour pressure (VP, kPa) is read from the weather file. If this value is unknown, it can be calculated using the wet (TWET) and dry (TDRY) temperature values of a psychrometer as VP = SVP - (TDRY-TWET)*PSYCH.

2.14.5 Drying power term

```
      WDF          = 2.63*(1.0+0.54*WN)
      DRYP         = (SVP-VP) * WDF
      EVAPD        = (PSYCH/(DELTA+PSYCH)) * DRYP
```

There exists a lot of confusion about the drying power term in the Penman equation (DRYP, mm d^{-1}) since the numerical values used in the above equation are not unitless and depend on the units of wind speed (WD) and the vapour pressures (VP and SVP). The numerical values in the equation used above are valid for WD (m s^{-1}), VP (kPa) and SVP (kPa), all measured at standard WMO height.

2.14.6 Output variables

The cumulative amount of the potential evapotranspiration since the start of the simulation (TPENM, mm) is computed as well as the cumulative amounts for the radiation term (TEVAPR, mm) and the drying power term (TEVAPD, mm).

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

2.15 The soil water balance

2.15.1 Introduction

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

The root system is usually in contact with several parts of the soil profile that differ in texture, compaction and water content. Most soil water balances are more intensive near the surface. The soil profile should have a minimum of three horizontal layers. The upper layer (TKL1, mm) should be 100-200 mm thick, the second (TKL2, mm) 200-400 mm and the third (TKL3, mm) 400-1000 mm. Thickness and physical characteristics of each layer are inputs to the model. Their sum (TKLT, mm) should slightly exceed the maximum rooted depth. The model can easily be extended to account for more heterogeneous situations by adding more layers. The soil profile that is used here contains four layers.

```
TKLT        = TKL1 + TKL2 + TKL3 + TKL4
```

For parametric simulation (time step of simulation equals one day, DELT=1) four specific points of the soil water content - water potential relation (Water Retention or pF-curve) are needed: the volumetric water content (m^3 m^{-3}) at saturation (WCST), at field capacity (WCFC), at wilting point (WCWP) and when air dry (WCAD).

The soil water content at saturation (WCST) is equal to the soil porosity. When the soil is saturated there is no air left in the soil. If this situation continues for several days roots may die due to a lack of oxygen. Maize grows optimally in a deep and well-drained soil.

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 water 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 (depending on environmental conditions), plants may wilt during the day and recover at night when the evaporative demand is low. Beyond a certain value of water suction, plants do not recover and wilt permanently. The soil water suction then usually has a value of about 1600 kPa or pF 4.2, but this 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 strongly depends on soil type. The amount of water available for uptake by the crop is the total amount of water in the soil, minus the amount of water at permanent wilting point. The soil water content when the soil is air dry is one third or less of the content at wilting point. This concept is not well-defined, but simulation results are not sensitive to its value. The soil water suction of an air dry soil is assumed to be 1 GPa, or pF 7.

2.15.2 Interception

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

The actual amount of rainfall intercepted by the canopy (AINTC, mm d^{-1}) equals the interception capacity of one layer of leaves (INTC, mm d^{-1}) times the leaf area index (LAI). Obviously, this amount can only be intercepted if rainfall (RAIN) exceeds this amount, hence the use of the MIN function. Potential transpiration is reduced with half (as the average of values 0.3-1.0 as reported by Sing and Szeicz, 1979) the amount of actual interception (c.f. Chapter 2.17.2).

2.15.3 Runoff

Not all the water that reaches the surface infiltrates into the soil, especially during heavy rain. Runoff from a field can be 0-50% of the precipitation, and even more on unfavourable surfaces or with large and intensive showers (Stroosnijder & Kone, 1982). On the other hand, runoff can be negligible under proper soil management conditions, like conservation farming. Runoff occurs when the rate of water supply at the soil surface exceeds the maximum infiltration rate and the excess water accumulated at the soil surface exceeds the surface storage capacity. The maximum infiltration rate is a function of the water content of the topsoil layer.

Table 2.2 *Examples of runoff parameters for three geographically-different locations*

	ROFAC	ROTHR
Machakos (Kenya)	0.10	2.1
Niono (Mali)	0.24	5.0
Jatikerto (Indonesia)	0.45	1.4

The values of the parameters used in the runoff equation are site and management specific and may be adapted for any other site or land management practice (Table 2.2). For instance, surface storage in Niono varied between 0 and 5 mm for crusted and tilled soils respectively (Hoogmoed, Berkout & Stroosnijder, 1992).

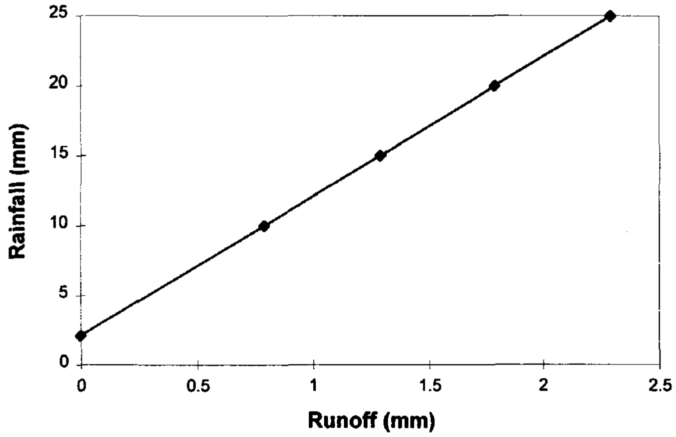

Fig. 2.2 *The relation between runoff and rainfall is characterised by the threshold (ROTHR) and the lineair slope (ROFAC).*

```
          RNOFF       = MAX(0., (ROFAC*(RAIN-ROTHR)))
PARAMETER ROFAC       = 0.10
PARAMETER ROTHR       = 2.1
```

In this model a simplified approach is used according to the following equation. In the first order runoff equation stated above runoff (RNOFF, mm) is related to rainfall (RAIN, mm) through the runoff factor (ROFAC,-). This factor will be triggered after reaching a threshold value of the surface storage capacity (ROTHR, mm; Fig. 2.2), which is directly related to surface roughness.

2.15.4 Infiltration

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

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

2.15.5 Redistribution

```
          WLFL2       = MAX(0.,WLFL1-(WCFC1-WCL1)*TKL1)
          WLFL3       = MAX(0.,WLFL2-(WCFC2-WCL2)*TKL2)
          WLFL4       = MAX(0.,WLFL3-(WCFC3-WCL3)*TKL3)
          WLFL5       = MAX(0.,WLFL4-(WCFC4-WCL4)*TKL4)
PARAMETER WCFC1       = 0.26; WCFC2 = 0.26; WCFC3 = 0.34; WCFC4 = 0.32
```

Most of the redistribution of water that has infiltrated in the soil profile, occurs within 24 hours (except in heavy clay soils). Since a one-day time step is used in this model, it is assumed that redistribution occurs within that time step. Simulation is, therefore, straightforward; if on any day more water infiltrates into a soil layer than can be retained at field capacity, the excess water drains into the next layer, i.e. WLFL2, WLFL3, WLFL4 WLFL5 (mm d^{-1}, positive in downward direction).

2.15.6 External drainage

```
        DRAIN        = MIN(DRATE,WLFL5)
        WLFL6        = INSW((DRATE-WLFL5),(WLFL5-DRATE),0.)
  PARAMETER DRATE    = 12.
```

If more water enters the deepest layer than can be retained at field capacity, the excess is either drained below the root zone (DRAIN, mm d^{-1}) or fills up (WLFL6) the soil layer above field capacity causing water logging, because drainage is limited by the maximum drainage rate of the subsoil (DRATE, mm d^{-1}). A high value implies perfect drainage, a low value implies restricted drainage and waterlogged conditions may occur during wet periods. A zero value means no drainage at all (impermeable layer).

2.15.7 Waterlogging

```
        WLFL7        = INSW((DRATE-WLFL5),MAX(0.,...
                       WLFL6-((WCST4-WCFC4)*TKL4)),0.)
        WLFL8        = INSW((DRATE-WLFL5),MAX(0.,...
                       WLFL7-((WCST3-WCFC3)*TKL3)),0.)
        WLFL9        = INSW((DRATE-WLFL5),MAX(0.,...
                       WLFL8-((WCST2-WCFC2)*TKL2)),0.)
        WLFL10       = INSW((DRATE-WLFL5),MAX(0.,...
                       WLFL9-((WCST1-WCFC1)*TKL1)),0.)
  PARAMETER WCST1    = 0.40; WCST2 = 0.40; WCST3 = 0.38; WCST4 = 0.37
```

Water that cannot drain fills up the soil until saturation. This occurs first in the deepest layer (WLFL6, mm d^{-1}; this flow is upward!) simulating the formation of a pseudo-groundwater table. If still more excess water has to be stored in the soil profile overlying layers are successively filled up (through WLFL7, WLFL8 and WLFL9) until saturation occurs here as well. If the whole soil profile is saturated, water flows off above the surface (WLFL10). This way to account for waterlogged conditions will not always be satisfactory. Dynamic simulation of waterlogged conditions can be executed with models like SAWAH (Ten Berge et al., 1992) and SHIELD (Kiepe, 1995) when transport characteristics of the soil are known.

2.15.8 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 soil layers is calculated later in the model (Chapter 2.18 and 2.17, respectively).

2.15.9 Soil water content

```
        DWL1         = WLFL1-WLFL2+WLFL9-WLFL10-EVSW1-TRWL1
        DWL2         = WLFL2-WLFL3+WLFL8-WLFL9-EVSW2-TRWL2
        DWL3         = WLFL3-WLFL4+WLFL7-WLFL8-EVSW3-TRWL3
        DWL4         = WLFL4-WLFL5+WLFL6-WLFL7-EVSW4-TRWL4

        WL1          = INTGRL(WL1I,DWL1)
        WL2          = INTGRL(WL2I,DWL2)
        WL3          = INTGRL(WL3I,DWL3)
        WL4          = INTGRL(WL4I,DWL4)
```

```
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 daily change in water amount (DWL1-4, mm) in each of the soil layers is calculated. Then the total amount of water (WL1-4, mm) present in each of the layers is tracked by integration of the water fluxes. The volumetric water content (WCL1-4, m^3 m^{-3}) is subsequently computed by dividing the amount of water by the thickness of the respective layers. Finally the relative water content (RWCL1-4,-) for each layer is computed. The relative water content will be used in Chapter 2.17.

2.15.10 Output variables

```
TAINTC      = INTGRL(ZERO,AINTC)
TDRAIN      = INTGRL(ZERO,DRAIN)
TSTORE      = INTGRL(ZERO,WLFL10)
TRNOFF      = INTGRL(ZERO,RNOFF)
```

A number of output variables is computed, like the total amount of intercepted water (TAINTC, mm), the total drainage (TDRAIN, mm), the total surface storage (TSTORE, mm) and the total runoff (TRNOFF, mm).

2.15.11 Control variables

```
WCUM        = WL1+WL2+WL3+WL4
CHKWTR      = TRAIN+WCUMI-TAINTC-TRNOFF-...
              WCUM-TDRAIN-TATRAN-TAEVAP
```

Finally, check values are computed, like the total amount of water in the profile (WCUM, mm) and a check on the tightness of the water balance (CHKWTR, mm). Ideally, the latter should be zero. For calculation of TATRAN and TAEVAP see Chapters 2.17 and 2.18 respectively.

2.16 Rooted depth

2.16.1 Introduction

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

The rooted depth (ZRT, mm) is defined as the lower depth from which the crop effectively extracts water. A root density of 1.0 mm per cm^3 of soil volume may be adopted as the lower density limit for adequate water uptake. This is a low threshold value as water is mobile and flows relatively easy to roots. The rooted depth is computed as the integral of the rate of root elongation (EZRT, mm d^{-1}) with the initial value of the integral at emergence (ZRTI, mm) defined in the initial section of the model (Chapter 2.2).

2.16.2 Elongation of roots

```
        EZRT         = EZRTF*WSERT*REAAND(ZRTM-ZRT,1.0-DVS)*...
                       INSW(-DVS,1.,0.)
        CALL SUBGRT  (ZRT,TKL1,TKL2,TKL3,WCL1,WCL2,WCL3,WCL4,WCFC1,...
                       WCFC2,WCFC3,WCFC4,WCWP1,WCWP2,WCWP3,WCWP4,...
                       WSERT)
  PARAMETER EZRTF    = 38.5
```

The length of fibrous roots can vary enormously without much dependence on root weight. Hence, rooted depth is calculated independently of the growth of the root mass. Rooted depth can increase at a rate of 30-50 mm d^{-1} (EZRTF, mm d^{-1}), but soil physical, chemical and biological factors can reduce it (Taylor & Klepper, 1978). Root growth generally stops around flowering or earlier if the maximum rooted depth (ZRTM, mm) is reached. These limitations are introduced through the FST-function REAAND (for DVS>1.0 or ZRT>ZRTM this function assumes the value 0). Low soil temperatures or water stress reduce root growth. For conditions with temperatures between 20-30 °C, there is no temperature effect on EZRT. Accounting for water stress it is assumed that root elongation decreases when the root tip reaches a soil layer with a lower soil moisture content and that it ceases at, or below, wilting point (Taylor & Ratcliff, 1969; Jones et al., 1991). It is described in the self-defined FORTRAN subroutine SUBGRT (Chapter 2.24).

2.16.3 Maximum depth of roots

```
        ZRTM         = MIN(ZRTMC,ZRTMS,TKLT)
  PARAMETER ZRTMS    = 1500.; ZRTMC = 1200.
```

The model takes as maximum rooted depth (ZRTM) the minimum of the values that are set either by soil properties (ZRTMS, mm), crop characteristics (ZRTMC, mm), or the calculated total soil depth (TKLT). Roots grow to a maximum rooting depth of crops (ZRTMC) if they are not restricted by soil conditions. The value is species specific and ranges from 0.5-1.5 m or even more. Significant differences between cultivars have been reported (Tear & Peet, 1983).

A very dense soil offers mechanical resistance, which hampers root elongation 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 due to soil preparation in irrigated rice where a hardpan is required to reduce water losses due to drainage. A compacted layer can develop unintentionally due to the tire pressure of heavy machinery. A physical limitation to rooting depth is approximated by specification of a maximum depth as a soil property (ZRTMS).

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

2.17 Transpiration

2.17.1 Introduction

The potential transpiration rate (PTRANS, mm d^{-1}) is calculated in the model with the Penman-Monteith combination equation. The rate of water uptake follows this potential rate closely under ample water supply. However, uptake cannot meet the demand if there is not sufficient water available in the soil. When the actual transpiration (ATRANS, mm d^{-1}) is below the potential transpiration the stomata close. 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 per cm rooted depth for different soils. This implies that, if soil evaporation could be avoided, a C_3 crop could produce 170-800 kg ha^{-1} total dry matter on the water stored in each 0.1 m 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 of the cropping season there is a wet and at least 0.5-0.7 m 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.

2.17.2 Potential canopy transpiration

```
PTRANS     = (1.-EXP(-0.5*LAI)) * EVAPR + EVAPD * ...
             MIN(2.5,LAI) - 0.5 * AINTC
```

If not all radiation is intercepted by the canopy, only part of the radiation term (EVAPR) of potential evapotranspiration will be used by the crop. It is exponentially related to leaf area (LAI). Radiation that is 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 2.5. Lower leaves do not contribute much to transpiration because little light penetrates deep into the canopy, hence their stomatal resistance is higher. Also air humidity is higher and wind speed is reduced. Potential transpiration is reduced by half the amount of interception, the average of the values 0.3-1.0 (Singh & Szeicz, 1979).

2.17.3 Actual transpiration

```
FUNCTION EDPTFT  = -.50,0., -0.05,0., 0.0,0.15, 0.15,0.6, ...
                   0.30,0.8, 0.50,1., 2.0,1.
      ERLB       = ZRT1*AFGEN(EDPTFT,RWCL1)+...
                   ZRT2*AFGEN(EDPTFT,RWCL2)+...
                   ZRT3*AFGEN(EDPTFT,RWCL3)+...
                   ZRT4*AFGEN(EDPTFT,RWCL4)
      TRRM       = PTRANS/(ERLB+1.E-10)

      TRWL1      = TRRM*WSE1*ZRT1*AFGEN(EDPTFT,RWCL1)
      TRWL2      = TRRM*WSE2*ZRT2*AFGEN(EDPTFT,RWCL2)
      TRWL3      = TRRM*WSE3*ZRT3*AFGEN(EDPTFT,RWCL3)
      TRWL4      = TRRM*WSE3*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 soil water uptake in semi-arid regions Van Keulen (1975) assumed that the uptake is evenly distributed over the rooted depth in a uniformly wetted profile. This implies that the major resistance to water flow is assumed in the soil and not in the roots.

Usually, soil water content is not uniform. In the model, each layer is treated separately, but compensatory effects can be accommodated. When part of the root system is in a dry soil layer, while another part of the root system is in a wetter layer, the part present in the wetter layer will take up more water (c.f. 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 layer (Van Keulen & Seligman, 1987). 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 layers, thus allowing increased uptake by roots in wetter layers. Effective root length for each soil layer is obtained by multiplying the root penetration depth (ZRT) with the root activity coefficient.

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

The uptake per layer (TRWL1-4, mm d^{-1}) 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 water contents (WSE1-4), and by the effective root length per soil layer. Total water uptake (ATRANS, mm d^{-1}) is the sum of water drawn from the individual soil layers.

2.17.4 Effect of water stress

The multiplication factors for water uptake due to low soil water contents (between 1 and 0) for the individual soil layers (WSE1-4) are discussed in Chapter 2.19.

2.17.5 Output variables

```
        TPTRAN      = INTGRL(ZERO,PTRANS)
        TATRAN      = INTGRL(ZERO,ATRANS)
```

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

2.18 Soil evaporation

Soil evaporation is important for bare soils, but is much less than transpiration under a well-developed crop canopy. Water can evaporate until the soil is air dry.

2.18.1 Potential evaporation under the crop

```
        PEVAP       = EXP(-0.7*LAI) * (EVAPR + EVAPD)
```

Shading by living and dead leaves is accounted for in this computation; the extinction coefficient for short wave radiation (together with the near infrared radiation) in the crop canopy is about 0.7 (Monteith, 1969).

2.18.2 Effect of soil dryness

```
  INCON DSLRI       = 1.
        DSLR        = INSW(RAIN-0.5,1.,1.00001-NDSLR)/DELT
        NDSLR       = INTGRL(DSLRI,DSLR)
```

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

2.18.3 Actual evaporation

```
        AEVAP       = INSW(NDSLR-1.1,EVSH,EVSD)
        EVSH        = MIN(PEVAP,(WL1-WCAD1*TKL1)/DELT)
  PARAMETER WCAD1   = 0.06
```

While calculating the actual evaporation (AEVAP, mm d^{-1}) a distinction is made, with the aid of NDSLR, 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 layer cannot be depleted beyond the air dry water content (WCAD). For days without rain the evaporation rate (EVSD) is below the potential rate calculated as:

```
EVSD          = MIN(PEVAP,0.6*PEVAP*(SQRT(NDSLR)-...
                SQRT(NDSLR-1.)))
```

The evaporation rate decreases as the topsoil starts drying. The reduction in potential evaporation rate during drying is approximated using the experimental field observation that cumulative evaporation is proportional to the square root of time (Stroosnijder, 1982; 1987). The proportionality factor (mm $d^{-0.5}$) is assumed to be equal to 60% of the potential evaporation rate. Rainfall that is too small to trigger resetting of days since the last rain is added to the evaporation, since it is assumed to be lost the same day.

2.18.4 Extraction of water from soil layers

```
      FEVL1         = MAX(WL1-WCAD1*TKL1,0.1)*EXP(-EES*(0.25*TKL1))
      FEVL2         = MAX(WL2-WCAD2*TKL2,0.1)*EXP(-EES*(TKL1+...
                      (0.25*TKL2)))
      FEVL3         = MAX(WL3-WCAD3*TKL3,0.1)*EXP(-EES*(TKL1+TKL2+...
                      (0.25*TKL3)))
      FEVL4         = MAX(WL4-WCAD4*TKL4,0.1)*EXP(-EES*(TKL1+TKL2+...
                      TKL3+(0.25*TKL4)))
PARAMETER EES       = 0.002
PARAMETER WCAD2     = 0.06; WCAD3 = 0.09; WCAD4 = 0.09
```

Partitioning parameters (FEVL1-4) are computed for all four layers. In this way, the redistribution of water due to developing potential gradients is mimicked by extracting water for evaporation from all layers with a water content above air dryness. This is achieved through the use of a soil-specific extinction coefficient (EES, mm^{-1} from Van Keulen, 1975). Weighting also accounts for depth and thickness of layers (TKL) and their respective water contents. The extinction coefficient, which in principle has to be determined on the basis of experimental data, is approximately 1.E-3 mm^{-1} for heavy (clay) soils and 3.E-3 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 layer.

2.18.5 Output variables

```
TPEVAP        = INTGRL(ZERO,PEVAP)
TAEVAP        = INTGRL(ZERO,AEVAP)
```

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

2.19 Effect of water stress

2.19.1 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 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 (θ_{fc}). At some point beyond field capacity, transpiration is hampered again (Jackson & Drew, 1984). The shape of this response curve is depicted in Fig. 2.3, 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, c.f. Chapters 2.19.2 and 2.24), the current value of water content determines which linear segment should be used.

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

$$S = (\theta - \theta_{wp})\ (\theta_{fc} - \theta_{wp})^{-1}$$

The critical soil water content θ_c, which denotes the transition from water-limited to potential transpiration rate, is not a fixed value. Restriction of water uptake 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 and 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. 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. The characteristic potential transpiration rate $T_{S=0.5}$ is given in Table 2.3 for the five crop groups of Driessen (1986).

Table 2.3 *Characteristic potential transpiration rates for five crop groups according to Driessen (1986, from Doorenbos et al., 1978).*

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

A soil water depletion fraction p is then calculated as:

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

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

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

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

$$T/T_m = \mathrm{WSE} = S\,(1 - p)^{-1}$$

WSE serves to show the resulting dependence of actual transpiration on the two environmental conditions, potential rate T_m (through p) and actual water content θ (WCL through S), on the two soil parameters θ_{fc} and θ_{wp}, and on the plant parameter $T_{S=0.5}$.

Implementation of 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  = 0.11; WCWP2 = 0.11; WCWP3 = 0.16; WCWP4 = 0.16
```

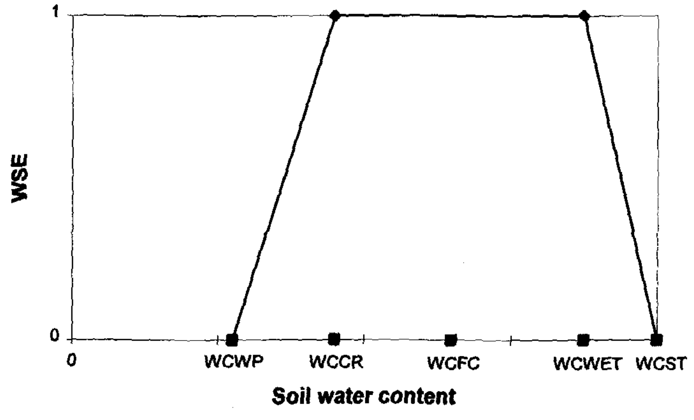

Fig. 2.3 *Water stress factor (WSE) as a function of soil water content (θ).*

The effect of availability of soil water on uptake in a compartment is presented by a factor (WSE1-4), with a value between 0 and 1 (Fig. 2.3).

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

2.19.2 Description of subroutine SUBFR

```
SUBROUTINE SUBFR(WCL,WCFC,P,WCWP,WCWET,WCST, WSE)
IMPLICIT REAL (A-Z)
SAVE
```

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

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

IF (WCL.GT.WCWET) THEN
    FR = (WCST-WCL)/(WCST-WCWET)
ELSE IF (WCL.LE.WCWET .AND. WCL.GT.WCCR) THEN
    FR = 1.
ELSE IF (WCL.LE.WCCR .AND. WCL.GT.WCWP) THEN
    FR = (WCL-WCWP)/(WCCR-WCWP)
ELSE
    FR = 0.
ENDIF

WSE = MIN(1.,MAX(0., FR))

RETURN
END
```

Water stress factors for the individual layers (WSE1-4) are used to compute the total water uptake in Chapter 2.17. This leads to the actual transpiration (ATRANS, mm).

2.19.3 Effect on CO_2 assimilation

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

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

The factor used to reduce photosynthesis is the production stress factor (PRODSF, -). In the calculation of GPHOT in the model (Chapter 2.6) the daily total gross CO_2 assimilation (DTGA, kg CO_2 ha^{-1} d^{-1}) is, therefore, multiplied by PRODSF.

2.19.4 Effect on carbohydrate partitioning

```
  PARTSF      = MIN(1.,0.5+ATRANS/(PTRANS+1.E-10))
```

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

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

It is further assumed that the relative partitioning of carbohydrates within the shoots between leaves, stems and storage organs is affected similarly to the partitioning between shoots and roots. The partitioning stress factor (PARTSF, -; that takes a value between 1 and 0) is used in the model as a multiplier in the calculation of total dry matter increase allocated to the shoots (FSH), to the leaves (FLV) and stems (FST), see Chapter 2.8.

2.20 Water use efficiency

```
TAR        = TATRAN*1.E4/(TDTGA+1.E-10)
TDTGA      = INTGRL(ZERO,DTGA)
TRC        = TATRAN*1.E4/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 may vary substantially among locations and years due to the inclusion of soil evaporation. Therefore, the crop water requirement itself is not calculated here. In stead, three other factors are: the transpiration/assimilation ratio, the transpiration coefficient and the crop factor.

The transpiration coefficient is still a crude concept in crop physiological studies. Therefore, a `water use coefficient' of the crop, TAR (transpiration/assimilation ratio), defined as the amount of water transpired per unit gross photosynthesis in gram water per gram CO_2 may be used (Van Keulen & Van Laar, 1986). This TAR can be calculated on a daily basis (ATRANS/DTGA) as well as using cumulative values (TATRANS/TDTGA). Values for this water use coefficient range from about less than 50 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.

The transpiration coefficient (TRC), which is the inverse of the water use efficiency, is defined as the total amount of water transpired (TATRAN), divided by the total amount of biomass produced (TDRW, kg DM ha^{-1}). Note that soil evaporation is not included in this coefficient. It was established many years ago (De Wit, 1958; Tanner & Sinclair, 1982), that the transpiration coefficient during water stress is equal to the one 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 (e.g. between C_3 and C_4 species).

Crop water requirements may also be expressed in terms of the Penman reference evaporation through the use of 'crop factors' (CROPF, c.f. Doorenbos & Pruitt, 1987; Feddes, 1987). In MAIZE2 this approach is not used, but CROPF is calculated to facilitate comparison with this common approach.

2.21 Carbon balance check

```
        CHKIN       = (WLV-WLVI)*CFLV+(WST-WSTI)*CFST+(WRT-WRTI)*...
                      CFRT+WCB*CFCB
        CHKFL       = TNASS * (12./44.)
        TNASS       = INTGRL(ZERO,GNASS)
        GNASS       = ((GPHOT-MAINT)*44./30.)-(GRT*CO2RT+GLV*CO2LV+...
                      (GST+TRANSL)*CO2ST+GCB*CO2CB+(1.-CONVF)*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)
        CO2CB       = 44./12.*(ASRQCB*12./30.-CFCB)

        CHKCRB      = (CHKIN-CHKFL)/(NOTNUL(CHKIN))

  PARAMETER CFLV=0.459; CFST=0.494; CFRT=0.467; CFCB=0.491
```

2.22 Run control

```
        DAYEM       = STTIME + EMPER
PARAMETER EMPER     = 6.
        DAE         = MAX(0.,TIME-DAYEM)
        DAP         = TIME - STTIME

  FINISH CHKCRB     > 1.E-6
  FINISH CHKWTR     > 1.E-3
  FINISH DVS        > 2.
```

Similar to the carbon balance check (CHKCRB) described in Chapter 1.15, the simulation is stopped by the water balance check (CHKWTR, mm) if water is mysteriously trickling in or oozing out of the system (FINISH CHKWTR > 1.E-3).

```
  TIMER STTIME      = 303.; FINTIM = 500.; DELT=1.; PRDEL=1.

  WEATHER WTRDIR='C:\SYS\WEATHER\';CNTR='KENYA';ISTN=2;IYEAR=1993

  TRANSLATION_FSE

  PRINT DVS,DAE,CROPF,TRC,TAR,TRAIN,WGRAIN,...
        DAYL,HI,TPTRAN,TPEVAP,TEVAPD,TEVAPR,TSTORE

END
STOP
ENDJOB
```

2.23 Listing of the MAIZE2 model

```
TITLE MAIZE2.FST (ver. 98.08)- simulates the water-limited maize
TITLE production in a tropical environment.

*              © Leo Stroosnijder and Paul Kiepe

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*              Department of Environmental Sciences
*           Erosion and Soil & Water Conservation Group
*     Nieuwe Kanaal 11, 6707 AD Wageningen, The Netherlands
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* 2.1 Declarations

DECLARATIONS
  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,INPUT,...
                      OUTPUT)
  DEFINE_CALL SUBFR  (INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
                      OUTPUT)


* 2.2 Initial conditions

MODEL
  INITIAL
  INCON ZERO       = 0.

*      Location    = Machakos, Kenya
       WL1I        = WCL1I * TKL1
       WL2I        = WCL2I * TKL2
       WL3I        = WCL3I * TKL3
       WL4I        = WCL4I * TKL4
       WCUMI       = WL1I + WL2I + WL3I + WL4I
  PARAMETER WCL1I  = 0.12; WCL2I = 0.17; WCL3I = 0.20; WCL4I = 0.19
  PARAMETER TKL1   = 100.; TKL2 = 200.; TKL3 = 800.; TKL4 = 400.

*      Genotype    = Katumani Composite B
       LAII        = NPL * LA0
       NPL         = 3.7
  PARAMETER LA0    = 1.58E-3
  INCON ZRTI       = 58.
  INCON WLVI       = 0.; WSTI = 0.; WRTI = 0.
       TNASSI      = (WLVI*CFLV+WSTI*CFST+WRTI*CFRT)*44./12.


* 2.3 Crop development

  DYNAMIC
       DVS         = INTGRL(ZERO,DVR)
       DVR         = INSW(DVS-1.,DVRV,DVRR) * EMERG
       EMERG       = INSW(TIME-DAYEM,0.,1.)
       DVRV        = 0.029*(1.-EXP(-0.212*(DDTMP-12.)))
       DVRR        = 0.003744 + 0.000491*DDTMP
```

```
* 2.4 Leaf CO2 assimilation

        AMAX          = AMX * AMDVS
        AMDVS         = AFGEN(AMDVT,DVS)
  PARAMETER AMX       = 70.
  FUNCTION AMDVT      = 0.0,1.0, 1.2,0.9, 1.6,0.5, 2.0,0.2, 2.5,0.2
* 2.5 Daily gross CO2 assimilation

        CALL TOTASS (DOY,LAT,RDD,SCP,AMAX,EFF,KDF,LAI,  DAYL,DTGA,DSO)
  PARAMETER EFF       = 0.45; KDF = 0.65; SCP = 0.20


* 2.6 Carbohydrate production

        GPHOT         = DTGA * RDFRL * PRODSF * 30./44.
        RDFRL         = LIMIT(0.,1.,(RESLMX-RESL)/(RESLMX-FEEDB*RESLMX))
        RESL          = (WRES/ASRQCB) / (NOTNUL(WST))
  PARAMETER RESLMX = 0.1; FEEDB = 0.2


* 2.7 Maintenance

        MAINT         = MAINTS * TEFF * MNDVS
        MAINTS        = MAINLV*WLV+MAINST*WST+MAINRT*WRT+...
                        MAINCB*(WCH+WGRAIN)
        MNDVS         = WLVG/(NOTNUL(WLV))
        TEFF          = Q10**((DAVTMP-TREF)/10.)
  PARAMETER MAINLV = 0.03; MAINST=0.015; MAINRT=0.015; MAINCB=0.01
  PARAMETER TREF      = 35.
  CONSTANT Q10        = 2.


* 2.8 Dry matter partitioning

        FSHP          = AFGEN(FSHTB,DVS)
        FSH           = (FSHP*PARTSF)/(1.+(PARTSF-1.)*FSHP)
        FRT           = 1. - FSH
  FUNCTION FSHTB      = 0.,0.4, 0.5,0.5, 0.8,0.6, 1.,0.8, 1.1,1., 2.5,1.

        FLV           = AFGEN(FLVTB,DVS)
        FSC           = 1. - FLV
  FUNCTION FLVTB      = 0.,1., 0.4,1., 1.2,0., 2.5,0.

        FST           = AFGEN(FSTTB, DVS)
        FCB           = 1. - FST
  FUNCTION FSTTB      = 0.,1., 0.9,1., 1.3,0.1, 2.5,0.1

        FCH           = AFGEN(FCHTB,DVS)
        FRES          = 1.-FCH
  FUNCTION FCHTB      = 0.,1., 1.,1., 1.2,0.5, 1.4,0.1, 2.5,0.1


* 2.9 Growth of organs and reserves

        ASRQ          = FSH*(ASRQLV*FLV+ASRQST*FST+ASRQCB*FCB)+ASRQRT*FRT

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

```
      GRT          = FRT * GTW
      GLV          = FLV  * FSH * GTW
      GST          = FST  * FSH * GTW - TRANSL
      GCB          = FCB  * FSH * GTW
      GCH          = FCH  * FCB * FSC   * FSH * GTW / ASRQCB
      GRES         = FRES * FCB * FSC   * FSH * GTW / ASRQCB
PARAMETER ASRQRT = 1.444; ASRQLV=1.463; ASRQST=1.513; ASRQCB=1.491
PARAMETER CONVF  = 0.947; FRTRL  = 0.20

* 2.10 Development of grains

      GGR          = MAX(0.,MIN(GRSINK,GRSOUR))

      GRSINK       = NGRAIN * 0.01 * PGRI * GRDVS * GRTMP
      GRDVS        = AFGEN(GRDVST,DVS)
      GRTMP        = AFGEN(GRTMPT,DAVTMP)
FUNCTION GRDVST  = 0.,0., 1.0,0., 1.1,0.25, 1.3,0.35, 1.4,1.,...
                   1.5,1., 1.6,0.35, 1.8,0.25, 2.0,0., 2.5,0.
FUNCTION GRTMPT  = 0.,0., 10.,0., 16.,1., 34.,4.

      NGRAIN       = INTGRL(ZERO,GNGRN)
      GNGRN        = (NGA * NPL + NGB * TADRW) * ...
                     INSW(DVS-1., 0., 1.) * INSW(-NGRAIN, 0., 1.)
PARAMETER NGA    = -50.; NGB = 0.5
      PGRI         = PKRWT / (0.364 * GFD16)
PARAMETER PKRWT  = 260.; GFD16 = 50.

      WRES         = INTGRL(ZERO,GWRES)
      GWRES        = GRES - DRES
      DRES         = (GGR * ASRQCB) - GRES

      GRSOUR       = (GRES + WRES) / ASRQCB / TC
PARAMETER TC     = 1.5


* 2.11 Leaf development

      LAI          = INSW(TIME-DAYEM,0.,TLAI)
      TLAI         = INTGRL(LAII,GLAI)
      GLAI         = INSW(LAI-1.0,GLAJ,GLAM)
      GLAJ         = EMERG*LAII*RGRL*DTEFAE*EXP(RGRL*TSUMAE)
PARAMETER RGRL   = 0.025

      GLAM         = SLA * (GLV - DLV)
PARAMETER SLA    = 0.0014

      DLV          = WLVG * INSW (DVS-C1, 0.0, OLVDF)
      OLVDF        = INSW (DVS-C2, RDR, 0.0)
PARAMETER C1     = 0.4; C2 = 2.; RDR = 0.024


* 2.12 Dry matter production

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

```
        WCB          = INTGRL(ZERO,GCB)
        WCH          = INTGRL(ZERO,GCH)
        WGRAIN       = INTGRL(ZERO,GGR)

        WLV          = WLVG + WLVD
        TADRW        = WLV + WST + WCH + WGRAIN + WRES
        TDRW         = TADRW + WRT
        HI           = WGRAIN / NOTNUL(TADRW)


* 2.13 Weather functions

        DAVTMP       = (TMMN + TMMX)/2.
        DDTMP        = 1.12*DAVTMP

        DTEFF        = MAX(0.,DAVTMP-TBASE)
        DTEFAE       = EMERG*DTEFF
        TSUMAE       = INTGRL(ZERO,DTEFAE)
  PARAMETER TBASE    = 10.

        TRAIN        = INTGRL(ZERO,RAIN)


* 2.14 Potential evapotranspiration (Penman/Monteith)

        PENMAN       = EVAPR + EVAPD

        EVAPR        = (1./LHVAP) * (DELTA/(DELTA+PSYCH)) * NRAD
        DELTA        = 4.1586 * 1.E2 * SVP / (DAVTMP + 239.)**2
        SVP          = 0.611 * EXP(17.4 * DAVTMP / (DAVTMP + 239.))
  PARAMETER LHVAP    = 2.4E6; PSYCH  = 0.067

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

        RLWN         = FTEMP * FVAP * FCLEAR
        FTEMP        = BOLTZM * (DAVTMP+273.)**4
  CONSTANT BOLTZM    = 4.897E-3
        FVAP         = 0.56-0.25*SQRT(VP)
        FCLEAR       = 0.1+0.9*CLEAR
        CLEAR        = LIMIT(0.,1.,((RDD/DS0)-ANGSTA)/ANGSTB)
  PARAMETER ANGSTA   = 0.25; ANGSTB = 0.45

        WDF          = 2.63 * (1.0+0.54*WN)
        DRYP         = (SVP-VP) * WDF
        EVAPD        = (PSYCH/(DELTA+PSYCH)) * DRYP

        TEVAPR       = INTGRL(ZERO,EVAPR)
        TEVAPD       = INTGRL(ZERO,EVAPD)


* 2.15 The soil water balance

        TKLT         = TKL1 + TKL2 + TKL3 + TKL4

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

```
      RNOFF        = MAX(0.,(ROFAC*(RAIN-ROTHR)))
PARAMETER ROFAC    = 0.10
PARAMETER ROTHR    = 2.1

      WLFL1        = MAX(0.,RAIN-AINTC-RNOFF)
      WLFL2        = MAX(0.,WLFL1-(WCFC1-WCL1)*TKL1)
      WLFL3        = MAX(0.,WLFL2-(WCFC2-WCL2)*TKL2)
      WLFL4        = MAX(0.,WLFL3-(WCFC3-WCL3)*TKL3)
      WLFL5        = MAX(0.,WLFL4-(WCFC4-WCL4)*TKL4)
PARAMETER WCFC1    = 0.26; WCFC2 = 0.26; WCFC3 = 0.34; WCFC4 = 0.32

      DRAIN        = MIN(DRATE,WLFL5)
      WLFL6        = INSW((DRATE-WLFL5),(WLFL5-DRATE),0.)
PARAMETER DRATE    = 12.

      WLFL7        = INSW((DRATE-WLFL5),MAX(0.,...
                     WLFL6-((WCST4-WCFC4)*TKL4)),0.)
      WLFL8        = INSW((DRATE-WLFL5),MAX(0.,...
                     WLFL7-((WCST3-WCFC3)*TKL3)),0.)
      WLFL9        = INSW((DRATE-WLFL5),MAX(0.,...
                     WLFL8-((WCST2-WCFC2)*TKL2)),0.)
      WLFL10       = INSW((DRATE-WLFL5),MAX(0.,...
                     WLFL9-((WCST1-WCFC1)*TKL1)),0.)
PARAMETER WCST1    = 0.40; WCST2 = 0.40; WCST3 = 0.38; WCST4 = 0.37

      DWL1         = WLFL1-WLFL2+WLFL9-WLFL10-EVSW1-TRWL1
      DWL2         = WLFL2-WLFL3+WLFL8-WLFL9-EVSW2-TRWL2
      DWL3         = WLFL3-WLFL4+WLFL7-WLFL8-EVSW3-TRWL3
      DWL4         = WLFL4-WLFL5+WLFL6-WLFL7-EVSW4-TRWL4

      WL1          = INTGRL(WL1I,DWL1)
      WL2          = INTGRL(WL2I,DWL2)
      WL3          = INTGRL(WL3I,DWL3)
      WL4          = INTGRL(WL4I,DWL4)

      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)

      TAINTC       = INTGRL(ZERO,AINTC)
      TDRAIN       = INTGRL(ZERO,DRAIN)
      TSTORE       = INTGRL(ZERO,WLFL10)
      TRNOFF       = INTGRL(ZERO,RNOFF)

      WCUM         = WL1+WL2+WL3+WL4
      CHKWTR       = TRAIN+WCUMI-TAINTC-TRNOFF-...
                     WCUM-TDRAIN-TATRAN-TAEVAP


* 2.16 Rooted depth

      ZRT          = INTGRL(ZRTI,EZRT)
```

```
      EZRT          = EZRTF*WSERT*REAAND(ZRTM-ZRT,1.0-DVS)*...
                      INSW(-DVS,1.,0.)
      CALL SUBGRT  (ZRT,TKL1,TKL2,TKL3,WCL1,WCL2,WCL3,WCL4,WCFC1,...
                      WCFC2,WCFC3,WCFC4,WCWP1,WCWP2,WCWP3,WCWP4,...
                      WSERT)
PARAMETER EZRTF     = 38.5

      ZRTM          = MIN(ZRTMC,ZRTMS,TKLT)
PARAMETER ZRTMS     = 1500.; ZRTMC = 1200.


* 2.17 Transpiration

      PTRANS        = (1.-EXP(-0.5*LAI)) * EVAPR + EVAPD * ...
                      MIN(2.5,LAI) - 0.5 * AINTC

FUNCTION EDPTFT     = -.50,0., -0.05,0., 0.0,0.15, 0.15,0.6, ...
                      0.30,0.8, 0.50,1., 2.0,1.
      ERLB          = ZRT1*AFGEN(EDPTFT,RWCL1)+...
                      ZRT2*AFGEN(EDPTFT,RWCL2)+...
                      ZRT3*AFGEN(EDPTFT,RWCL3)+...
                      ZRT4*AFGEN(EDPTFT,RWCL4)
      TRRM          = PTRANS/(ERLB+1.E-10)
      TRWL1         = TRRM*WSE1*ZRT1*AFGEN(EDPTFT,RWCL1)
      TRWL2         = TRRM*WSE2*ZRT2*AFGEN(EDPTFT,RWCL2)
      TRWL3         = TRRM*WSE3*ZRT3*AFGEN(EDPTFT,RWCL3)
      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

      TPTRAN        = INTGRL(ZERO,PTRANS)
      TATRAN        = INTGRL(ZERO,ATRANS)


* 2.18 Soil evaporation

      PEVAP         = EXP(-0.7*LAI) * (EVAPR + EVAPD)

INCON DSLRI         = 1.
      DSLR          = INSW(RAIN-0.5,1.,1.00001-NDSLR)/DELT
      NDSLR         = INTGRL(DSLRI,DSLR)

      AEVAP         = INSW(NDSLR-1.1,EVSH,EVSD)
      EVSH          = MIN(PEVAP,(WL1-WCAD1*TKL1)/DELT+WLFL1)
PARAMETER WCAD1     = 0.06
      EVSD          = MIN(PEVAP,0.6*PEVAP*(SQRT(NDSLR)-...
                      SQRT(NDSLR-1.))+WLFL1)

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

```
      FEVL4        = MAX(WL4-WCAD4*TKL4,0.1)*EXP(-EES*(TKL1+TKL2+...
                     TKL3+(0.25*TKL4)))
  PARAMETER EES    = 0.002
  PARAMETER WCAD2  = 0.06; WCAD3 = 0.09; WCAD4 = 0.09

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

      TPEVAP       = INTGRL(ZERO,PEVAP)
      TAEVAP       = INTGRL(ZERO,AEVAP)


* 2.19 Effect of water stress

      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  = 0.11; WCWP2 = 0.11; WCWP3 = 0.16; WCWP4 = 0.16

      PRODSF       = ATRANS/(PTRANS+1.E-10)
      PARTSF       = MIN(1.,0.5+ATRANS/(PTRANS+1.E-10))


* 2.20 Water use efficiency

      TAR          = TATRAN*1.E4/(TDTGA+1.E-10)
      TDTGA        = INTGRL(ZERO,DTGA)
      TRC          = TATRAN*1.E4/NOTNUL(TDRW)
      CROPF        = (PTRANS+PEVAP)/PENMAN


* 2.21 Carbon balance check

      CHKIN        = (WLV-WLVI)*CFLV+(WST-WSTI)*CFST+(WRT-WRTI)*...
                     CFRT+WCB*CFCB
      CHKCFL       = TNASS * (12./44.)
      TNASS        = INTGRL(TNASSI,GNASS)
      GNASS        = ((GPHOT-MAINT)*44./30.)-(GRT*CO2RT+GLV*CO2LV+...
                     (GST+TRANSL)*CO2ST+GCB*CO2CB+(1.-CONVF)*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)
      CO2CB        = 44./12.*(ASRQCB*12./30.-CFCB)

      CHKCRB       = (CHKIN-CHKCFL)/(NOTNUL(CHKIN))

  PARAMETER CFLV=0.459; CFST=0.494; CFRT=0.467; CFCB=0.491
```

```
* 2.22 Run control

         DAYEM        = STTIME + EMPER
   PARAMETER EMPER    = 6.
         DAE          = MAX(0.,TIME-DAYEM)
         DAP          = TIME - STTIME

   FINISH CHKCRB      > 1.E-6
   FINISH CHKWTR      > 1.E-3
   FINISH DVS         > 2.

   TIMER STTIME       = 303.; FINTIM = 500.; DELT=1.; PRDEL=1.

   WEATHER WTRDIR='C:\SYS\WEATHER\';CNTR='KENYA';ISTN=2;IYEAR=1993

   TRANSLATION_FSE

   PRINT DVS,DAE,CROPF,TRC,TAR,TRAIN,WGRAIN,...
         DAYL,HI,TPTRAN,TPEVAP,TEVAPD,TEVAPR,TSTORE

END
STOP
ENDJOB
```

2.24 Listing of MAIZE2 subroutines

```
*----------------------------------------------------------------------*
*  SUBROUTINE ASTRO                                                    *
*  Purpose: This subroutine calculates astronomic day length,         *
*           diurnal radiation characteristics such as the daily       *
*           integral of sine of solar elevation and solar constant.   *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)    *
*  name    type meaning                                    units  class *
*  ----    ---- -------                                    -----  ----- *
*  DOY     R4  Daynumber (Jan 1st = 1)                       -      T  *
*  LAT     R4  Latitude of the site                       degrees   I  *
*  SC      R4  Solar constant                             J m-2 s-1 O  *
*  DS0     R4  Daily extraterrestrial radiation           J m-2 d-1 O  *
*  SINLD   R4  Seasonal offset of sine of solar height       -      O  *
*  COSLD   R4  Amplitude of sine of solar height             -      O  *
*  DAYL    R4  Astronomic daylength (base = 0 degrees)       h      O  *
*  DSINB   R4  Daily total of sine of solar height           s      O  *
*  DSINBE  R4  Daily total of effective solar height         s      O  *
*                                                                      *
*  FATAL ERROR CHECKS (execution terminated, message)                 *
*  condition: LAT > 67, LAT < -67                                      *
*----------------------------------------------------------------------*

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

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

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

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

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

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

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

      DSINB  = 3600.*(DAYL*SINLD+24.*COSLD*SQRT (1.-AOB*AOB)/PI)
      DSINBE = 3600.*(DAYL*(SINLD+0.4*(SINLD*SINLD+COSLD*COSLD*0.5))+
     &         12.0*COSLD*(2.0+3.0*0.4*SINLD)*SQRT (1.-AOB*AOB)/PI)

*-----solar constant (SC) and daily extraterrestrial radiation (DS0)
      SC  = 1370.*(1.+0.033*COS (2.*PI*DOY/365.))
      DS0 = SC*DSINB
```

```
      RETURN
      END


*----------------------------------------------------------------------*
*  SUBROUTINE TOTASS                                                   *
*  Purpose: This subroutine calculates daily total gross               *
*           assimilation (DTGA) by performing a Gaussian integration   *
*           over time. At three different times of the day,            *
*           radiation is computed and used to determine assimilation   *
*           whereafter integration takes place.                        *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name    type meaning                                   units  class *
*  ----    ---- -------                                   -----  ----- *
*  DOY      R4  Day number (January 1 = 1)                  -      T   *
*  LAT      R4  Latitude of the site                      degrees  I   *
*  DTR      R4  Daily total of global radiation           J/m2/d   I   *
*  SCP      R4  Scattering coefficient of leaves for visible           *
*               radiation (PAR)                              -     I   *
*  AMAX     R4  Assimilation rate at light saturation      kg CO2/ I   *
*                                                         ha leaf/h    *
*  EFF      R4  Initial light conversion factor           kg CO2/J/ I  *
*                                                         ha/h m2 s    *
*  KDF      R4  Extinction coefficient for diffuse light     -     I   *
*  LAI      R4  Leaf area index as used for photosynthesis  ha/ha  I   *
*               Note: This can involve stem, flower or                 *
*                     ear area index!!                                 *
*  DAYL     R4  Astronomic daylength (base = 0 degrees)       h     O  *
*  DTGA     R4  Daily total gross assimilation          kg CO2/ha/d O  *
*  DS0      R4  Daily extraterrestrial radiation            J/m2/s  O  *
*                                                                      *
*                                                                      *
*  SUBROUTINES and FUNCTIONS called : ASTRO, ASSIM                     *
*----------------------------------------------------------------------*

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

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

      PI   = 3.141592654

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

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

      DO 10 I1=1,IGAUSS

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

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

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

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

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

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

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

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

10    CONTINUE

      DTGA = DTGA * DAYL

      RETURN
      END


*----------------------------------------------------------------------*
*  SUBROUTINE ASSIM                                                    *
*  Purpose: This subroutine performs a Gaussian integration over       *
*           depth of canopy by selecting five different LAI's and      *
*           computing assimilation at these LAI levels. The            *
*           integrated variable is FGROS.                              *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                  units  class *
*  ----   ---- -------                                  -----  ----- *
*  SCP     R4  Scattering coefficient of leaves for visible            *
*              radiation (PAR)                            -       I   *
*  AMAX    R4  Assimilation rate at light saturation     kg CO2/  I   *
*                                                       ha leaf/h     *
*  EFF     R4  Initial light conversion factor           kg CO2/J/ I   *
*                                                       ha/h m2 s     *
*  KDF     R4  Extinction coefficient for diffuse light           I   *
*  LAI     R4  Leaf area index as used for photosynthesis  ha/ha  I   *
*              Note: This can involve stem, flower or                  *
*                    ear area index!!                                  *
*  SINB    R4  Sine of solar height                        -      I   *
*  PARDR   R4  Instantaneous flux of direct radiation (PAR) W/m2  I   *
*  PARDF   R4  Instantaneous flux of diffuse radiation(PAR) W/m2  I   *
```

```
*  FGROS   R4  Instantaneous assimilation rate of          kg CO2/  0  *
*              whole canopy                               ha soil/h    *
*                                                                      *
*----------------------------------------------------------------------*

      SUBROUTINE ASSIM (SCP, AMAX, EFF, KDF, LAI, SINB, PARDR, PARDF,
     &                  FGROS)
      IMPLICIT REAL(A-Z)
      REAL XGAUSS(5), WGAUSS(5)
      INTEGER I1, I2, IGAUSS

*-----Gauss weights for five point Gauss
      DATA IGAUSS /5/
      DATA XGAUSS /0.0469101,0.2307534,0.5      ,0.7692465,0.9530899/
      DATA WGAUSS /0.1184635,0.2393144,0.2844444,0.2393144,0.1184635/
*-----reflection of horizontal and spherical leaf angle distribution
      SQV  = SQRT(1.-SCP)
      REFH = (1.-SQV)/(1.+SQV)
      REFS = REFH*2./(1.+2.*SINB)

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

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

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

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

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

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

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

```
            FGRSUN = FGRSUN + FGRS * WGAUSS(I2)
20       CONTINUE

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

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

10    CONTINUE
      FGROS = FGROS * LAI

      RETURN
      END


*----------------------------------------------------------------------*
* Subroutine SUBGRT                                                    *
* Purpose: To calculate the water stress effect on root growth         *
*          (value between 1 and 0)                                     *
*----------------------------------------------------------------------*

      SUBROUTINE SUBGRT(ZRT,TKL1,TKL2,TKL3,WCL1,WCL2,WCL3,WCL4,WCFC1,
     $                  WCFC2,WCFC3,WCFC4,WCWP1,WCWP2,WCWP3,WCWP4,
     $                  WSERT)
      IMPLICIT REAL(A-Z)
      SAVE

      IF (ZRT.LE.TKL1) THEN
          IF (WCL1.LT.WCWP1) THEN
              WSERT = 0.
          ELSEIF (WCL1.GE.WCWP1 .AND. WCL1.LE.WCFC1) THEN
              WSERT = (WCL1-WCWP1)/(WCFC1-WCWP1)
          ELSE
              WSERT = 1.
          ENDIF
      ELSEIF (ZRT.GT.TKL1 .AND. ZRT.LE.(TKL1+TKL2)) THEN
          IF (WCL2.LT.WCWP2) THEN
              WSERT = 0.
          ELSEIF (WCL2.GE.WCWP2 .AND. WCL2.LE.WCFC2) THEN
              WSERT = (WCL2-WCWP2)/(WCFC2-WCWP2)
          ELSE
              WSERT = 1.
          ENDIF
      ELSEIF (ZRT.GT.(TKL1+TKL2) .AND. ZRT.LE.(TKL1+TKL2+TKL3)) THEN
          IF (WCL3.LT.WCWP3) THEN
              WSERT = 0.
          ELSEIF (WCL3.GE.WCWP3 .AND. WCL3.LE.WCFC3) THEN
              WSERT = (WCL3-WCWP3)/(WCFC3-WCWP3)
          ELSE
              WSERT = 1.
          ENDIF
      ELSE
          IF (WCL4.LT.WCWP4) THEN
              WSERT = 0.
```

3 Some applications of the MAIZE1 and MAIZE2 models

3.1 Example of a MAIZE1 application

MAIZE1 simulates the maize production in a stress-free environment. An example of such an environment is a well-fertilized irrigated field, kept free from weeds, pests and diseases. Theoretically, the potential production is achieved in this environment.

3.1.1 Potential production of maize in relation to planting date

There are two environmental factors that influence the potential production: radiation and temperature (Chapter 1.1). In the hills of Machakos there is a distinct drop in radiation and temperature in the middle of the year, due to an overcast sky. This period is locally called the cold dry season. Planting maize in this period will have a distinct negative effect on the production. MAIZE1 can be used to explore the potential production for any planting date (Fig. 3.1).

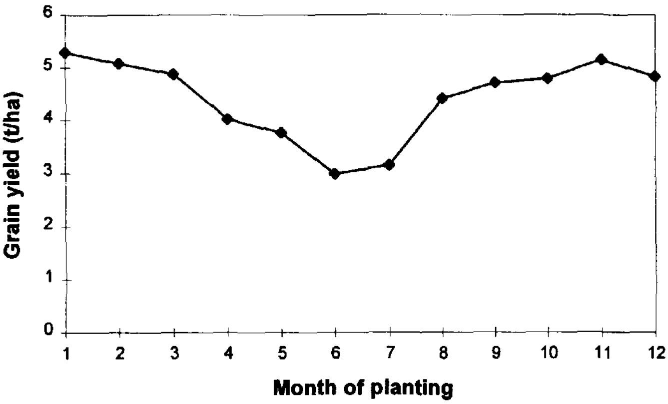

Fig. 3.1 *The potential maize production in Machakos in relation to planting date, at the first day of each month.*

The maize cultivar that was used for this study (Katumani Composite B) matures within 120 days after planting. However, when temperatures are less than usual it may even take 140 days. In the first case, planting three crops per year can be considered, while in the latter case only two crops can be planted.

Considering the option of planting two crops per year, the optimal planting dates will be in February-March for the first crop and in August-September for the second crop. If the crop matures within 120 days, planting three crops per year can be considered. The optimal planting dates will then be in April, August and December. However, the use of simulation models provides the opportunity to explore many more options. More complicated planting schemes, like the optimum planting dates for growing five crops in at two year time span, can be calculated with little difficulty.

3.2 Examples of MAIZE2 applications

MAIZE2 simulates the maize production under rainfed conditions. MAIZE2 offers a wealth of possible analyses. Two of them will be shown here, i.e. the effect of water availability on planting density and the effect of runoff on crop yield.

3.2.1 Effect of planting density on crop yield

The effect of planting density on crop yield is closely related to plant available water and will, therefore, vary from season to season. Individual plants are sharing limited water resources, which leads to a crash in crop production when the planting density is too high (Fig. 3.2).

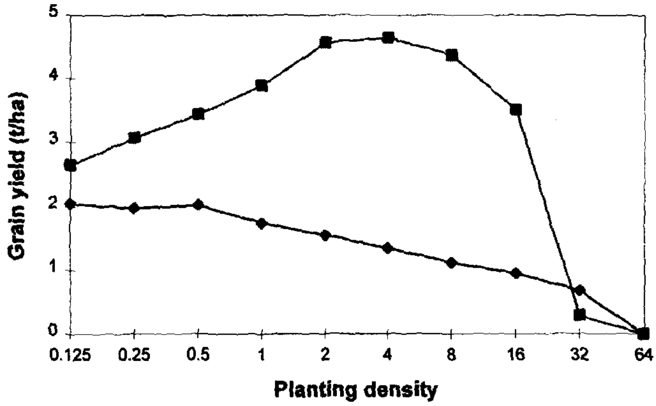

Fig. 3.2 *The effect of planting density (plants m^{-2}) on crop yield (t ha^{-1}) in a season with abundant rainfall (■) and a season with low rainfall (◆).*

In a season with abundant rainfall the optimal planting density will be around 4 plants m^{-2}, which coincides with the national recommendations of 3.7 plants m^{-2} for this particular maize cultivar (Katumani Composite B) in this particular environment (Machakos District). In a season with low rainfall the optimal density is much lower, 0.5 plants m^{-2} or less. As a consequence, farmers may be recommended to plant at a density of 3.7 plants m^{-2} or higher and, if the rainfall is less than optimal, start thinning. This strategy was advocated by Stewart and Hash (1982) for the Machakos area. The planting density and the fertilizer application rate should be adjusted to the rainfall predictions in the course of the season. This way it is possible to boost crop production in a good season and to avoid total crop failure and fertilizer losses in seasons with low rainfall.

3.2.2 Effect of runoff on crop yield

The effect of a diminishing amount of water entering the soil will also lead to less water per individual plant and, subsequently, to a decrease in production (Fig. 3.3). The negative effects of surface runoff on crop yield and, consequently, the positive effects of water conservation on crop yield can be simulated with MAIZE2. The simulation results can subsequently be used in a feasibility study of the application of water conservation technologies like e.g. conservation tillage or water harvesting.

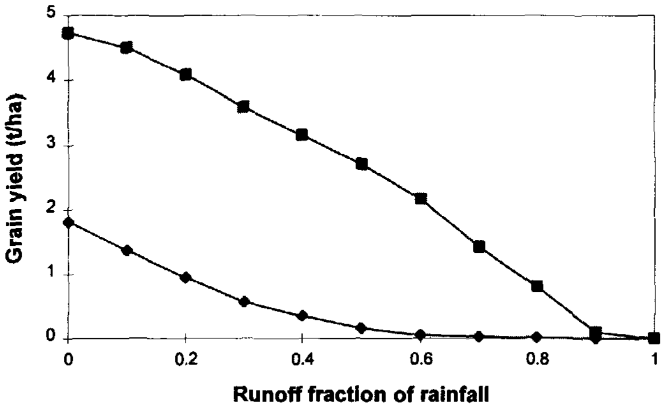

Fig 3.3 *The effect of an increasing amount of runoff, given the same rainfall, on crop production in a season with abundant rainfall (■) and a season with low rainfall (◆).*

Similar to the example of increasing planting density above, the effect of runoff on the attainable crop production is closely related to the rainfall amount (and distribution) per season (Fig. 3.3). It can vary enormously. It is, therefore, recommended to run as many simulations as possible, i.e. for many different rainfall patterns, in order to get a sharp picture of the possible effects in various seasons. The rerun facility of the FST program (Rappoldt & Van Kraalingen, 1996) makes it very easy to run simulations for a number of occasions.

3.3 Example of a combined MAIZE1 and MAIZE2 application

3.3.1 Yield gap analysis

The analysis of a difference in crop yield that is due to technical or environmental constraints is called yield gap analysis. Yield gap analyses can be applied to all kinds of causes of yield differences. For instance, a yield gap exists between on-station and on-farm yields. It can be caused by a lack of transfer of knowledge and technologies, or a difference in the input of resources on-station, human as well as material resources, or both. Furthermore, there exists a yield gap between potential and attainable yield, which is due to water constraints, as well as a yield gap between attainable and actual yield, which is due to the occurrence of weeds, pests and diseases and plant nutrient constraints (Rabbinge & Van Ittersum, 1994).

The yield gap between potential and attainable yield can be analysed with the help of both MAIZE1 and MAIZE2. First, MAIZE1 is executed to calculate the potential production. Then MAIZE2 is executed, using the same weather file and the same starting date (STTIME), to calculate the attainable production. Analysis of the yield gap of crop production in a season with abundant rainfall shows a period when the attainable production is virtually equal to the potential production (Fig. 3.4). If the crop is planted at the right time, in this case from day 310 until day 345, and with ample fertilizer a bumper harvest will be the result.

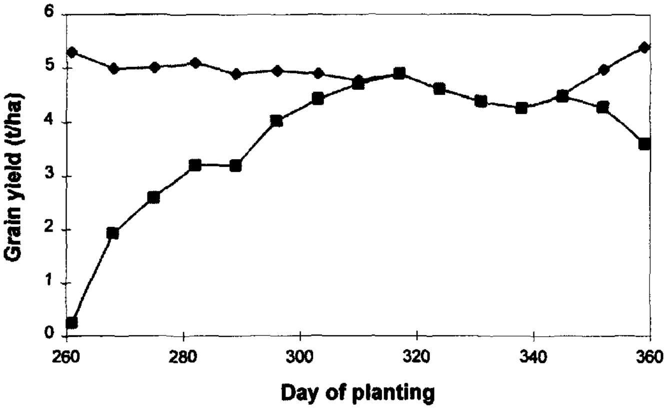

Fig 3.4 *Yield gap between potential production (■) and attainable production (◆) in a season with abundant rainfall.*

Yield gap analysis of crop production in a season with low rainfall will show quite a different situation. Without supplementary irrigation, the attainable yield will never reach the level of potential production (Fig. 3.5).

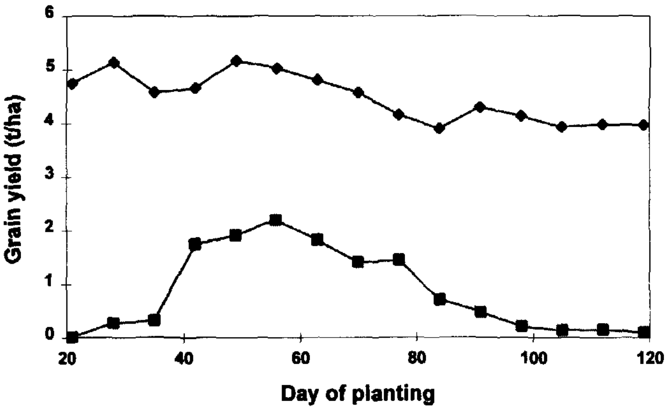

Fig 3.5 *Yield gap between potential production (■) and attainable production (◆) in a season with low rainfall.*

The most favourable planting date of this season is day 56 (Fig. 3.5), although the yield will only be forty percent of the potential yield. The simulation run that started on day 56 (STTIME = 56.) will reveal the periods of water constraints in the output file. This information can be used for the optimum timing of supplementary irrigation.

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Glossary

Definitions of the abbreviations used in MAIZE1 and MAIZE2

Name	Description	Units
AEVAP	Actual soil evaporation rate	mm d^{-1}
AFGEN	FST function for linear interpolation	-
AINTC	Actual amount of rain intercepted by the canopy	mm d^{-1}
ALB	Albedo; refection coefficient for short-wave radiation	-
ALBS	Albedo; refection coefficient for soil surface	-
AMAX	Leaf CO_2 assimilation rate	kg CO_2 ha^{-1} leaf h^{-1}
AMDVS	Factor accounting for aging of leaves	-
AMDVT	Table of AMDVS as a function of DVS	-,-
AMX	Potential leaf CO_2 assimilation rate at light saturation	kg CO_2 ha^{-1} leaf h^{-1}
ANGSTA	Parameter A in the Angstrom formula	-
ANGSTB	Parameter B in the Angstrom formula	-
ASRQ	Assimilate (CH_2O) requirement for dry matter production	kg CH_2O kg^{-1} DM
ASRQCB	Assimilate requirement for cob dry matter production	kg CH_2O kg^{-1} DM
ASRQLV	Assimilate requirement for leaf dry matter production	kg CH_2O kg^{-1} DM
ASRQRT	Assimilate requirement for root dry matter production	kg CH_2O kg^{-1} DM
ASRQST	Assimilate requirement for stem dry matter production	kg CH_2O kg^{-1} DM
ASSIM	FORTRAN subroutine that computes assimilation	-
ASTRO	FORTRAN subroutine that computes diurnal radiation	-
ATRANS	Total actual transpiration rate of the canopy	mm d^{-1}
BOLTZM	Boltzmann constant	J m^2 d^{-1} $^{o}K^{-4}$
C1	Threshold value of DVS used in DLV computation	-
C2	Threshold value of DVS used in DLV computation	-
CALL	FST command to activate a subroutine	-
CFCB	Mass fraction carbon in the cob	kg C kg^{-1} DM
CFLV	Mass fraction carbon in the leaves	kg C kg^{-1} DM
CFRT	Mass fraction carbon in the roots	kg C kg^{-1} DM
CFST	Mass fraction carbon in the stem	kg C kg^{-1} DM
CHKCFL	Sum of integrated carbon fluxes into and out of the crop	kg C ha^{-1}
CHKCRB	Carbon balance check	kg C ha^{-1}
CHKIN	Carbon in the crop accumulated from the start	kg C ha^{-1}
CHKWTR	Sum of integrated water fluxes into and out of the soil	mm d^{-1}
CLEAR	Penman's original clearness factor	-
CNTR	FST statement to address the country	-
CO2CB	CO_2 production factor for growth of cobs	kg CO_2 kg^{-1} DM
CO2LV	CO_2 production factor for growth of leaves	kg CO_2 kg^{-1} DM
CO2RT	CO_2 production factor for growth of roots	kg CO_2 kg^{-1} DM
CO2ST	CO_2 production factor for growth of stems	kg CO_2 kg^{-1} DM
CONSTANT	FST statement for a constant value	-
CONVF	Conversion factor	-
CROPF	Crop factor for crop water requirement	-
DAE	Number of days after emergence	d
DAP	Number of days after planting	d
DAVTMP	Daily average temperature	°C
DAYEM	Day of emergence	d
DDTMP	Daytime temperature	°C
DECLARATIONS	FST statement listing all subroutines that will be called	-
DEFINE_CALL	FST statement of a particular subroutine that will be called	-

DELT	Time steps of integration	d
DELTA	Tangent between saturated vapour pressure and temperature	kPa °C^{-1}
DLV	Dying-back rate of leaves	kg ha^{-1} d^{-1}
DOY	Day of year	d
DRAIN	Drainage rate below the root zone	mm d^{-1}
DRATE	Maximum drainage rate	mm d^{-1}
DRES	Rate of depletion of reserves	kg CO_2 ha^{-1} d^{-1}
DRYP	Drying power term in the Penman equation	J kPa^{-1}
DS0	Extra-terrestrial radiation or Angot value	J m^{-2} d^{-1}
DSLR	Days since the last rainy day	d
DSLRI	First day since the last rainy day	d
DTEFAE	Daily effective temperature after emergence	°C
DTEFF	Daily effective temperature	°C
DTGA	Daily total gross CO2 assimilation of the crop	kg CO_2 ha^{-1} leaf h^{-1}
DTR	Incoming short wave radiation	J m^{-2} d^{-1}
DVR	Development rate of the crop	d^{-1}
DVRR	Table of DVR in pre-anthesis phase as function of DDTMP	-,-
DVRV	Table of DVR in post-anthesis phase as function of DDTMP	-,-
DVS	Development stage of the crop	-
DWL1-4	Fluctuation of amount of water in layer 1-4	mm d^{-1}
DYNAMIC	FST statement that starts of the dynamic part of the model	-
EDPTFT	Table of the root activity coefficient	-,-
EES	Soil-specific extinction coefficient	mm^{-1}
EFF	Initial light-use efficiency for individual leaves	-
EMERG	Development phase of crop between planting and emergence	-
EMPER	Period between sowing and emergence	d
END	FORTRAN statement indicating the end of the model	-
ENDJOB	FORTRAN statement indicating the end of the simulation	-
ERLB	Cumulative effective root length	mm
EVAPD	Potential soil evaporation due to drying power of the air	mm d^{-1}
EVAPR	Potential soil evaporation due to radiation	mm d^{-1}
EVSD	Evaporation rate on days without rain	mm d^{-1}
EVSH	Evaporation rate on rainy days	mm d^{-1}
EVSW1-4	Rate of soil evaporation	mm d^{-1}
EXP	FORTRAN statement that indicates an exponential function	-
EZRT	Rate of root elongation	mm d^{-1}
EZRTF	Constant for root elongation	mm d^{-1}
FCB	Fraction of dry matter allocated to cobs	-
FCH	Fraction of dry matter allocated to chaff	-
FCHTB	Table of FCH as a function of DVS	-,-
FCLEAR	Sky clearness function of the net long-wave radiation	-
FEEDB	Feedback factor in assimilation when reserves are formed	-
FEVL1-4	Distribution factors for soil water extraction of layer 1-4	-
FEVLT	Sum of distribution factors 1-4	-
FINISH	FST statement stops the simulation at a preset condition	-
FINTIM	FST statement stops the simulation at a preset day	-
FLV	Fraction of dry matter allocated to leaves	-
FLVTB	Table of FLV as a function of DVS	-,-
FRES	Fraction of dry matter allocated to reserves	-
FRT	Fraction of dry matter allocated to roots	-
FRTRL	*Fraction of stem weight translocated to storage organs*	-
FSC	Fraction of dry matter allocated to stems and cobs	-
FSH	Fraction of dry matter allocated to shoots	-
FSHP	Potential fraction of dry matter allocated to shoots	-
FSHTB	Table of FSH as a function of DVS	-,-
FST	Fraction of dry matter allocated to stems	-

FSTTB	Table of FST as a function of DVS	-,-
FTEMP	Temperature effect on RLWN (Bolzmann equation)	-
FUNCTION	FST-statement indicating a functional relationship	-
FVAP	Vapour pressure effect on RLWN (Brunt equation)	-
GCB	Growth rate of cobs	kg DM ha^{-1} d^{-1}
GCH	Growth rate of chaff	kg DM ha^{-1} d^{-1}
Genotype	The cultivar specification of the crop	-
GFD16	Duration of grain filling period	d
GGR	Growth rate of grains	kg DM ha^{-1} d^{-1}
GLAI	Growth rate of LAI	ha ha^{-1} d^{-1}
GLAJ	Growth rate of LAI in juvenile stage	ha ha^{-1} d^{-1}
GLAM	Growth rate of LAI in mature stage	ha ha^{-1} d^{-1}
GLV	Growth rate of leaves	kg DM ha^{-1} d^{-1}
GNASS	Net carbon assimilation rate	kg C ha^{-1} d^{-1}
GNGRN	Increase in the number of grains	m^{-2}
GPHOT	Rate of carbohydrate production	kg CO$_2$ ha^{-1} d^{-1}
GRDVS	Factor describing grain growth	-
GRDVST	Table of GRDVS as a function of DVS	-,-
GRES	Gross growth rate of reserves	kg DM ha^{-1} d^{-1}
GRSINK	Sink-determined growth rate of grains	kg DM ha^{-1} d^{-1}
GRSOUR	Source-determined growth rate of grains	kg DM ha^{-1} d^{-1}
GRT	Growth rate of roots	kg DM ha^{-1} d^{-1}
GRTMP	The effect of temperature on GRSINK	-
GRTMPT	Table of GRTMP as a function of DAVTMP	-,-
GST	Growth rate of stems	kg DM ha^{-1} d^{-1}
GTW	Gross growth rate of crop dry matter (incl. translocation)	kg DM ha^{-1} d^{-1}
GWLVG	Growth rate of green leaves	kg DM ha^{-1} d^{-1}
GWRES	Net growth rate of reserves	kg DM ha^{-1} d^{-1}
INCON	FST statement for the initial value of a parameter	-
INITIAL	FST statement regulating the initialization of the model	-
INPUT	FST statement designating input parameters in a subroutine	-
INSW	FST function (Y=Y1 if X<0, Y=Y2 if X>0)	-
INTC	Interception capacity of rain by the crop canopy	mm d^{-1}
INTGRL	FST function for integration	-
ISTN	FST statement for the meteorological station number	-
IYEAR	FST statement for the year the simulation starts	-
KDF	Extinction coefficient for leaves	m m^{-1}
LAI	Leaf area index	m m^{-1}
LAIE	Leaf area index at emergence	m m^{-1}
LA0	Initial leaf area index	m^2 plant^{-1}
LAT	Latitude of the site	°
LHVAP	Latent heat of water evaporation	J kg^{-1}
Location	Name of place and country of the site	-
MAINCB	Maintenance respiration coefficient of cobs	kg CO$_2$ kg^{-1} DM
MAINLV	Maintenance respiration coefficient of leaves	kg CO$_2$ kg^{-1} DM
MAINRT	Maintenance respiration coefficient of roots	kg CO$_2$ kg^{-1} DM
MAINST	Maintenance respiration coefficient of stems	kg CO$_2$ kg^{-1} DM
MAINT	Maintenance respiration of the crop	kg CO$_2$ ha^{-1} d^{-1}
MAINTS	Maintenance respiration at reference temperature	kg CO$_2$ ha^{-1} d^{-1}
MAX	FST function taking the maximum of the arguments	-
MIN	FST function taking the minimum of the arguments	-
MNDVS	Factor for the effect of DVS on maintenance respiration	-
MODEL	FST statement indicating the start of the model	-

NDSLR	Total number of days since the last rainy days	d
NGA	Parameter in computation of NGRAIN	-
NGB	Parameter in computation of NGRAIN	-
NGRAIN	Number of maize grains	m^{-2}
NOTNUL	FST-function to avoid division by zero	-
NPL	Number of plants	plants m^{-2}
NRAD	Net radiation	$J\ m^2\ d^{-1}$
OLVDF	Die-back factor for old leaves	-
OUTPUT	FST statement designating output parameters in a subroutine	-
P	Soil water depletion factor	-
PARAMETER	FST-statement for a parameter value	-
PARTSF	Stress factor that influences the carbohydrate allocation	-
PENMAN	Penman's reference value for potential evapotranspiration	mm d^{-1}
PEVAP	Potential soil evaporation	mm d^{-1}
PGRI	Potential growth rate of grains	mg DM $grain^{-1}\ d^{-1}$
PKRWT	Maximum kernel weight	mg DM $grain^{-1}$
PRDEL	FST statement indicating the printed time interval	-
PRINT	FST statement indicating variables that will be printed	-
PRODSF	Stress factor that reduces the carbohydrate production	-
PTRANS	Potential transpiration as derived from the Penman equation	mm d^{-1}
PSYCH	Psychrometric instrument coefficient	kPa $^{o}C^{-1}$
Q10	Temperature dependency of maintenance respiration	-
RDD	Global radiation	$J\ m^{-2}\ d^{-1}$
RDFRL	Reduction factor for assimilation when reserves are present	-
RDR	Relative death rate of leaves	d^{-1}
REAAND	FST function: y=1 if both x1=0 and x2=0, otherwise y=0	-
RESL	Fraction of reserves/weight of stem	-
RESLMX	Maximum allowable RESL	-
RGRL	Relative growth rate of leaf area during exponential growth	$^{o}C^{-1}\ d^{-1}$
RLWN	Net long-wave radiation	$J\ m^{-2}\ d^{-1}$
RNOFF	Runoff	mm d^{-1}
ROFAC	Runoff factor	-
ROTHR	Runoff threshold	mm d^{-1}
RWCL1-4	Reduced volumetric water content in soil layer 1-4	-
SCP	Parameter in subroutine TOTASS	-
SLA	Specific leaf area	ha kg^{-1}
STOP	FORTRAN statement terminating the simulation run	-
STTIME	FST statement indicating the starting time of simulation	-
SUBFR	FORTRAN subroutine that computes stress on water uptake	-
SUBGRT	FORTRAN subroutine that computes stress on root growth	-
SVP	Saturated vapour pressure	kPa
TADRW	Total above-ground biomass	kg DM ha^{-1}
TAEVAP	Total actual soil evaporation	mm d^{-1}
TAINTC	Total amount of rain intercepted by the canopy	mm d^{-1}
TAR	Transpiration/assimilation ration	kg H_2O kg^{-1} CO_2
TATRAN	Total actual amount transpired by the crop	mm
TBASE	Base temperature for juvenile leaf area growth	^{o}C
TC	Time constant in utilization of reserves	d^{-1}
TDRAIN	Total amount drained from the profile	mm
TDRW	Total biomass	kg DM ha^{-1}
TDTGA	Total gross CO_2 assimilation of the crop	kg CO_2 ha^{-1}
TEFF	Temperature effect on maintenance respiration	-

TEVAPD	Total potential soil evaporation due to the drying power	mm
TEVAPR	Total potential soil evaporation due to radiation	mm
TIMER	FST statement that controls the time specifications	-
TITLE	FST statement indicating the title of the program	-
TKL1-4	Thickness of soil layer 1-4	mm
TKLT	Total thickness of the entire profile considered	mm
TLAI	Total leaf area index (including dead leaves)	$m\ m^{-1}$
TMMN	Daily minimum temperature	°C
TMMX	Daily maximum temperature	°C
TNASS	Cumulative net carbon assimilation	$kg\ CO_2\ ha^{-1}$
TNASSI	Initial cumulative net carbon assimilation	$kg\ CO_2\ ha^{-1}$
TOTASS	FORTRAN subroutine that computes the daily assimilation	-
TPEVAP	Total potential evaporation from the soil	mm
TPTRAN	Total potential transpiration	mm
TRAIN	Total rainfall	mm
TRANSC	Characteristic potential transpiration rate	$mm\ d^{-1}$
TRANSL	Translocation rate of stem dry matter to storage organs	$kg\ DM\ ha^{-1}\ d^{-1}$
TRANSLATION	FST statement indicating the type of computation to be used	-
TRC	Transpiration coefficient	$kg\ H_2O\ kg^{-1}\ DM$
TREF	Reference temperature	°C
TRNOFF	Total runoff	mm
TRRM	Potential uptake rate per mm effective rooted depth	$mm\ d^{-1}$
TRWL1-4	Transpiration rate from soil layer 1-4	$mm\ d^{-1}$
TSTORE	Total surface storage due to water logging	mm
TSUMAE	Cumulative temperature sum above TBASE after emergence	d °C
VP	Actual vapour pressure	kPa
WCAD1-4	Volumetric water content when soil layer 1-4 is air dry	-
WCB	Weight of cobs	-
WCCR	Critical volumetric water content	-
WCFC1-4	Volumetric water content when layer 1-4 at field capacity	-
WCH	Weight of chaff	$kg\ DM\ ha^{-1}$
WCL1-4	Volumetric water content of soil layer 1-4	-
WCL1-4I	Initial volumetric water content of soil layer 1-4	-
WCST1-4	Volumetric water content when soil layer 1-4 is saturated	-
WCUM	Total amount of water in the soil profile	mm
WCUMI	Total initial amount of water in the soil profile	mm
WCWET1-4	Volumetric water content where water logging starts	-
WCWP1-4	Volumetric water content of layer 1-4 at wilting point	-
WDF	Wind function	$mm\ d^{-1}\ kPa^{-1}$
WEATHER	FST statement with details about the weather files	-
WGRAIN	Weight of grains	$kg\ DM\ ha^{-1}$
WL1-4	Amount of water in soil layer 1-4	mm
WL1-4I	Initial amount of water in soil layer 1-4	mm
WLFL1-10	Water fluxes into and out of soil layer 1-4	$mm\ d^{-1}$
WLV	Weight of leaves	$kg\ DM\ ha^{-1}$
WLVD	Weight of dead leaves	$kg\ DM\ ha^{-1}$
WLVG	Weight of green leaves	$kg\ DM\ ha^{-1}$
WLVI	Initial weight of leaves	$kg\ DM\ ha^{-1}$
WN	Average wind speed	$m\ s^{-1}$
WRES	Weight of reserves	$kg\ CH_2O\ ha^{-1}$
WRT	Weight of roots	$kg\ DM\ ha^{-1}$
WRTI	Initial root weight	$kg\ DM\ ha^{-1}$
WSE1-4	Factor for uptake availability of soil water	-
WSERT	Auxiliary variable to calculate root extension	-
WST	Weight of stems	$kg\ DM\ ha^{-1}$

WSTI	Initial stem weight	kg DM ha^{-1}
WTRDIR	FST statement showing the path to the weather files	-
ZRT	Rooted depth	mm
ZRT1-4	Thickness of rooted layer	mm
ZRTI	Initial value for rooted depth	mm
ZRTM	Maximum value for rooted depth	mm
ZRTMC	Maximum rooted depth due to crop characteristics	mm
ZRTMS	Maximum rooted depth due to soil properties	mm

List of previous publications/Ont déjà paru dans cette série:

No. 1 L'Agroforesterie au Burkina Faso; bilan et analyse de la situation actuelle. J.J. Kessler et J. Boni, Ouagadougou, 1991, 144 p.
No. 2 Aspects de l'Aménagement Intégré des Ressources Naturelles au Sahel. E. Bognetteau-Verlinden, S. van der Graaf et J.J. Kessler, Wageningen, 1992, 104 p.
No. 3 Perspectives pour le Développement Soutenu des Systèmes de Production Agrosylvopastorale au Sanmatenga, Burkina Faso. R. van der Hoek, A. Groot, F. Hottinga, J.J. Kessler et H. Peters, Wageningen, 1993, 73 p.
No. 4 Le Système d'Elevage Peulh dans le Sud du Burkina Faso: une étude agro-écologique du département de Tô (Province de la Sissili). W.F. de Boer et J.J. Kessler, Wageningen, 1994, 106 p.
No. 5 L'Aménagement des terroirs villageois: une contribution à la gestion durable des ressources naturelles. Une étude de cas du projet Reboisement Rive Droite Téra, Niger. J. van den Briel, P. Schuthof et E. Topper, Wageningen, 1994, 114 p.
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No. 7 La régénération de l'espace sylvo-pastoral au Sahel: Une étude de mesures de conservation des eaux et des sols au Burkina Faso. F.G. Hien, Wageningen, 1995, 223 p.
No. 8 Choix et modalités d'exécution des mesures de conservation des eaux et des sols au Sahel. C.A. Kessler, W.P. Spaan, W.F. van Driel et L. Stroosnijder, Wageningen, 1995, 94 p.
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No. 17 A Participatory Agroforestry Approach for Soil and Water Conservation in Ethiopia. A. Bekele-Tesemma, Wageningen, 1997, 229 p.
No. 18 Conservation and utilization of natural resources in the East Usambara Forest reserves, conventional views and local perspectives. J.F. Kessy, Wageningen, 1998, 168 p.

Abstract

This book is written for students and researchers with a keen interest in the quantification of the field soil water balance in tropical environments and the effect of conservation farming on crop production. Part 1 of this book deals with the potential production, i.e. crop growth under ample supply of water and nutrients in a pest, desease and weed free environment. Part 2 deals with crop production under rainfed or water-limited conditions by including the crop water balance as well as the soil water balance. Both models use maize as example. The way the MAIZE models are presented differs from the modular structure of present day models, where separate data blocks for soil, crop and climate are added at the end of a main program. Here, the explanatory text follows as closely as possible the computer listing of the model. Each chapter starts with a number of lines that was copied from the listing. Subsequently, the terminology is justified and the input data and dimensions of variables are explained. Another special feature is the fact that parameter and function values are defined directly after the line where they are used for the first time. This method highlights the places where the model needs input from the user. In this way it is stressed that the accuracy of the model depends on the availability and quality of the input data, next to the correct understanding and description of the processes involved. The third part of this book contains a number of applications.

Résumé

Ce livre est destiné aux étudiants et aux chercheurs qui ont un intérêt ardent pour la quantification du bilan d'eau du sol au champ dans les milieux tropicaux et de l'effet des mesures de conservation sur la production agricole. La première partie de ce livre traite de la production potentielle, i.e. la croissance des cultures dans les conditions où il y a amplement de l'eau et des nutriments dans un environnement sans peste, maladie et herbes sauvages. La deuxième partie traite de la production de cultures pluviales ou de cultures dans des conditions où l'eau est limitée en incluant le bilan d'eau de la culture aussi bien que le bilan d'eau du sol. Les deux modèles utilisent le maïs comme exemple. La manière dont les modèles MAIZE sont présentés est différente de la structure modulaire des modèles d'aujourd'hui où des blocs séparés de données de sol, de culture et du climat sont fournis à la fin d'un programme principal. Ici le texte explicatif suit aussi étroitement que possible l'énumération du modèle fournie par l'ordinateur. Chaque chapitre commence avec un certain numéros de lignes qui été copiées du listing. Par conséquent, la terminologie est justifiée et les données et dimensions des variables sont expliquées. Une autre caractéristique spéciale est le fait que les valeurs de fonctions et paramètre sont définis directement après la ligne où ils sont employés pour la première fois. Cette méthode souligne les endroits où le modèle veut que l'utilisateur lui fournisse des données. Ainsi il est précisé que la fiabilité du modèle dépend de la disponibilité et de la qualité des données fournies, en fonction de la compréhension et de la description correcte des procédés utilisés. La troisiéme partie de ce livre contient un certain nombres d'applications.

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