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SARP Research Proceedings

ORYZA1

An ecophysiological model for irrigated rice production

M.J. Kropff, H.H. van Laar & R.B. Matthews (Editors)

SARP Research Proceedings - September 1994

DLO-Research Institute for Agrobiology and Soil Fertility, Wageningen
WAU-Department of Theoretical Production Ecology, Wageningen
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Preface

This book describes an ecophysiological model for irrigated rice production. The model ORYZA1 has been developed in the SARP project (Simulation and Systems Analysis for Rice Production) which is coordinated by IRRI and Wageningen. It is based on the models SUCROS and MACROS-L1D. This book gives a description of the FST version of the model (Fortran Simulation Translator, see D.W.G. van Kraalingen, C. Rappoldt & H.H. van Laar, Appendix 5 in Goudriaan & van Laar, 1994). The model described is Version 1.3.

The introduction summarizes the history of the development of ORYZA1. Chapter 2 describes the FST version of the model in detail (also a version in Fortran-77 is available). Sections of the model are listed and subsequently a brief explanation is given. You may wish to use the appendices while reading, especially the list of variables. In the text we did not explain all variables to keep it as compact as possible. Chapter 3 describes the procedures for parameterization of the model and Chapter 4 describes the evaluation of the model using data from contrasting growing seasons. The different types of application of the model are described in Chapter 5.

We hope that this model will be of use in your research. We assume that some of you will modify statements in the model or derive new parameters, which can easily be done in the user friendly FST. Please keep us informed of those developments, so that the model can be updated as quickly as possible.

Los Baños, Wageningen,
September, 1994

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Simulation and Systems Analysis for Rice Production (SARP)

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Contents

1 Introduction

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The potential yield of a crop is determined only by varietal characteristics and the seasonal pattern of environmental variables such as temperature and radiation. Thus, crop yield potential differs between sites and between years and seasons at a specific site. Maximum rice yields of 10 t ha^{-1} have been achieved in tropical environments, and yields of up to 15 t ha^{-1} are possible in more temperate environments such as Australia and China (Yoshida, 1981; R.L. Williams and L. Lewin, personal communication). Crop simulation models can be used to quantify yield potential in different environments. However, these models have to be parameterized and evaluated with data from experiments where yield potential is achieved. The model presented here was parameterized in an IRRI research project (International Rice Research Institute, Los Baños, Philippines) in which two issues were addressed that are related to yield potential in rice: the problem of declining rice yields in long-term experiments and the need for rice plant types with an increased yield potential.

In the 1980s and early 1990s, maximum yields with current varieties were much lower than yields obtained on the IRRI farm in the early 1970s with the first semi-dwarf variety IR8 (7 t ha^{-1} *vs* 9.5 t ha^{-1}). These current varieties are resistant to major pests and have a much shorter duration than the early modern rice varieties. Because the early modern varieties are susceptible to diseases such as tungro, which cannot be controlled, it is difficult to compare the yield potential of recent and early modern varieties directly. Rice simulation models that were calibrated using the available data sets like MACROS and CERES-Rice, therefore, simulated maximum potential yields of only 8 t ha^{-1} for Los Baños weather conditions (Herrera-Reyes & Penning de Vries, 1989; Penning de Vries, 1991; 1992, U. Singh, personal communication). These simulated yields suggested that yield potential of current varieties is lower than that of IR8, which yielded 9 - 10 t ha^{-1} in the late 1960s. It was hypothesized that the current low yields at IRRI's farm were partly related to a change in the N supply environment causing low N concentrations in leaf tissue, especially in the grainfilling period resulting in early senescence of leaves and low rates of photosynthesis (Kropff et al., 1994; Cassman et al., 1994). Therefore, a study was initiated in 1991 at IRRI, in which experimentation was integrated with modelling. Field experiments were conducted to quantify the yield potential and determinants of yield potential with improved agronomic management.

In the 1991 wet season (WS) and in the 1992 dry season (DS), IR72 and a new elite line IR58109-113-3-3-2 were grown at IRRI's farm under irrigated conditions. Nitrogen inputs were 110 kg N ha^{-1} (WS) and 225 kg N ha^{-1} (DS). These rates were 30 kg N ha^{-1} (WS) and 105 kg N ha^{-1} (DS) higher than the current practice at IRRI, and included a late application at flowering to maintain leaf N status during grainfilling. Dry weights of organs and N concentration of tissue were measured periodically. The ecophysiological growth model INTERCOM (Kropff & van Laar, 1993) was evaluated with the data from both seasons (Kropff et al., 1993).

Total dry matter production and grain yield differed markedly in the WS and DS for both varieties (Table 1.1). Yields were comparable to yields reported in the late 1960s for IR8 (Yoshida, 1981): about 6 t ha^{-1} in the WS and 9 - 10 t ha^{-1} in the DS, indicating that the genetic potential of rice had not changed, despite differences in growth duration (IR72 has a growth duration of about 110 days *versus* 125 days for IR8). The use of a systems approach and modelling was very useful in the project. After the 1991 wet season experiments, the model ORYZA1 was developed and parameterized and used to predict yields and N requirements for a dry season. Using the varietal parameters derived from the 1991 WS experiments (like development rates, dry matter distribution patterns and leaf N concentrations), the model predicted yields of about 8 t ha^{-1} with typical DS weather data (Kropff et al., 1994). If the leaf N concentration measured in the dry season was input to the model, yields of about 9.5 t ha^{-1} were simulated with the DS weather data. These results demonstrate that differences in weather and crop N status determined yield differences between WS and DS. The need for changes in N management practices to sustain high yields in intensive rice systems was also demonstrated in a long-term intensive rice cropping experiment at IRRI's experimental farm. In the late 1960s and early 1970s, when intensive rice cropping just started at IRRI's experimental farm, 100 kg N ha^{-1} was sufficient to obtain yields of about 9 t ha^{-1}, whereas 190 kg N ha^{-1} was needed to obtain these yield levels in 1992. This leads to the conclusion that the increased amount of N fertilizer, needed to obtain these high yields, has to be the result of a reduced soil N supply, because N recovery rates are similar (Cassman et al., 1994, Kropff et al., 1994).

The model ORYZA1 was developed and evaluated based on these data sets and version 1.3 is presented here. The main structure and basic routines are from the Wageningen models for potential production (INTERCOM - Kropff & van Laar, 1993; SUCROS -

Table 1.1. Observed and simulated grain yields (panicle dry weight) for the 1991 wet season and the 1992 dry season with IR72 and a new line elite IR58109-113-3-3-2. After: Kropff et al., 1993.

	1991 Wet Season		1992 Dry Season	
	Observed ($kg\ ha^{-1}$)	Simulated ($kg\ ha^{-1}$)	Observed ($kg\ ha^{-1}$)	Simulated ($kg\ ha^{-1}$)
IR72	5674±229	5981	9558±288	9372
IR58109-113-3-3-2	6111±182	6034	9709±242	10024

Spitters et al., 1989; van Laar et al., 1992; MACROS module L1D - Penning de Vries et al., 1989). The differences between the ORYZA1 and the L1D rice model are:

- The model ORYZA1 simulates growth in the seedbed and the effect of transplanting shock on the relevant processes,
- Leaf area development now includes a source- and sink-limited phase,
- Phenological development is now calculated using an optimum curve, which is more realistic,
- Photosynthesis parameters are calculated from leaf N,
- The latest routines for canopy photosynthesis from the SUCROS model are used,
- A new procedure for calculation of spikelet numbers and grain numbers needed for sink limitation was introduced, and
- The effect of CO_2 on photosynthetic processes is included for climate change studies.

The model ORYZA1 can be used as a tool in rice research for different types of studies:

1. Detailed physiological analysis of field experiments. It enables interpretation of treatment differences in yield in terms of LAI development, leaf N content, weather conditions and varietal characteristics determining physiological and morphological processes. For this purpose, detailed measurements are required on LAI and leaf N content, preferably throughout the growing season, although a single measurement at flowering can be seen as a minimum data set.
2. Extrapolation of experimental findings to other environments. Given the N content of the leaves throughout the growing season and the varietal characteristics, attainable yields can be estimated for other environments (planting date, irradiation, temperature).
3. Estimation of yield potential for a given environment (planting date, latitude, radiation, temperature, variety as input) based on the leaf N content of the highest yielding experiments. The leaf N contents measured in the recent IRRI experiments used for model development (see Chapter 4) can be used as a starting point.
4. Estimation of the effect of climate change on yield potential.

An important advantage of the current model is that it can be used to simulate realistic yields and to assess the impact of planting date, weather, latitude at measured leaf N contents. This is in contrast to models for potential production, that have a fixed pattern of leaf photosynthesis in time.

2 Description of the model ORYZA1 (Version 1.3)

M.J. Kropff[1], H.H. van Laar[2], R.B. Matthews[1,3], J. Goudriaan[2] & H.F.M. ten Berge[3]

with contributions of
J.C. Shin[4], S. Mohandass[5], S. Singh[6], Zhu Defeng[7], Moon Hee Lee[4], A. Elings[3], B.A.M. Bouman[3]

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General structure of the model ORYZA1

The general structure of the model is presented in Figure 2.1. Under favourable growth conditions, light, temperature and varietal characteristics for phenological, morphological and physiological processes are the main factors determining the growth rate of the crop on a specific day. The model follows the daily calculation scheme for the rates of dry matter production of the plant organs, and the rate of phenological development (Figure 2.1). By integrating these rates over time, dry matter production of the crop is simulated throughout the growing season.

The total daily rate of canopy CO_2 assimilation is calculated from the daily incoming radiation, temperature and the leaf area index. The model contains a set of subroutines that calculate the daily rate by integrating instantaneous rates of leaf CO_2 assimilation. The calculation is based on an assumed sinusoidal time course of radiation over the day and the exponential light profile within the canopy. On the basis of the photosynthesis characteristics of single leaves, which depend upon the N concentration, the photosynthesis profile in the canopy is obtained. Integration over the leaf area index of the canopy and over the day gives the daily CO_2 assimilation rate. After subtraction of respiration requirements, the net daily growth rate in kg dry matter per ha per day is obtained. The dry matter produced is partitioned among the various plant organs. The effect of the ambient CO_2 concentration on the photosynthetic parameters was included in this version of the model.

Phenological development rate is tracked in the model as a function of ambient daily

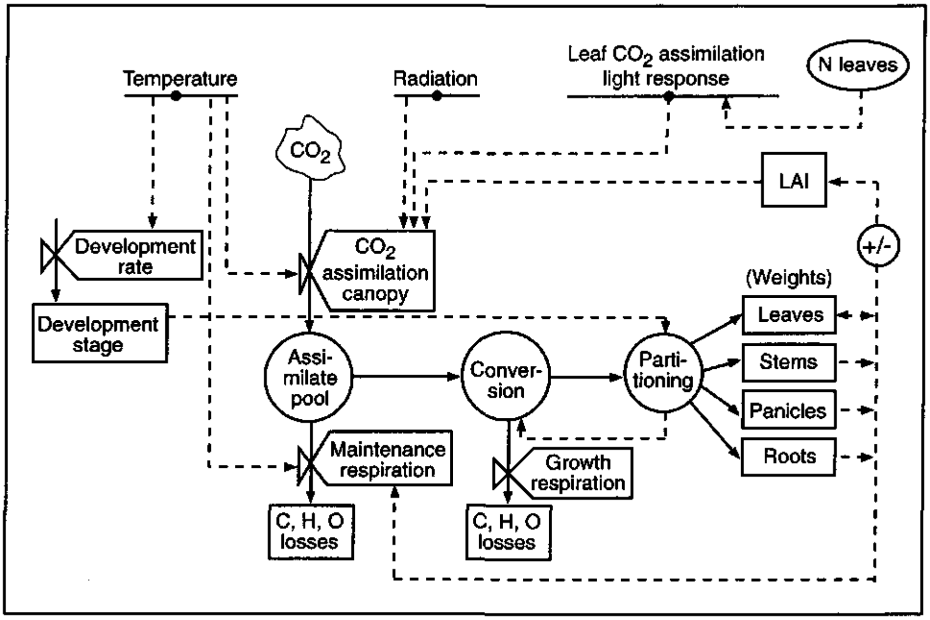

Figure 2.1. A schematic representation of the model ORYZA1. Boxes are state variables, valves are rate variables, circles are intermediate variables. Solid lines are flows of material, dotted lines are flows of information.

average temperature and photoperiod. When the canopy is not yet closed, leaf area increment is calculated from daily average temperature, because carbohydrate production does not limit leaf expansion. When the canopy closes, the increase in leaf area is obtained from the increase in leaf weight. Integration of daily growth rates of the organs and leaf area results in dry weight increment during the growing season.

A simple procedure is used in the model to simulate sink limitation as a result of spikelet sterility at high or low temperatures.

Input requirements of the model are: geographical latitude, daily weather data (radiation, minimum and maximum temperature), plant density, date of crop emergence and transplanting, and parameter values that describe the morpho-physiological characteristics of the plant species. Time step of integration is one day.

The model can be used to analyse experimental data with measured LAI as input as well as with LAI simulated. It is useful to analyse experimental data with LAI as input as a first step, because the carbon balance part of the model is better developed and tested than the morphological part (Kropff, 1990; Spitters et al., 1989; Kropff & Goudriaan, 1989). So, inaccuracy in the simulation of morphological characteristics cannot confound conclusions made in the first analysis if LAI is used as an input. As a second step, LAI can be simulated as well. If no experimental data are available, LAI has to be simulated. In the model, an assumed time course of leaf N content can be used or the actual measured data. For temperate environments, where the seedbed is often covered by a plastic greenhouse, a special procedure can be used to account for the temperature effects.

In this manual, the different subsequent sections of the listing of the FST version of the model will be discussed. FST (FORTRAN Simulation Translator) is a simulation language developed by D.W.G. van Kraalingen and C. Rappoldt (AB-DLO, Wageningen, The Netherlands). This 'preprocessor' generates a Fortran source code, and is described in detail by van Kraalingen et al. (1994). The FST-structure of the model is given in Appendix 4.

2.1 Initial conditions

```
INITIAL
INCON ZERO      = 0.,    DVSI   = 0.
INCON WLVGI     = 0.,    WSTI   = 0.
INCON WSOI      = 0.,    WRTI   = 0.
PARAM SWILAI    = -1.,   SWINLV = -1., SWITMP = -1.
PARAM SWICOV    = -1.,   SWIDS  = -1.
```

In this section, the initial conditions of the simulation are set. In most integrals where the initial conditions are 0., the variable ZERO is used. The initial development stage and weights of the leaves, stems, storage organs and roots (DVSI, WLVGI, WSTI, WSOI, WRTI) are set to 0. kg ha^{-1}, as the initial weight is not significant compared to final yields. In the model, there is an option to use five switches: one for leaf area development (SWILAI, measured (−1.) or simulated (1.) LAI *vs* time); one for leaf N content in time (SWINLV, measured (−1.) leaf N *vs* daynumber or an assumed leaf N content as a function of development stage (1.)); one for the use of temperature changes (General Circulation Models, GCM) (SWITMP, no change (−1., current climate) or changed (1., future climate)); one for the cover in the seedbed (SWICOV, no cover (−1.), cover (1.)); and one to simulate direct-seeded (1.) or transplanted rice (-1), SWIDS.

2.2 Phenological development of the crop

```
   CALL SUBDD  (TMAX,TMIN,TBD, TOD,TMD, HU  )
   CALL PHENOL (DAS,DVS,DVRJ,DVRI,DVRP,DVRR, HU,DAYL,MOPP,PPSE, ...
                TS,SHCKD,DOYTR,DOYS,    DVR,TSHCKD)
   CALL SUBCD  (DOY, DOYTR, TAV,TIME, NCOLD)

   DVS     = INTGRL (DVSI,  DVR)
```

The developmental stage (DVS) of a plant defines its physiological age and is characterized by the formation of the various organs and their appearance. The most important phenological change is the one from the vegetative to the reproductive stage, determining the most important change in dry matter allocation over organs. As many physiological and morphological processes change with the phenological stage of the plant, accurate quantification of phenological development is essential in any simulation model for plant growth.

Temperature is the main driving force for developmental changes. However, in photoperiod-sensitive varieties, daylength determines induction of flowering as well. The subroutine SUBDD calculates the daily effective heat units for phenological development (HU), the subroutine PHENOL calculates the development rate DVR (d^{-1}) as a function of the development stage, heat units and daylength, and the subroutine SUBCD calculates the number of days on which it is too cold for rice growth. When the number of subsequent cold days exceeds a given value, the crop dies and the model stops (see Section 2.7).

For many annual species, the developmental stage can be easily described using a dimensionless variable (D, DVS) which has the value 0 at emergence, 1 at flowering and 2 at maturity (van Keulen et al., 1982). The developmental stage D is the integral of the developmental rate D_r (DVR, $(°Cd)^{-1}$) over time expressed in degree-days. This developmental rate is the inverse of the period (expressed in °Cd) required for completing a developmental unit (e.g. flowering - maturity).

Calculation of the effective temperature for phenological development

```
      SUBROUTINE SUBDD(TMAX,TMIN,TBD,TOD,TMD, HU)
      IMPLICIT REAL (A-Z)
      INTEGER I

      TM     = (TMAX + TMIN)/2.
      TT     = 0.
      DO 10 I = 1, 24
           TD = TM + 0.5*ABS(TMAX-TMIN)*COS(0.2618*FLOAT(I-14))
        IF ((TD.GT.TBD) .AND. (TD .LT. TMD)) THEN
           IF (TD.GT.TOD) TD = TOD-(TD-TOD)*(TOD-TBD) / (TMD-TOD)
        TT = TT + (TD-TBD)/24.
        ENDIF
 10   CONTINUE
      HU = TT
      RETURN
      END
```

It has been observed in many crops that the rate of development (i.e. the reciprocal of the duration it takes to complete a certain phenological event, such as the grainfilling phase) is linearly related to the daily mean temperature above a base temperature up to an optimum temperature, beyond which the rate decreases, again linearly, until a maximum temperature is reached (e.g. Kiniry et al., 1991). For temperatures below the base temperature or above the maximum temperature, the rate of development is zero. Three 'cardinal' temperatures can, therefore, be identified: base temperature (T_{base}), the optimum temperature (T_{opt}), and the maximum temperature (T_{high}). For rice, these values are typically 8, 30 and 42 °C, respectively (Gao et al., 1992). This 'bilinear' response is generally observed only when the daily temperatures are constant (e.g. in a controlled environment); if the temperature

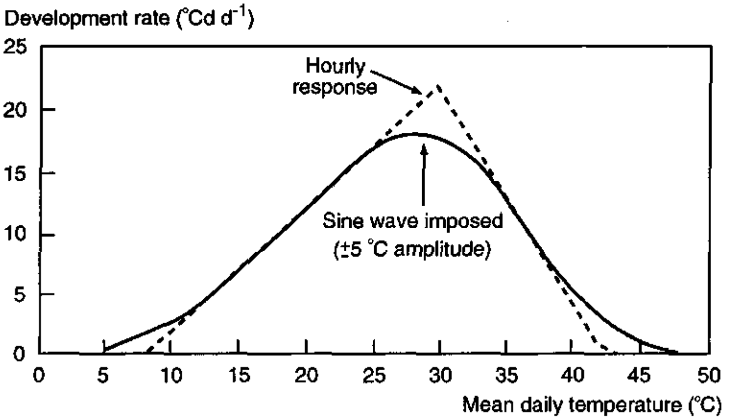

Figure 2.2. The response functions of phenological development rate to temperature as used in ORYZA1 version 1.3. Simulations with T_{base} = 8 °C, T_{opt} = 30 °C and T_{max} = 42.5 °C.

fluctuates between a minimum and a maximum value, as is the case in normal field experiments, the response becomes more curvilinear, particularly near each cardinal temperature. The linear and curvilinear responses are shown in Figure 2.2.

Although this curvilinear response to daily mean temperature can be described by complex exponential equations (e.g. Gao et al., 1992; Yin et al., in prep), the simpler approach used by Matthews & Hunt (1994) in their cassava model was used in ORYZA1. In this approach, it is assumed that the response of development rate to temperature over short time periods, such as one hour, is described by the bilinear model, and that the response to daily mean temperature is achieved by superimposing onto this model a temperature response approximated by a sine function alternating between the daily minimum (T_{min}) and maximum (T_{max}) temperatures (Figure 2.2).

In the model, hourly temperature (T_d) is calculated from T_{min} and T_{max} according to the relation:

$$T_d = (T_{min} + T_{max})/2 + (T_{max} - T_{min}) \cos(0.2618\ (h - 14))/2 \qquad (2.1)$$

where h is the time of day. Hourly increments in heat units (HUH, °Cd h^{-1}) are calculated according to:

$$\begin{array}{ll} T_d \le T_{base},\ T_d \ge T_{high} & : HUH = 0 \\ T_{base} < T_d \le T_{opt} & : HUH = (T_d - T_{base})/24 \\ T_{opt} < T_d < T_{high} & : HUH = [T_{opt} - (T_d - T_{opt}) \times (T_{opt} - T_{base})/(T_{high} - T_{opt})]/24 \end{array} \qquad (2.2)$$

where T_{base} is the base temperature, T_{opt} is the optimum temperature and T_{high} is the maximum temperature for phenological development. The daily increment in heat units (°Cd d^{-1}) is then calculated as:

$$HU = \sum_{h=1}^{24} (HUH) \qquad (2.3)$$

Calculation of phenological development rates

In the subroutine PHENOL, the development rate of the crop is calculated, based on development rate constants for the different phenological stages, the effective temperature (HU) and the photoperiod.

```
      SUBROUTINE PHENOL (DAS,DVS,DVRJ,DVRI,DVRP,DVRR,HU,DAYL,MOPP,PPSE,
     &                    TS,SHCKD,DOYTR,DOYS,
     &                   DVR,TSHCKD)
      IMPLICIT REAL (A-Z)
      INTEGER IDAS, ISA

      IDAS = INT(DAS)
      ISA  = INT(DOYTR) - INT(DOYS)
      IF (ISA.LT.0) THEN
          ISA = ISA + 365
        ELSE
          ISA = ISA
      ENDIF
```

In this first section, the seedling age (ISA) is calculated with a specific procedure to avoid problems when the crop is sown before the end of the year and transplanted in the next year. The seedling age is needed for the calculation of transplanting shock effects on phenological development.

```
          IF (DVS.GE.0.    .AND. DVS.LT.0.40) DVR = DVRJ * HU
          IF (DVS.GE.0.40 .AND. DVS.LT.0.65) THEN
              DL = DAYL + 0.9
              IF (DL.LT.MOPP) THEN
                  PPFAC = 1.
                ELSE
                  PPFAC = 1.-(DL-MOPP)*PPSE
              ENDIF
              PPFAC = MIN(1., MAX(0., PPFAC))
              DVR   = DVRI * HU * PPFAC
          ENDIF
          IF (DVS.GE.0.65 .AND. DVS.LT.1.00) DVR = DVRP * HU
          IF (DVS.GE.1.00)                   DVR = DVRR * HU

          IF (IDAS.EQ.ISA) TSTR = TS
          TSHCKD = SHCKD * TSTR
          IF (IDAS.GT.ISA .AND. TS.LT.(TSTR+TSHCKD)) DVR = 0.
      RETURN
      END
```

The life cycle of the rice crop is divided into four main phenological phases:

1 The basic vegetative phase (BVP), from sowing (DVS=0) to the start of the photoperiod-sensitive phase (DVS=0.4). The development rate constant in this phase is DVRJ.
2 Photoperiod-sensitive phase (PSP), from the end of the basic vegetative phase to panicle initiation (DVS=0.65). The development rate constant in this phase is DVRI.
3 Panicle formation phase (PFP), from panicle initiation to first flowering (DVS=1). The development rate constant in this phase is DVRP.
4 Grainfilling phase (GFP), from first flowering to physiological maturity (DVS=2). The development rate constant in this phase is DVRR.

The photoperiod is calculated from the daylength +0.9 to account for the effect of low radiation levels after sunset and before sunrise.

For each of these four phases there is a variety-specific development rate constant which is the inverse of the temperature sum required to complete a specific phase at the optimum photoperiod. Differences between varieties in the total crop duration are usually due to differences in the duration of the BVP rather than the other phases (Vergara & Chang, 1985). Suboptimal photoperiods, (daylength (DL) smaller than optimum photoperiod (MOPP)), will result in a longer photoperiod sensitive phase (PPFAC<1.). The photoperiod sensitivity of a variety is quantified by the factor PPSE.

In transplanted rice, the situation becomes more complicated because of the transplanting shock, which causes a delay in phenological development. In especially designed experiments, it was found that the delay in phenological development is a function of the age of the seedlings that are transplanted, expressed in degree-days (TSTR). In the model the delay is expressed in degree-days (TSHCKD, °Cd), indicating the period after transplanting during which no development occurs. The procedure is illustrated in Figure 2.3. The model starts at sowing and calculates the developmental rate and state. At transplanting, the transplanting shock is determined from the seedling age expressed in degree-days, using the

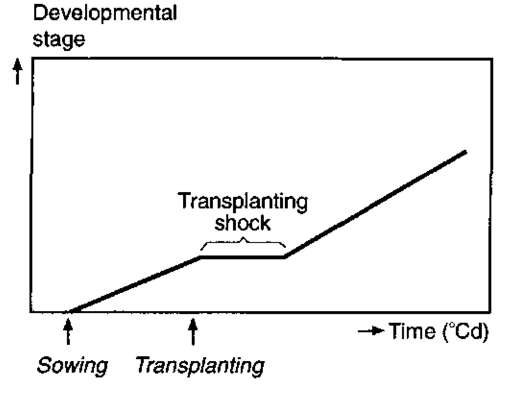

Figure 2.3. Procedure for simulation of transplanting shock effect on phenological development. After transplanting, the developmental rate is 0 for a period expressed in degree-days (TSHCKD, °Cd).

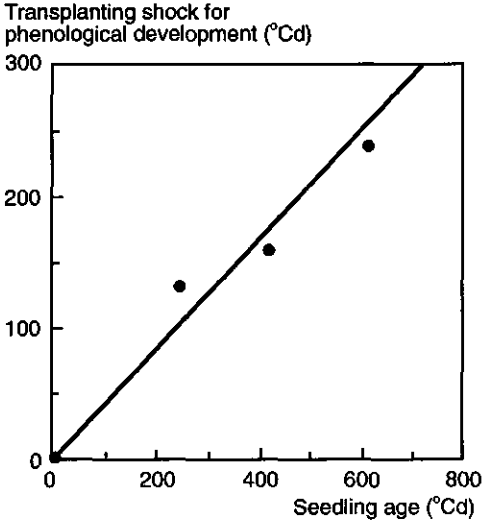

Figure 2.4. Relation between the transplanting shock effect on phenological development in rice expressed in a period where no development occurs (TSHCKD in °Cd) and the seedling age at transplanting, also expressed in degree-days. Data are from a wet season 1991 experiment with IR72 at IRRI, Los Baños, Philippines (Torres, Liboon, Kropff & Cassman, IRRI, unpubl.).

parameter SHCKD (degree-day delay per unit of seedling age (°Cd)) (Figure 2.4). For this purpose, the temperature sum (TS) is calculated in the model besides the developmental stage (see Section 2.5).

Effect of prolonged periods of low temperature on crop survival

```
      SUBROUTINE SUBCD(DOY,DOYTR,TAV,TIME,  NCOLD)
      IMPLICIT REAL(A-Z)
      SAVE
      IF(DOY.EQ.DOYTR) NCOLD=0.
      IF(TAV.LT.12.) THEN
        NCOLD = NCOLD + 1.
      ELSE
        NCOLD = 0.
      ENDIF

      IF (NCOLD.GT.3.) THEN
        WRITE (6,10) NCOLD, TIME
10      FORMAT (/,'* * * Number of cold days (<12 C) exceeded 3* * *',/,
     &  ' NCOLD',F8.3, ' at TIME=',F6.1)
        ENDIF
      RETURN
      END
```

This routine was developed to ensure that the crop dies when the number of days on which the average temperature is lower than 12 °C exceeds 3 days. This estimate is based on Horie (personal communication).

2.3 Daily dry matter production

The section in which daily dry matter production is calculated is the core of the model. The following steps can be distinguished and will be described, separately:

- CO_2 assimilation of the canopy,
- Maintenance respiration,
- Daily growth rate of the crop expressed in dry matter by accounting for conversion losses or growth respiration, and
- Dry matter partitioning.

2.3.1 Daily rate of gross CO_2 assimilation of the canopy (DTGA) and light absorption by the canopy (DPARI)

```
CALL TOTASP (DOY,LAT,DTR,SCP,EFF,REDFT,KDF,KNF,ALAI,CO2,NFLV, ...
             DAYL,AMAX,DTGA,DPAR,DPARI)

NFLV    = INSW(SWINLV, XNFLV, AFGEN(NFLVTB, DVS))
REDFT   = AFGEN (REDFTT,TAVD)
CO2EFF  = (1.-EXP(-0.00305*CO2    -0.222))/  ...
          (1.-EXP(-0.00305*CO2REF-0.222))
EFF     = AFGEN (EFFTB, TAVD) * CO2EFF
KNF     = AFGEN (KNFTB,  DVS)
KDF     = AFGEN (KDFTB,  DVS)

PARCUM = INTGRL (ZERO, DPARI)
PARI1  = (1.-0.06) * DTR * 0.5 * (1.- EXP (-KDF * ALAI))/1.E6
PARCM1 = INTGRL(ZERO, PARI1)
```

In the main program, the extinction coefficients for visible light in the canopy (KDF) and for N distribution in the canopy (KNF) are read from tables as a function of the developmental stage. The leaf N content is read as a function of DVS or daynumber, depending on the value of SWINLV (which has the value 1. if it is a function of DVS, and −1. if it is a function of daynumber for simulation of a specific experiment).

The initial light use efficiency of a single leaf (ε, EFF (kg CO_2 ha^{-1} h^{-1} / J m^{-2} s^{-1})) is read from a table as a function of average daytime temperature (TAVD) and is multiplied by a factor that accounts for the effect of CO_2. For the effect of CO_2 the relationship derived by Jansen (1990) from data by Akita (1980) and van Diepen et al. (1987) was used:

$$\varepsilon = \varepsilon_{340\ ppm}\,(1-\exp\,(-0.00305\ CO_2-0.222))/(1-\exp\,(-0.00305\times340-0.222)) \quad (2.4)$$

This relationship (Eqn 2.4) gives very similar results to the theoretical relationship derived by Goudriaan & van Laar (1994). The maximum rate of CO_2 assimilation of a leaf (AMAX, kg CO_2 ha^{-1} h^{-1}) is calculated from the N content of the leaves and a reduction factor that accounts for the effect of the average daytime temperature (TAVD) on AMAX in the subroutine ASSIMP which is called in TOTASP. Leaf N and as a result AMAX follow an exponential profile in the canopy (determined by KNF).

The calculation procedure for the daily rate of crop CO_2 assimilation is schematically represented in Figure 2.5. In the main program, the subroutine TOTASP is called, which calls the subroutine ASTRO. ASTRO calculates the daylength and the integral of the sine of the solar elevation over the day. TOTASP calls on specified moments of the day the subroutine ASSIMP, that computes instantaneous canopy CO_2 assimilation and this rate is integrated over the day in TOTASP. The subroutine TOTASP needs as inputs the day of the year (DOY), the latitude of the site (LAT), the daily total radiation (DTR) and a series of parameter values, which are defined in the parameter section.

In this section, the cumulative absorbed radiation is calculated from a detailed calculation of absorbed radiation (PARCUM) in the subroutine TOTASP, and in the main program a simple procedure (PARCM1) is included as well.

Calculation of daily canopy photosynthesis (TOTASP)

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

In TOTASP, first the subroutine ASTRO is called which calculates daylength (DAYL), some intermediate variables for the calculation of the sine of the solar elevation (SINB) and the integral of SINB.

```
*-----(SUBROUTINE ASTRO)
*-----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
```

These calculations involve some empirical relationships that calculate from the daynumber and latitude the daylength and the integral of the sine of the solar angle (SINB). First the declination is calculated from the daynumber. Then the intermediate variables SINLD and COSLD are calculated to make the other equations more simple. Daylength is calculated and

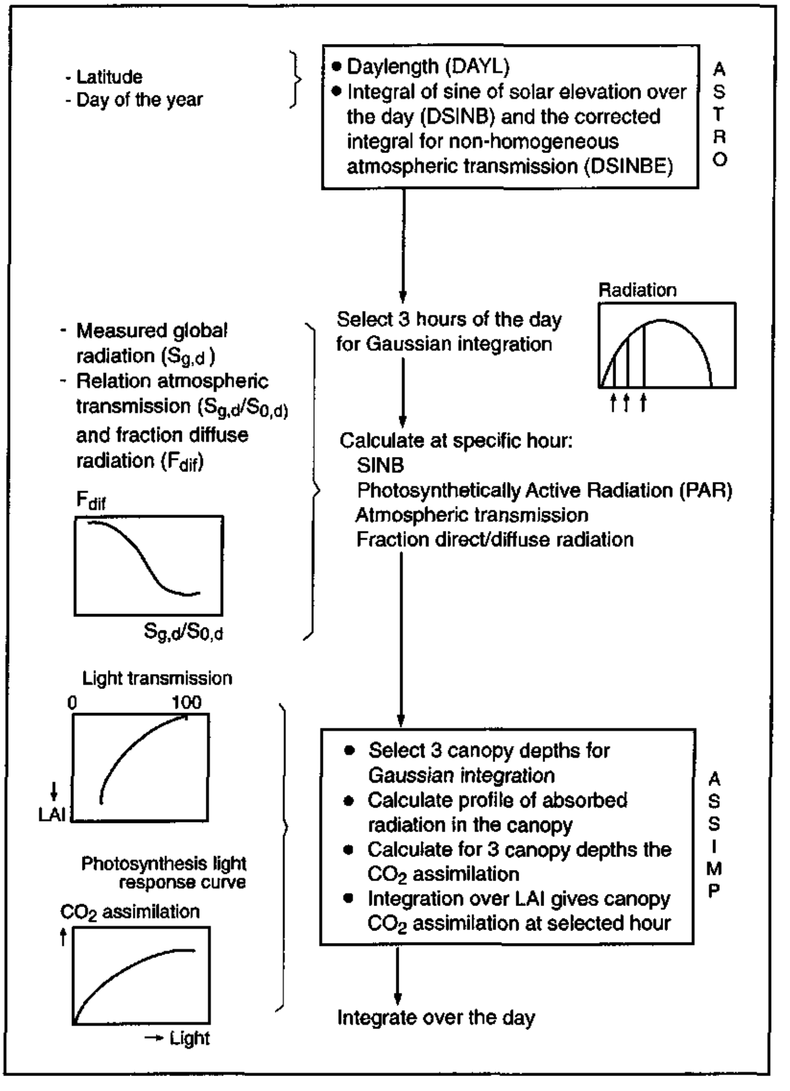

Figure 2.5. Schematic representation of the calculation procedure for daily rates of canopy CO_2 assimilation in the subroutine TOTASP, which calls the subroutines ASTRO and ASSIMP.

two versions of the integral of the sine of the solar elevation: the first (DSINB) is the straightforward integral of SINB, that can be used for the calculation of daily total extraterrestrial radiation (DSO) and the second one (DSINBE) is a modified integral for radiation at the earth surface, that takes into account the effect of the daily course in atmospheric transmission. Transmission is lower near the margins of the day because of haze in the morning and clouds in the afternoon. Besides that, the path length of the solar radiation in the atmosphere is longer (Spitters et al., 1986). DSINBE is used to calculate the actual radiation at a specific time of the day (see later).

The solar constant is calculated as a function of the daynumber, because the distance between earth and sun is not constant over the year.

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

      DO 10 I1=1,IGAUSS
*-------At the specified HOUR, radiation is computed and used
*       to compute assimilation
        HOUR = 12.0+DAYL*0.5*XGAUSS(I1)
*       (calculation of instantaneous assimilation (FGROS)
*        at the selected hour)

*-------Integration of assimilation rate to a daily total (DTGA)
        DTGA = DTGA+FGROS*WGAUSS(I1)
        DPAR = DPAR+PAR*WGAUSS(I1)
        DPARI= DPARI+PARINT*WGAUSS(I1)
  10    CONTINUE
        DTGA  = DTGA  * DAYL
        DPAR  = DPAR  * DAYL * 3600./1.E6
        DPARI = DPARI * DAYL * 3600./1.E6
```

In TOTASP, the integration loop is started for the calculation of daily rates of CO_2 assimilation (DTGA) and incoming and intercepted photosynthetically active radiation (DPAR and DPARI, resp.) from instantaneous rates of canopy assimilation (FGROS) and incoming and intercepted radiation (DPAR and DPARI), using Gaussian integration (Goudriaan, 1986). Another way of doing this could be by using a short time step (10 minutes - 1 hour) and using the usual rectangular integration method, but the Gaussian procedure gives very accurate estimates through only three calculations a day. In the three-point Gaussian integration method, the integral of a function is calculated by selecting three x-values (here: x is time of the day). For these values the y-values (here: canopy CO_2 assimilation and radiation intercepted) are calculated and a weighted average y-value is derived by using defined weights. The three points (XGAUSS) have to be (*i*) at 0.5 of the integration interval, (*ii*) at (0.5 + SQRT(0.15)) × the interval (=0.887298) and (*iii*) at (0.5–SQRT(0.15)) × the interval (=0.112702). Because radiation is homogeneously distributed over the day according to the sine of the solar elevation, the weighted average CO_2 assimilation rate is calculated for half a day only. For each of the three selected hours, a different weighting factor (WGAUSS) for the calculated assimilation is used, to obtain the weighted average rate of CO_2 assimilation (kg CO_2 ha^{-1} h^{-1}). Multiplying by the daylength results in the total daily rate of CO_2 assimilation.

```
*--------Sine of solar elevation
         SINB  = MAX (0., SINLD+COSLD*COS (2.*PI*(HOUR+12.)/24.))
         PAR   = 0.5*DTR*SINB*(1.+0.4*SINB)/DSINBE
```

The SINB at the specified hour is calculated first. Measured or estimated daily total solar irradiation (wavelength 300 - 3000 nm) is input for the model. Only half of this incoming radiation is photosynthetically active (*PAR*, Photosynthetically Active Radiation, wavelength 400 - 700 nm). This visible fraction, generally called 'light', is used in the calculation procedure of the CO_2 assimilation rate of the canopy. The instantaneous incoming photosynthetically active radiation is calculated from the daily total radiation by multiplying the total daily radiation with the ratio of the actual effective SINB (SINB× (1+ 0.4 × SINB)) and the integral of the effective SINB (DSINBE).

```
*--------Diffuse light fraction (FRDF) from atmospheric
*        transmission (ATMTR)
         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
```

A distinction is made between diffuse skylight (PARDF), with incidence under various angles, and direct sunlight with an angle of incidence equal to the solar angle (PARDR). It is important to distinguish these fluxes because of the large difference in illumination intensity between shaded leaves (receiving only diffuse radiation) and sunlit leaves (receiving both direct and diffuse radiation) and the non-linear CO_2 assimilation-light response of single leaves. The diffuse flux is the result of the scattering of sun rays by clouds, aerosols and gases in the atmosphere. The proportion of diffuse light (F_{dif} in Figure 2.5) in the total incident light flux (FRDF) depends on the status of the atmosphere, i.e. cloudiness, concentration of aerosols. This fraction is calculated from the atmospheric transmission (ATMTR) using an empirical function. This relationship is based on data from different meteorological stations from a wide range of latitudes and longitudes and is described in the IF statement block (Spitters et al., 1986). The atmospheric transmission is the ratio between actual irradiance ($S_{g,d}$ in Figure 2.5, measured J m^{-2} s^{-1}) and the quantity that would have reached the earth's surface in the absence of an atmosphere ($S_{0,d}$ in Figure 2.5) . The theoretical radiation flux (PAR) at the earth surface, assuming 100% atmospheric transmission, can be calculated from the solar constant (SC), which is the radiation flux perpendicular to the sun rays, and the sine of the solar elevation (β), which changes during the day (0.5 × SC × SINB). The fluxes of direct and diffuse PAR are calculated from the fraction diffuse radiation.

Calculation of instantaneous canopy CO_2 assimilation

```
      CALL ASSIMP (SCP,EFF,REDFT,KDF,KNF,LAI,SINB,PARDR,PARDF,
     &            NFLV,CO2,AMAX,FGROS,PARINT)
```

In the subroutine ASSIMP, the instantaneous rate of CO_2 assimilation of the canopy is calculated from the incoming fluxes of diffuse and direct PAR, SINB, LAI, and several parameters.

```
*-----(SUBROUTINE ASSIMP)
*-----reflection of horizontal and spherical leaf angle distribution
      SQV  = SQRT(1.-SCP)
      REFH = (1.-SQV)/(1.+SQV)
      REFS = REFH*2./(1.+2.*SINB)
*-----extinction coeff. for direct radiation and total direct flux
      CLUSTF = KDF / (0.8*SQV)
      KBL    = (0.5/SINB) * CLUSTF
      KDRT   = KBL * SQV
*-----calculate relative effect of CO2 level on AMAX
      CO2AMX = 49.57/34.26 * (1.-EXP(-0.208*(CO2-60.)/49.57))
      CO2AMX = MAX(0., CO2AMX)
```

First the reflection coefficient is calculated. Incoming radiation is partly reflected by the canopy. The reflection coefficient of a green leaf canopy with a random spherical leaf angle distribution (ρ, REFS), which indicates the fraction of the downward radiation flux that is reflected by the whole canopy, equals (Goudriaan, 1977):

$$\rho = [(1 - \sqrt{(1-\sigma)}) / (1 + \sqrt{(1-\sigma)})] \bullet [2 / (1 + 2 \sin \beta)] \tag{2.5}$$

in which σ represents the scattering coefficient fraction (transmission and reflection) of single leaves for visible radiation ($\sigma = 0.2$; SCP) (Goudriaan, cited by Spitters, 1986). A fraction $(1 - \rho)$ of the incoming visible radiation can be absorbed by the canopy.

Radiation fluxes attenuate exponentially within a canopy with increasing leaf area from the top downwards:

$$I_L = (1 - \rho)\, I_0 \exp(-k\, L) \tag{2.6}$$

where

- I_L is the net *PAR* flux at depth L in the canopy (with an LAI of L above that point) (J m^{-2} soil s^{-1}),
- I_0 is the flux of visible radiation at the top of the canopy (J m^{-2} soil s^{-1}),
- L the cumulative leaf are index (counted from the top of the canopy downwards) (m^2 leaf m^{-2} soil),
- ρ the reflection coefficient of the canopy (-), and
- k the extinction coefficient for PAR (-).

The diffuse and the direct flux have different extinction coefficients, which causes different light profiles within the canopy for diffuse and direct radiation.

Therefore, three different radiation fluxes are distinguished: (*i*) the diffuse flux (with extinction coefficient k_{df} (KDF), (*ii*) the total direct flux (with extinction coefficient $k_{dr,t}$) (KDRT) and (*iii*) the direct component of direct light (with extinction coefficient $k_{dr,bl}$ (KBL) with *bl* for black since direct radiation becomes diffuse as soon as the sun ray is partly absorbed, partly scattered by a leaf). Thus the total flux equals *i* + *ii*.

For a spherical leaf angle distribution (homogeneous, random), KDF equals:

$$k_{df,s} = 0.8 \sqrt{(1 - \sigma)} \tag{2.7}$$

which is about 0.71 (Goudriaan, 1977). However, in many situations like in rice, the leaf angle distribution is not spherical. In rice, the leaves are clustered (especially in the beginning as a result of planting on hills), and have a very vertical orientation. Other leaf angle distributions can be accounted for by a procedure described by Goudriaan (1986), which calculates k_{df} based on the frequency distribution of leaves with angles in three classes (0 - 30°, 30 - 60° and 60 - 90°). In the model, however, this is accounted for by using the cluster factor (*Cf*, CLUSTF) which is the measured KDF ($K_{df,m}$), relative to the theoretical one, for a spherical leaf angle distribution:

$$Cf = k_{df,m} / (0.8 \sqrt{(1 - \sigma)}\ ) \tag{2.8}$$

The direct component $k_{dr,bl}$ (KBL) can be calculated as (Goudriaan, 1977):

$$k_{dr,bl} = 0.5\ Cf\ / \sin \beta \tag{2.9}$$

$k_{dr,t}$ (KDRT) can be calculated as (Goudriaan, 1977):

$$k_{dr,t} = k_{dr,bl} \sqrt{(1 - \sigma)} \tag{2.10}$$

$k_{df,m}$ is the measured extinction coefficient under diffuse sky conditions being input in the model.

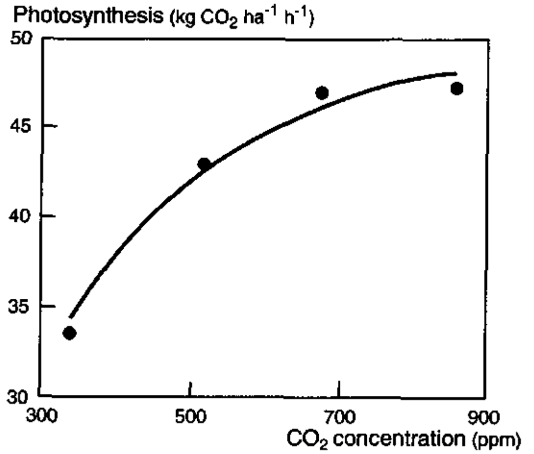

Figure 2.6. The relationship between the maximum rate of leaf photosynthesis at 1 g N m^{-2} and external CO_2 concentration during rice growth (data from Weerakoon, Olszyk and Ingram, IRRI/EPA).

For the effect of CO_2 on A_m the following relationship was derived by Kropff et al. (in prep., Figure 2.6)

$$A_m = A_{m,\,340\,ppm}\,(49.57/34.26\,(1 - \exp(-0.208\,(CO_2 - 60)/49.57))) \qquad (2.11)$$

```
*-----(SUBROUTINE ASSIMP)
*-----Selection of depth of canopy, can. assimilation is set to zero
      FGROS = 0.

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

      < calculation of FGL, the CO2 assimilation rate at the selected
        depths (LAIC) in the canopy(kg CO2/ha leaf/h),
        to be discussed later >

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

10    CONTINUE
      FGROS = FGROS * LAI
      PARINT = PARINT * LAI
```

Again a Gaussian integration procedure is used to calculate the momentaneous rate of canopy CO_2 assimilation and absorbed radiation by integration of the rates of leaf CO_2 assimilation and absorbed radiation over the canopy LAI (FGROS and PARINT). Three selected depths in the canopy are chosen (see above) at which the amount of absorbed radiation and leaf CO_2 assimilation is calculated. By using the weights, the weighted average rate of leaf CO_2 assimilation is simulated and total assimilation (FGROS) is easily obtained by multiplication with the total LAI.

```
*-------(SUBROUTINE ASSIMP)
*--------calculate leaf nitrogen for each layer,
*        based on exponential distribution
         IF (LAI.GT.0.01 .AND. KNF.GT.0.) THEN
          SLNI = NFLV * LAI * KNF * EXP(-KNF*LAIC)/(1.-EXP(-KNF*LAI))
         ELSE
          SLNI = NFLV
         ENDIF
*--------calculate actual photosynthesis from SLN, CO2 and temp.
         IF (SLNI .GE. 0.5) THEN
*          according to Shaobing Peng (IRRI, unpublished data):
           AMAX = 9.5 + (22. * SLNI) * REDFT * CO2AMX
         ELSE
```

```
        AMAX = MAX(0., (68.33 * (SLNI-0.2) * REDFT * CO2AMX))
      ENDIF
```

The maximum rate of CO_2 assimilation of a leaf (A_m, kg CO_2 ha^{-1} h^{-1}) is calculated from the N content of the leaves and the average daytime temperature. Because N content in the leaves is higher in the top leaves, these absorb most radiation, the N profile in the canopy is taken into account. From observations it was found that the N profile of N follows an exponential function with LAI counted from the top of the canopy with an extinction coefficient of about 0.4 around flowering (such as for radiation see Eqn 2.6). The relationship between leaf photosynthesis and specific leaf nitrogen (SLN) is based on recent measurements on IR72 at IRRI (Peng et al., unpublished). For SLN levels below 0.5 g m^{-2}, a relationship is used based on the assumption that A_m is 0 when SLN is 0.2.

```
*-------(SUBROUTINE ASSIMP)
*--------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)
```

The light absorbed at a depth L (LAIC) in the canopy ($I_{a,L}$) is obtained by taking the derivative of Eqn 2.6 with respect to the cumulative leaf area index:

$$I_{a,L} = -\,dI_L/dL = k\,(1-\rho)\,I_0\,\exp(-\,k\,L) \qquad (2.12)$$

If expressed for the different light components: the absorbed fluxes for the different components per unit leaf area at depth L in the canopy are:

$$I_{a,df} = -\,dI_{df,L}\,/\,dL = k_{df}\,(1-\rho)\,I_{0,df}\exp(-k_{df}\,L_L) \qquad (2.13)$$

$$I_{a,dr,t} = -\,dI_{dr,t,L}\,/\,dL = k_{dr,t}(1-\rho)\,I_{0,dr}\exp(-k_{dr,t}\,L_L) \qquad (2.14)$$

$$I_{a,dr,dr} = -\,dI_{dr,dr,L}\,/\,dL = k_{dr,dr}(1-\rho)\,I_{0,dr}\exp(-k_{dr,dr}\,L_L) \qquad (2.15)$$

where

$I_{a,df}$ is the absorbed flux of diffuse radiation (VISDF, J m^{-2} leaf s^{-1}),
$I_{a,dr,t}$ the absorbed flux of total direct radiation (VIST, J m^{-2} leaf s^{-1}), and
$I_{a,dr,dr}$ the absorbed flux of the direct component of direct radiation (VISD, J m^{-2} leaf s^{-1}).

```
*--------absorbed flux (J/m2/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.
         ENDIF
```

The total absorbed flux for shaded leaves (J m^{-2} leaf s^{-1}) equals:

$$I_{a,sh} = I_{a,df} + (I_{a,dr,t} - I_{a,dr,dr}) \tag{2.16}$$

```
*-----(SUBROUTINE ASSIMP)
*--------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.
             ENDIF
             FGRSUN = FGRSUN + FGRS * WGAUSS(I2)
             IASUN = IASUN + VISSUN * WGAUSS(I2)
20        CONTINUE
```

For sunlit leaves the situation is more complicated. They absorb the flux that shaded leaves absorb plus the direct component of the direct flux. However, the direct flux intensity differs for leaves with different orientation. The amount of the direct component of the direct flux absorbed by leaves perpendicular to the radiation beams equals:

$$I_{a,dr,dr} = (1 - \sigma)\, I_{0,dr} / \sin \beta \tag{2.17}$$

$I_{a,dr,dr}$ is the direct component of incoming *PAR*. The amount of absorbed direct radiation by leaves depends on the sine of incidence at the leaf surfaces. Therefore, for sunlit leaves, CO_2 assimilation rates have to be calculated separately for leaves with different angles and integrated over all leaf angles. This, again is done by Gaussian integration of CO_2 assimilation rates over the leaf angles (Goudriaan, 1986). Here, a spherical leaf angle distribution is assumed. A similar procedure is followed to calculate the absorbed radiation fluxes.

```
*-----(SUBROUTINE ASSIMP)
         FGRSH  = AMAX * (1.-EXP(-VISSHD*EFF/AMAX))
         FGRS   = AMAX * (1.-EXP(-VISSUN*EFF/AMAX))
```

The CO_2 assimilation-light response of individual leaves follows a saturation type of function, characterized by the initial slope (the initial light use efficiency) and the asymptote (A_m) and is described by the negative exponential function (Goudriaan, 1982):

$$A_L = A_m\,(1 - \exp(-\varepsilon\, I_a / A_m)) \tag{2.18}$$

where

A_L is the gross assimilation rate (FGRS or FGRSH, kg CO_2 ha^{-1} leaf h^{-1}),
A_m the gross assimilation rate at light saturation (AMAX, kg CO_2 ha^{-1} leaf h^{-1}),
ε the initial light use efficiency (EFF, kg CO_2 ha^{-1} leaf h^{-1} / (J m^{-2} leaf s^{-1})), and
I_a is the amount of absorbed radiation (VISSHD or VISSUN, J m^{-2} leaf s^{-1}).

```
FSLLA = CLUSTF * EXP(-KBL*LAIC)
FGL   = FSLLA  * FGRSUN + (1. - FSLLA) * FGRSH
IABS  = FSLLA * IASUN + (1.-FSLLA) VISSHD
```

From the absorbed light intensity at depth L, the assimilation rate at that specific canopy height is calculated for shaded and sunlit leaves separately with Eqn 2.18.

The assimilation rate per unit leaf area at a specific height in the canopy (FGL) is the sum of the assimilation rates of sunlit and shaded leaves, taking into account the proportion of sunlit and shaded leaf area at that depth in the canopy. The fraction sunlit leaf area (f_{sl}) equals the fraction of the direct radiation reaching that layer:

$$f_{sl} = Cf \bullet \exp(-k_{dr,bl} \bullet L_L) \tag{2.19}$$

where

$k_{dr,bl}$ is the extinction coefficient for the direct component of direct radiation (KBL),
Cf is the cluster factor (CLUSTF), and
L_L the leaf area index above depth L (LAIC).

Light absorption and CO_2 assimilation by stems and reproductive organs

In most models, for canopy CO_2 assimilation, only light absorption by leaves is accounted for, although stems and reproductive organs like panicles absorb a substantial amount of radiation. In rice, for example, Stem (or sheath) Area Index (*SAI*) may be as high as 1.5 m^2 stem m^{-2} ground and the Flower (Panicle) Area Index (*FAI*, m^2 flower m^{-2} ground) may be as high as 0.9 (M.J. Kropff and K.G. Cassman, IRRI, unpublished data). The model accounts for CO_2 assimilation of the stem, by adding 50% of the green stem area (SAI) to the LAI, because sheaths are less photosynthetically active than leaves. See section on leaf area development for further information (Section 2.4).

2.3.2 *Maintenance and growth respiration*

The assimilated CO_2 is converted into carbohydrates (CH_2O) in the CO_2 assimilation process. The energy for this reduction process is provided by the absorbed light. The overall chemical reaction of this complex process is:

$$6\ CO_2 + 6\ H_2O \xrightarrow{\text{light}} C_6H_{12}O_6 + 6\ O_2$$

or in a simplified form:

$$CO_2 + H_2O \xrightarrow{\text{light}} CH_2O + O_2$$

From this reaction it follows that for every kg of CO_2 taken up, 30/44 kg of CH_2O is formed; the numerical values representing the molecular weights of CH_2O and CO_2, respectively. Part of the carbohydrates produced in this process are respired to provide the energy for maintaining the existing biostructures. This process is characterized in the model as maintenance respiration. The remaining carbohydrates are converted into structural plant dry matter. The losses in weight as a result of this conversion are characterized as growth respiration.

Maintenance respiration

```
MNDVS  = WLVG/NOTNUL(WLVG+WLVD)
RMCR   = (WLVG*MAINLV + WST*MAINST + ...
          WSO *MAINSO + WRT*MAINRT) * TEFF * MNDVS
TEFF   = Q10**((TAV-TREF)/10.)
```

Maintenance respiration provides the energy for living organisms to maintain their biochemical and physiological status. Through the reaction which is the reverse of CO_2 reduction in CO_2 assimilation, the radiation energy which was fixed in the photosynthetic process in a chemical form is released in a suitable form (ATP and NADPH):

$CH_2O + O_2$ ---> $CO_2 + H_2O$ + energy

This process consumes roughly 15 - 30% of the carbohydrates produced by a crop in a growing season (Penning de Vries et al., 1989), which indicates the importance of accurate quantification of this process in the model. However, the process is poorly understood at the biochemical level and simple empirical approaches are inaccurate since it is impossible to measure maintenance respiration in the way it is defined (Penning de Vries et al., 1989; Amthor, 1984). The best way to quantify maintenance respiration is to measure the CO_2 production rate of plant tissue in the dark. The approach taken in the model is based on theoretical considerations, empirical studies and studies in which the carbon balance in the model was evaluated using crop growth and canopy CO_2 assimilation data.

Three components of maintenance respiration can be distinguished at the cellular level: maintenance of concentration differences of ions across membranes, maintenance of proteins and a component related to the metabolic activity of the tissue (Penning de Vries, 1975). Maintenance respiration can thus be estimated from mineral and protein concentrations and metabolic activity as presented by de Wit et al. (1978). In the model, we use an adapted version of the simple approach developed by Penning de Vries & van Laar (1982), in which maintenance requirements are approximately proportional to the dry weights of the plant organs to be maintained:

$$R_{m,r} = mc_{lv}\,W_{lv} + mc_{st}\,W_{st} + mc_{rt}\,W_{rt} + mc_{so}\,W_{so} \qquad (2.20)$$

in which

$R_{m,r}$ is the maintenance respiration rate at the reference temperature (25 °C) in kg CH_2O ha^{-1} d^{-1} (RMCR at 25 °C),

W_{lv}, W_{st}, W_{rt} and W_{so} are the weights of the leaves, stems, roots and storage organs (WLVG, WST etc., kg dry matter ha^{-1}) respectively, and

mc_{lv}, mc_{st}, mc_{rt} and mc_{so} are the maintenance coefficients for leaves, stems, roots and storage organs, respectively (MAINLV etc., CH_2O kg^{-1} DM d^{-1}).

The maintenance coefficients (kg CH_2O kg^{-1} dry matter d^{-1}) have different values for the different organs because of large differences in nitrogen contents. Standard values for maintenance coefficients are 0.03 for leaves, 0.015 for stems and 0.01 for roots (Spitters et al., 1989). For tropical crops, like rice, lower values are used: 0.02 for the leaves and 0.01 for the other plant organs (Penning de Vries et al., 1989). In the model, for mc_{so} a coefficient of 0.003 is used, which accounts for the small fraction of active tissue in the storage organs. Maintenance respiration can also be approached by using the coefficient for stem tissue for the active part (non-stored material) only.

The effect of temperature on maintenance respiration is simulated assuming a Q_{10} of 2 (doubling at every 10 °C increase) (Penning de Vries et al., 1989):

$$R_m = R_{m,r} \bullet 2^{(T_{av} - T_r)/10} \tag{2.21}$$

where

R_m is the actual rate of maintenance respiration (RMCR, kg CH_2O ha^{-1} d^{-1}),

T_{av} is the average daily temperature (TAV, °C), and

T_r is the reference temperature (TREF, °C).

To account for the metabolic effect, a special reduction factor is introduced in the model which accounts for the reduction in metabolic activity when the crop ages (MNDVS) (the NOTNUL statement is included to avoid division by zero, at emergence). When nitrogen content is simulated in the model, this factor can be related to the N content (van Keulen & Seligman, 1987). In the current model, the total rate of maintenance respiration is assumed to be proportional to the fraction of green leaves and basically accounts for the decrease in N content of the leaves. This procedure for calculating the effect of age on maintenance respiration was used in the SUCROS model (Spitters et al., 1989) and was based on studies in which measured crop growth and canopy CO_2 assimilation data were analysed using a simple simulation model (Louwerse et al., 1990; C.J.T. Spitters, CABO, unpubl. data).

Growth respiration

```
CRGCR   = FSH*(CRGLV*FLV  + CRGST *FST *(1.-FSTR) + ...
                            CRGSTR*FSTR*FST       + ...
                CRGSO*FSO) + CRGRT *FRT
```

The carbohydrates in excess of the maintenance costs are available for conversion into structural plant material. In the process of conversion, CO_2 and H_2O are released as scraps from the cut and paste process in biosynthesis. Following the reactions in the biochemical pathways of the synthesis of dry matter compounds (carbohydrates, lipids, proteins, organic acids and lignin from glucose (CH_2O)), Penning de Vries et al. (1974) derived the assimilate requirements for the different compounds. From the composition of the dry matter, the assimilate requirements for the formation of new tissue can be calculated. Typical values for leaves, stems, roots and storage organs (CGR...) have been presented by Penning de Vries et al. (1989). The average carbohydrate requirements for the whole crop (CRGCR) is calculated by weighting the coefficients with the fraction of dry matter allocation over the organs (FLV, FST etc.).

2.3.3 Daily growth rate from CO_2 assimilation and respiration rates

```
GCR    = ((DTGA*30./44.) - RMCR +                         ...
          (LSTR*LRSTR*FCSTR*30./12.))/CRGCR
NGCR   = GCR - LSTR * LRSTR * FCSTR * 30./12.
```

The daily growth rate (G_p, kg dry matter ha^{-1} d^{-1}) is calculated as follows:

$$G_p = (A_d \bullet (30/44) - R_m + R_t) / Q \qquad (2.22)$$

where

A_d is the daily rate of gross CO_2 assimilation (DTGA, kg CO_2 ha^{-1} d^{-1}),
R_m the maintenance respiration costs (RMCR, kg CH_2O ha^{-1} d^{-1}),
R_t the amount of available stem reserves for growth (kg CH_2O ha^{-1} d^{-1}), and
Q the assimilate requirement for dry matter production, (kg CH_2O kg^{-1} dry matter).

The amount of stem reserves (LSTR) is multiplied by LRSTR (=0.947) to account for 5.3% losses when reserves are allocated (Penning de Vries et al., 1989). These reserves are expressed in CH_2O by multiplying by the fraction carbon in the stem reserves (FCSTR) and the molecular weight of CH_2O and C (30./12.) to convert the carbon into assimilates that are available for new growth (dry matter production).

2.3.4 Dry matter partitioning

```
FSH    = AFGEN (FSHTB, DVS)
FRT    = AFGEN (FRTTB, DVS)
FLV    = AFGEN (FLVTB, DVS)
FST    = AFGEN (FSTTB, DVS)
FSO    = AFGEN (FSOTB, DVS)
LLV    = WLVG * AFGEN (DRLVT,DVS)
LSTR   = INSW (DVS-1., 0., WSTR / TCLSTR)
```

The total daily produced dry matter is partitioned among the various groups of plant organs (leaves, stems, storage organs and roots) according to partitioning coefficients (*pc*, kg dry matter organ kg^{-1} dry matter crop) defined as a function of the phenological development stage (*D*):

$$pc_k = f(D) \qquad (2.23)$$

The death or loss rate of the leaves (LLV) is calculated using a relative death rate of leaf weight (DRLVT), which is a function of DVS. The loss rate of stem reserves (LSTR) starts at flowering and is simulated by dividing the weight by a time coefficient (the inverse of the relative loss rate, TCLSTR).

```
      CALL SUBRTS (DOY,    DOYTR, GCR , FRT,    FSH , FLV, LLV , FST,...
                   FSTR,   LSTR , WLVG, WSTR , WSTS, WRT, NPLH ,NH ,...
                   NPLSB, DELT,                                    ...
                   GLV,    GSTR,  RWLVG,GRT,   RWSTR,GST,          ...
                   RWLVG1,GRT1,   RWSTR1,GST1)

*----------(SUBROUTINE SUBRTS)
         IF (DOY.EQ.DOYTR) THEN
              PLTR   = NPLH*NH/NPLSB
           ELSE
              PLTR   = 1.
         ENDIF

             RWLVG1 = (WLVG * (1. -PLTR))/DELT
             GST1   = (WSTS * (1. -PLTR))/DELT
             RWSTR1 = (WSTR * (1. -PLTR))/DELT
             GRT1   = (WRT  * (1. -PLTR))/DELT

         GRT     = GCR * FRT                     - GRT1
         GLV     = GCR * FSH * FLV               - RWLVG1
         RWLVG   = GLV - LLV
         GST     = GCR * FSH * FST * (1.-FSTR)   - GST1
         GSTR    = GCR * FSH * FST * FSTR        - RWSTR1
         RWSTR   = GSTR - LSTR
```

The growth rates of the different organs is calculated in the subroutine SUBRTS. First the growth rates at the day of transplanting are calculated, to account for the reduction in plant density. The dry matter is first distributed over shoot and root (FSH and FRT) and then the shoot fraction is divided between stems, leaves and storage organs (FSH × FLV, etc.). The growth rate of plant organ group k ($G_{p,k}$) is thus obtained by multiplying the total potential growth rate (G_p, Eqn 2.22, GCR) by the fraction allocated to that organ group k (pc_k):

$$G_{p,k} = pc_k \, G_p \qquad (2.24)$$

The growth rate of structural stem material is multiplied by (1.–FSTR) as the fraction allocated to the stem FST is based on total stem weight. The growth rate of the stem reserves pool (GSTR) is calculated in a similar way from FSTR.

Spikelet and grain formation

```
      CALL SUBGRN (GCR ,FSH,FSO ,DOY,DOYS, DOYTR,DVS,WRR,PWRR,        ...
                   SPGF,TAV,TMAX,NSP,TIME,    GRAINF,GSO,GGR,GNSP,GNGR)
```

The subroutine SUBGRN calculates the formation rate of spikelets and grains (GNSP and GNGR) and the fertility of spikelets as a function of temperature around flowering. The spikelet fertility routine was developed by Horie et al. (1992).

```
*------(SUBROUTINE SUBGRN)
      LOGICAL GRAINS
      SAVE

      GRAINF = 1.
      IF (DOY.EQ.DOYS) GRAINS = .FALSE.
      GSO = GCR*FSH*FSO
      IF (DVS.GT.1.) THEN
          GGR = GSO
      ELSE
          GGR = 0.
      ENDIF
      IF (GRAINS) THEN
         IF (WRR .GT. PWRR) GRAINF = -1.
         IF (GRAINF.LT.0.) THEN
           WRITE (6,10) GRAINF, TIME
10         FORMAT (/,' *** Sink limitation before DVS=2 !!!! ***,/,
     &      ' GRAINF',F8.3, ' at TIME=',F6.1)
         ENDIF
      ENDIF
```

When DVS is greater than 1. the grainfilling process is initiated. This procedure assumes that the non-grain components of the panicle are formed before DVS=1. (first flowering). When the maximum possible grain weight will (PWRR, see Section 2.3.5) be exceeded, the model stops and send a message that the sink is limiting.

```
      DVSPI = 0.65
      DVSF  = 1.
      IF ((DVS.GE.DVSPI) .AND. (DVS.LE.DVSF)) THEN
         GNSP = GCR * SPGF
      ELSE
         GNSP = 0.
      ENDIF
```

In grain crops, the carbohydrate production in the grainfilling period can be higher than the storage capacity of the grains, which is determined by the number of grains per m^2 and the maximum growth rate of the grains. This may result in the accumulation of assimilates in the leaves causing reduced rates of CO_2 assimilation through a feedback mechanism (Barnett &

Pearce, 1983). This can be very important in rice when it is grown in extreme environments as both low and high temperatures before flowering can induce spikelet sterility which results in a low sink capacity (Yoshida, 1981).

In wheat, it has been found that the size of the spike at flowering is proportional to the number of grains that are formed (Fischer, 1985), and that spike size is closely correlated with the amount of growth of the crop during the spike formation period. The amount of growth over this period depends both on the duration of the period, which is influenced by temperature, and the crop growth rate, which is influenced by temperature and radiation. Similar relationships have been found in rice (Yoshida & Parao, 1976) and were used by Islam & Morison (1992) relating rice yields in Bangladesh to the 'photothermal quotient' (Q), the ratio of solar radiation in the 30 days prior to flowering to the mean temperature over the same period minus a base temperature.

In experiments at IRRI, we have found a good relationship between the total crop growth over the period from panicle initiation to first flowering and the number of spikelets at flowering (Figure 2.7). This relationship holds across the wet and dry seasons, for levels of nitrogen application ranging from 0 to 285 kg ha^{-1}, from planting densities ranging from 25 to 125 plants m^{-2}, and for severe drought stress. A similar relationship is also found at the tiller level, so that the number of spikelets per tiller can be explained by the growth of each tiller during the period in which the panicle for that tiller is formed. The effects of solar radiation, temperature, nitrogen, competition, and water, on spikelet formation, therefore, seem to be able to be integrated by their effects on crop growth over the panicle formation period. We have called the slope of this relationship the spikelet formation factor (γ). For a given variety, the relationship is remarkably consistent, although there do appear to be differences between varieties. For IR72, for example, γ has a value of about 65 spikelets g^{-1} total dry matter, but ranges between about 45 and 70 spikelets g^{-1} in a number of varieties used in experiments at IRRI.

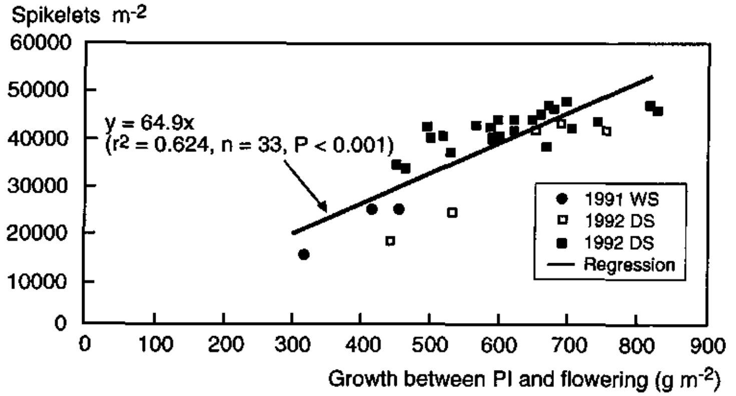

Figure 2.7. The relationship between spikelet numbers m^{-2} and crop growth between PI and flowering (data from Kropff, Cassman, Torres and Liboon (symbols ●, ▫) and S. Peng (■) IRRI, cultivar IR72).

In the model, the amount of growth from panicle initiation (defined as DVS = 0.65) to first flowering (defined as DVS = 1.0) is tracked, and the number of spikelets (S) is calculated as the product of this growth and γ, i.e.

$$S_i = \sum_{i=P}^{F} (G_i \bullet \gamma) \qquad (2.25)$$

where P and F are the dates of panicle initiation and first flowering, respectively, and G_i is increment in crop weight on day i. Thus, at flowering, a certain number of spikelets have been produced, which determines the maximum yield (Y_{max}, kg ha^{-1}) that can be achieved:

$$Y_{max} = S_f \bullet G_{max} \bullet 10^4 \qquad (2.26)$$

where S_f is the number of spikelets at flowering (spikelets m^{-2}), and G_{max} is the grain size (mg grain^{-1}), assumed to be constant for a variety (Yoshida, 1981). The actual grain yield (Y, kg ha^{-1}) depends on the amount of assimilates produced in the period from flowering to maturity (defined as DVS = 2.0) plus any translocated assimilates from stem reserves, provided Y does not exceed Y_{max}, i.e.

$$Y = \sum_{i=F}^{M} (G_i + T_i) \qquad Y \leq Y_{max} \qquad (2.27)$$

where F and M are the dates of flowering and maturity, respectively, and G_i and T_i are the increment in crop weight, and the amount of assimilates translocated, respectively, on day i. The model terminates the simulation when either $Y = Y_{max}$ or when maturity is reached (DVS = 2.0), whichever occurs first.

```
*--------(SUBROUTINE SUBGRN)
* Grain formation from spikelets (GNGR)
      IF (DOY.EQ.DOYTR) COLDTT = 0.
      IF (DOY.EQ.DOYTR) TFERT  = 0.
      IF (DOY.EQ.DOYTR) NTFERT = 0.

      IF ((DVS.GE.0.75) .AND. (DVS.LE.1.2)) THEN
         CTT    = MAX(0., 22.-TAV)
         COLDTT = COLDTT + CTT
         ENDIF
      IF ((DVS.GE.0.96) .AND. (DVS.LE.1.2)) THEN
         TFERT  = TFERT  + TMAX
         NTFERT = NTFERT + 1.
      ENDIF

      IF ((DVS.GE.1.2) .AND.(.NOT. GRAINS)) THEN
         GRAINS = .TRUE.
         SF1    = 1. - (4.6+0.054*COLDTT**1.56)/100.
         SF1    = MIN(1., MAX(0.,SF1))
         TFERT  = TFERT/(NTFERT)
```

```
   SF2    = 1./(1.+EXP(0.853*(TFERT-36.6)))
   SF2    = MIN(1., MAX(0.,SF2))
   SPFERT = MIN(SF1, SF2)
   GNGR   = NSP*SPFERT
ELSE
   GNGR   = 0.
ENDIF
```

This section calculates the spikelet fertility according to Horie et al. (1992). Using the 'cooling degree-day' concept (Uchijima, 1976), the relation between daily mean temperature (T_i) and the percentage sterility may be approximated by the equation that calculates SPF1 (Figure 2.8). The cooling degree-days (Q_t) are calculated as follows:

$$Q_t = \sum (22 - T_i) \qquad (2.28)$$

The summation of Eqn 2.28 is done for the period of highest sensitivity of the rice panicle to cool temperatures ($0.75 \leq DVS \leq 1.2$).

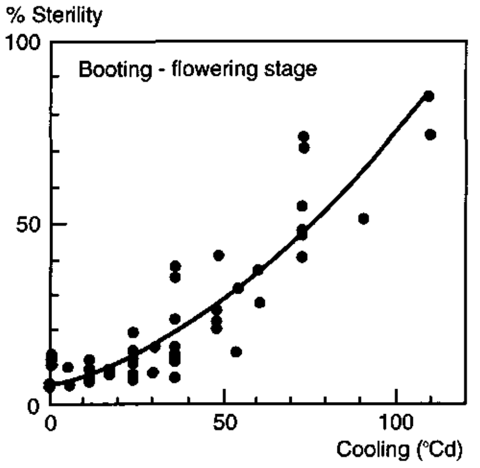

Figure 2.8. Relation between cooling degree-days and percentage spikelet (δ) sterility of 'Eiko' rice between booting and flowering stages (Horie, 1988).

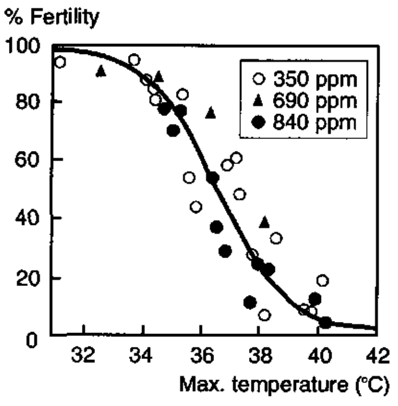

Figure 2.9. Relation between average daily maximum temperature during the flowering period and spikelet fertility in 'Akihikari' rice acclimated to different CO_2 concentrations (Horie, 1993).

Rice spikelets are also sensitive to high temperature, particularly at anthesis. Damage to the pollen occurs when the temperature at flowering is above approximately 35 °C (Satake & Yoshida, 1978; Matsui & Horie, 1992). Figure 2.9 represents the relationship between the fraction of fertile spikelets and the average daily maximum temperature over the flowering period (0.96 ≤ DVS≤ 1.22) for Akihikari rice grown in a temperature gradient tunnel (Horie, 1993) with elevated and ambient CO_2 concentrations. Figure 2.9 indicates that CO_2 concentration has no effect on the temperature and fertility relationship. The relation shown in Figure 2.9 may be approximated by

$$1 - \gamma = 1 - 1/(1 + \exp(0.853\ (T_M - 36.6))) \qquad (2.29)$$

where T_M is the average daily maximum temperature during the flowering period. Daily maximum temperature is employed to account for rice spikelets usually flowering during the daytime. Actual spikelet sterility is calculated as the minimum of that due to cool temperature and that due to high temperature (Eqn 2.29).

2.3.5 Dry matter production and number of grains and spikelets

```
WLVG    = INTGRL (WLVGI, RWLVG)
WLVD    = INTGRL (ZERO ,   LLV)
WSTS    = INTGRL (WSTI ,   GST)
WSTR    = INTGRL (ZERO , RWSTR)
WSO     = INTGRL (WSOI,    GSO)
WRT     = INTGRL (WRTI,    GRT)
WST     = WSTS + WSTR
WAGT    = WLVG + WST + WSO + WLVD
WAG     = WLVG + WST + WSO
WRR     = INTGRL (ZERO, GGR)
WRR14   = 1.14 * WRR
NGR     = INTGRL (ZERO, GNGR)
NSP     = INTGRL (ZERO, GNSP)
PWRR    = NGR * WGRMX
```

Total dry weights of the plant organs are obtained by integrating their daily growth rates over time. This approach to dry matter partitioning can be improved by introducing effects of other factors that determine partitioning patterns like the water and nutrient status of the crop (van Keulen & Seligman, 1987). The model simulates a pool of reserves in the stems ((WSTR) which are translocated to the grains after flowering.

2.4 Leaf area development

```
CALL SUBDD (TMAX,TMIN,TBLV,30.,42., HULV)
CALL SUBLAI(SWIDS,SWILAI,DAS,DOYS,DOYTR,LAPE, RGRL,  TSLV, ...
            NPLSB,  WLVG,  SLA,   NH, NPLH, SHCKL, DVS,    ...
```

```
                 LAISIM, TSHCKL)
      LAI     = INSW (SWILAI, XLAI, LAISIM)
      SSGA    = AFGEN(SSGATB, DVS)
      SAI     = SSGA * WST
      SLA     = AFGEN(SLATB , DVS)
      XLAI    = AFGEN(XLAITB, DOY)
      ALAI    = LAI + 0.5 * SAI
```

As discussed in the description of the subroutine ASSIMP, 50% of the green stem area index (SAI) is added to the leaf area index (LAI), because of lower photosynthetic activity. The SAI is calculated from the stem dry weight, using the SSGA (specific green stem area) which was estimated in experiments. After flowering, the SSGA is reduced because of death of sheath tissue (SSGA as a function of the development stage).

In the model, the measured leaf area index (XLAI, ha ha^{-1}) can be used (SWILAI=–1.), or the LAI can be simulated (LAISIM, SWILAI=1.).

The green leaf area of plants determines the amount of absorbed light and thus CO_2 assimilation. In early versions of the model (Penning de Vries et al., 1989), leaf area development was assumed to be only determined by the amount of carbohydrates available for leaf growth. Leaf area was calculated from leaf dry matter using the Specific Leaf Area (SLA, m^2 leaf kg^{-1} leaf). This caused strong overestimations of LAI by the model. The variability in SLA is caused by the fact that leaf expansion is mainly temperature driven in the early stages of crop growth when the leaves do not shade each other and leaf area development is not limited by the amount of available assimilates (Horie et al., 1979). Light intensity determines the rate of CO_2 assimilation and hence the supply of assimilates to the leaves, whereas temperature affects the rates of cell division and expansion.

The subroutine SUBLAI

```
      SUBROUTINE SUBLAI(SWIDS,SWILAI,DAS,DOYS, DOYTR,LAPE,RGRL,TSLV,
     &                  NPLSB, WLVG,  SLA,   NH, NPLH, SHCKL, DVS,
     &                  LAISIM, TSHCKL)
      IMPLICIT REAL (A-Z)
      INTEGER IDAS,ISA
      SAVE

      IDAS = INT(DAS)
      IF (SWIDS.LT.0.) THEN
        ISA  = INT(DOYTR) - INT(DOYS)
        IF (ISA.LT.0) THEN
            ISA = ISA + 365
          ELSE
            ISA = ISA
        ENDIF
```

```
  LAIEXS = 0.
  WLVEXS = 0.
        IF (IDAS.LT.ISA) THEN
           IF (LAISIM.LT.1.) THEN
              LAPI   = LAPE * (EXP(RGRL*TSLV))
              LAISIM = LAPI * NPLSB
              WLVEXS = WLVG
              LAIEXS = LAISIM
           ELSE
              LAISIM = SLA*(WLVG-WLVEXS)+LAIEXS
           ENDIF
        ELSE
           IF (IDAS.EQ.ISA) THEN
              LAII   = LAISIM * NH * NPLH / NPLSB
              TSLVTR = TSLV
              TSHCKL = SHCKL * TSLVTR
           ENDIF
           IF (TSLV.LT.(TSLVTR+TSHCKL)) THEN
              LAISIM = LAII
           ELSE
              IF ((LAISIM.LT.1.0) .AND. (DVS.LT.1.0)) THEN
                 LAISIM = LAII*(EXP(RGRL*(TSLV-TSLVTR-TSHCKL)))
                 WLVEXP = WLVG
                 LAIEXP = LAISIM
              ELSE
                 LAISIM = LAIEXP+SLA*(WLVG-WLVEXP)
              ENDIF
           ENDIF
        ENDIF
      ENDIF
IF (SWIDS.GT.0.) THEN
   IF (IDAS.EQ.0.) LAISIM = NPLSB * LAPE
      IF (LAISIM.LT.1.) THEN
          LAPI   = LAPE * (EXP(RGRL*TSLV))
          LAISIM = LAPI * NPLSB
          WLVEXS = WLVG
          LAIEXS = LAISIM
      ELSE
          LAISIM = SLA * (WLVG-WLVEXS) + LAIEXS
      ENDIF
ENDIF
IF (SWILAI.LT.0.) LAISIM = 0.
RETURN
END
```

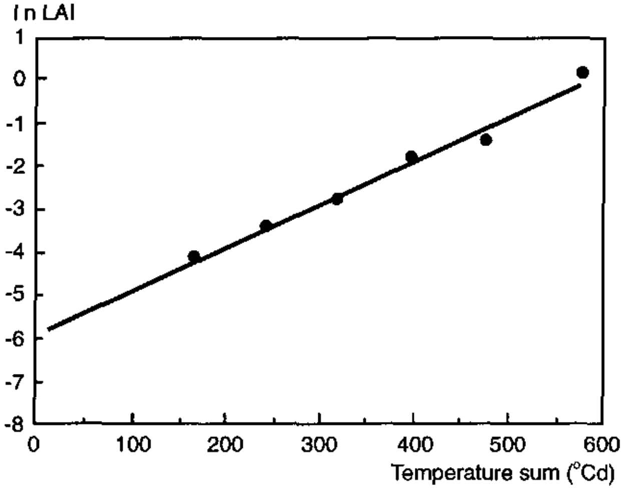

Figure 2.10. The relation between the natural logarithm of leaf area of free growing direct-seeded young rice plants and the temperature sum (°Cd). Data are from a wet season 1991 experiment with IR72 at IRRI, Los Baños, Philippines (Torres, Liboon, Kropff & Cassman, IRRI, unpublished).

The LAI is simulated in the subroutine SUBLAI. It contains two sections, one for transplanted rice and one for direct-seeded rice. For the different phases, different sections were introduced.

For a closed canopy, the LAI is calculated from the leaf dry weight using the SLA. When the canopy is not closed the plants grow exponentially as a function of the temperature sum TSLV (Figure 2.10):

$$LAI_{ts} = N\, L_{p,0} \exp(R_l\, ts) \qquad (2.30)$$

where

LAI_{ts} is the leaf area index (m^2 leaf m^{-2} ground) at a specific temperature sum (*ts*, TSLV, °Cd) after emergence,
N the number of plants per m^2,
$L_{p,0}$ the initial leaf area per plant at seedling emergence (LAPE, m^2 $plant^{-1}$), and
R_l the relative leaf area growth rate (RGRL, $(°Cd)^{-1}$).

The temperature sum *ts* is calculated using the same procedure to calculate heat units as for phenological development. The exponential phase ends when the portion of assimilates allocated to non-leaf tissue sharply increases, or when mutual shading becomes substantial. As a yardstick for these events, one can use LAI = 1.0 as the end of the exponential growth period, when leaves start to overlap. This can easily be checked by plotting ln(LAI) versus *ts* and determining the LAI up to which growth is linear (Figure 2.10). In transplanted rice, LAI development in the seedbed is simulated in the same way.

On the date of transplanting the seedling age in degree-days (TSLV, °Cd) is calculated (TSLVTR). Based on this seedling age the duration of the transplanting shock (no LAI growth) in degree-days is calculated (TSHCKL) (Figures 2.11A and B). After the transplanting shock period, growth is exponential again when LAI<1., and when LAI exceeds 1 the SLA concept is used. In case of direct-seeded rice, the procedure is the same as in the seedbed.

To account for leaf senescence, a relative leaf death rate is defined, being a function of the development stage. In the model, the relative death rate of the leaves is applied to the leaf weight to calculate the weight loss of the leaves (LLV). The reduction in leaf area is calculated from the loss of leaf weight using the specific leaf area (SLA).

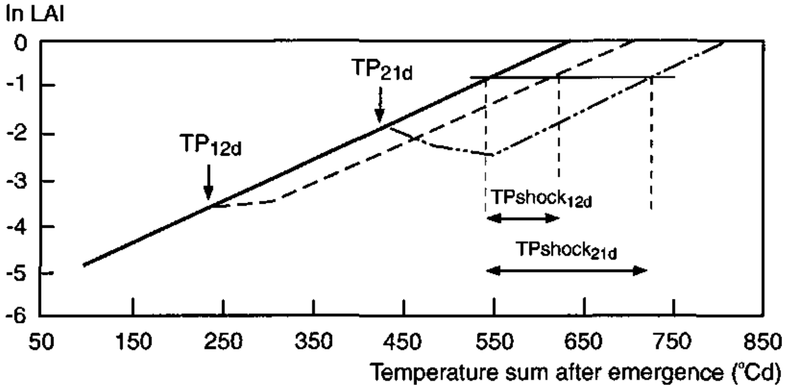

Figure 2.11A. The relation between the natural logarithm of leaf area of free growing direct-seeded and transplanted (at 12 days and 21 days after emergence) young rice plants and temperature sum (°Cd). Data are from a wet season 1991 experiment with IR72 at IRRI, Los Baños, Philippines (Torres, Liboon, Kropff & Cassman, IRRI, unpublished).

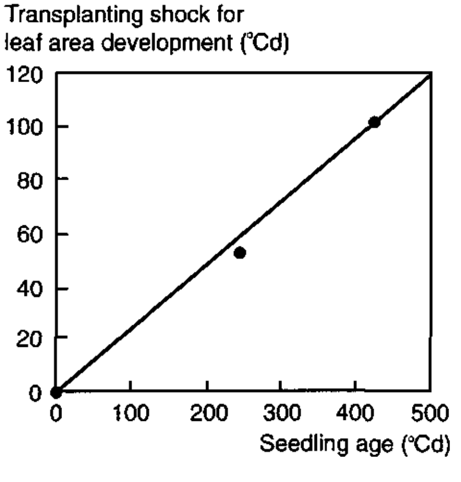

Figure 2.11B. Relation between the transplanting shock effect on leaf area development in rice expressed as a period where no growth occurs (TSHCKL, °Cd) and the seedling age at transplanting, also expressed in degree-days. Data are from a wet season 1991 experiment with IR72 at IRRI, Los Baños, Philippines (Torres, Liboon, Kropff & Cassman, IRRI, unpublished).

2.5 Time and environmental variables

```
WEATHER WTRDIR='C:\WEATHER\', CNTR='PHIL', ISTN=1, IYEAR=1992
*  Reading weather data:
*  RDD    Daily global radiation       J/m2/d
*  TMMN   Daily minimum temperature    degree C
*  TMMX   Daily maximum temperature    degree C
*  VP     Vapour pressure              kPa
*  WN     Wind speed                   m/s
*  RAIN   Precipitation                mm
*  LAT    Latitude of the side         degree
*  DOY    Day of year                  d

      TMAXC  = INSW (SWITMP, 0., AFGEN(TMCTB, DOY))
      TMINC  = INSW (SWITMP, 0., TMAXC)

      CALL COVER (SWICOV, DAS, DOYTR, DOYS, TMPCOV)
      DAS    = INTGRL (ZERO, RDAS)
      RDAS   = 1.

      TAV    = (TMIN + TMAX)/2.
      TAVD   = (TMAX + TAV) /2.
      TS     = INTGRL (ZERO, HU  )
      TSLV   = INTGRL (ZERO, HULV)
      DTR    = RDD
      TMIN   = TMMN + TMINC
      TMAX   = TMMX + TMAXC + TMPCOV
```

```
*----------------------------------------------------------
*  Station Name: IRWE0001
*  Author      : Climate Unit, IRRI      -99.000: nil value
*  Source      : International Rice Research Institute
*
*  Comments    : This file is extracted from CLICOM database
*  Longitude: 121 15 E   Latitude:  14 11 N   Altitude:  21 m
*
*  Column     Daily Value
*     1       Station number
*     2       Year
*     3       Day
*     4       Irradiation              KJ m-2 d-1
*     5       min temperature              oC
*     6       max temperature              oC
*     7       early morning vp            kPa
*     8       mean wind speed            m s-1
*     9       precipitation              mm d-1
*----------------------------------------------------------
121.25 14.18   21 0.00 0.00
  1 1991   1   9683.  23.6  28.4  2.82    .9   2.1
  1 1991   2  14867.  23.7  30.5  2.85   1.6    .0
  1 1991   3  10187.  21.6  28.5  2.45   1.6    .0
  1 1991   4  19294.  21.3  30.1  2.47   2.2    .0
  1 1991   5  19546.  20.6  31.0  2.60   1.1    .0
  1 1991   6   9431.  21.0  28.0  2.46   1.7   2.0
```

Figure 2.12. The content of file PHIL1.991, the weather file for Los Baños, Philippines, Station 1, Year 1991. Check whether your weather data have the same units. Note: radiation is expressed in KJ m^{-2} d^{-1} and will be (in the model) automatically converted into J m^{-2} d^{-1}.

Table 2.1. Indicative values for the empirical constants a_A and b_A in the Ångström formula, in relation to latitude used by the Food and Agriculture Organization, FAO. Source: Frère and Popov, 1979.

	a_A	b_A
Cold and temperate zones	0.18	0.55
Dry tropical zones	0.25	0.45
Humid tropical zones	0.29	0.45

The weather file has a strict format and the data have specified units (see header of the weather data file, Figure 2.12). The first letters of the weather file indicate the name of the country, the following digit indicates the station number in the country, and as extension, the year is given e.g. 1991 is 991. So, if the weather file is called MALA5.993 (Malaysia, Station no 5 (self-chosen number) and year 1993), you have to give the following information in the WEATHER statement to identify the file and the directory where the file is located:

```
WEATHER WTRDIR='C:\WEATHER\', CNTR='MALA', ISTN=5, IYEAR=1993
```

If only sunshine hours are available, the radiation can be calculated from the Ångström formula:

$$S_g = S_0 \bullet (a_A + b_A \bullet (n_s/N_s)) \tag{2.31}$$

where

S_0 is the theoretical amount of global radiation without an atmosphere,
a_A an empirical constant (see Table 2.1),
b_A an empirical constant (see Table 2.1), and
n_s/N_s the ratio between the amount of bright sunshine hours (n_s) and the maximum amount of sunshine hours (N_s).

The values of S_0 and N_s can be calculated using the procedures given in Section 2.3.1 (DS0 and daylength), which are calculated in the subroutine ASTRO.

For climate change studies, daily maximum and minimum temperatures can be altered by using the function TMCTB, which defines the temperature change as a function of time (TMAXC, TMINC), and the parameter SWITMP has to be set at 1.

```
CALL COVER (SWICOV, DAS, DOYTR, DOYS, TMPCOV)
```

If a plastic cover is used in the seedbed, like in Japan, the maximum temperature is raised by 9 °C based on preliminary observations by Horie (pers. comm.). The parameter SWICOV has to be set at 1 in case of use of a cover, otherwise SWICOV=–1.

2.6 Carbon balance check

```
CALL SUBCBC (CKCIN,CKCFL,TIME,  CBCHK)
CKCIN  = (WLVG+WLVD-WLVGI)*FCLV        +    ...
         (WSTS-WSTI)*FCST + WSTR*FCSTR +    ...
         (WRT -WRTI)*FCRT + WSO *FCSO
CKCFL  = TNASS * (12./44.)
CTRANS = RWLVG1*FCLV  + GST1*FCST +         ...
         RWSTR1*FCSTR + GRT1*FCRT
TNASS  = INTGRL(ZERO, RTNASS)
RTNASS = ((DTGA*30./44. - RMCR)*44./30.) - RGCR -   ...
           (CTRANS*44./12.)
RGCR   = (GRT +GRT1)  *CO2RT + (GLV+RWLVG1)*CO2LV + ...
         (GST +GST1)  *CO2ST + GSO*CO2SO          + ...
         (GSTR+RWSTR1)*CO2STR                     + ...
         (1.-LRSTR)*LSTR*FCSTR*44./12.
CO2RT  = 44./12. * (CRGRT *12./30. -  FCRT)
CO2LV  = 44./12. * (CRGLV *12./30. -  FCLV)
CO2ST  = 44./12. * (CRGST *12./30. -  FCST)
CO2STR = 44./12. * (CRGSTR*12./30. - FCSTR)
CO2SO  = 44./12. * (CRGSO *12./30. -  FCSO)
```

The model contains a carbon balance check, to be sure that total net assimilated carbon (CKCFL) exactly equals the carbon fixed in dry matter and the carbon lost as a result of growth and maintenance respiration (CKCIN). The model gives an error message (in the subroutine CBCHK) if the amount of carbon not accounted for is more than 0.1% of the total assimilated carbon. Of course, in a good model the difference between CKCIN and CKCFL has to be 0.

CKCIN is calculated by multiplying all weight integrals by the fraction carbon in dry matter (from: Penning de Vries et al., 1989). Total net assimilated carbon is calculated from the gross CO_2 assimilation (DTGA) and the carbon losses as a result of maintenance respiration (RMCR) and growth respiration (RGCR). Carbon losses as a result of losses through growth respiration are calculated from the dry matter growth rates multiplied by the CO_2 production factor (Penning de Vries et al., 1989). This CO_2 production factor is calculated from the assimilate requirements of an organ (CRG..) and the fraction carbon in the dry matter produced. The numbers indicate the ratio's of the molecular weights of carbon (12), CO_2 (44) and CH_2O (30), e.g.:

```
CO2RT  = 44./12. * (CRGRT *12./30. -  FCRT)
```

in dimension analysis:

$$CO_2 = \frac{CO_2}{C} \times \left(\frac{CH_2O}{DM} \times \frac{C}{CH_2O} - \frac{C}{DM}\right) = CO_2 \text{ per unit of DM produced.}$$

The part of the stem reserves is complex, because during the translocation process, losses of 5.3% are accounted for in the model. Those losses are quantified in the calculation of RGCR.

2.7 Run control

```
FINISH DVS        > 2.
FINISH NCOLD      > 3.
FINISH GRAINF     < 0.
TIMER STTIME      = 4., FINTIM = 300., DELT = 1., PRDEL = 5.
TRANSLATION_GENERAL DRIVER='EUDRIV'
PRINT      DOY,DVS,TS,TSLV,XLAI,LAI,ALAI,LAISIM,NFLV,XNFLV,    ...
           GST,GLV,GSO,GSTR,GRT,WRT,WLVG,XWLVG,WLVD,XWLVD,     ...
           WST,XWST,WSO,XWPA,WAG,XWTDM,TSHCKD,TSHCKL,WGR,DTGA,...
           AMAX,CBCHK, DPAR, DPARI, NGCR
```

In the model, several finish conditions have been defined (e.g. FINISH DVS > 2). In the FST timer statement, the start day of simulation is given, the finish time of simulation (FINTIM), the time step of integration (DELT which has to be 1!!, because of the semi-analytical integration of CO_2 assimilation in the TOTASP routine). PRDEL indicates the time interval at which output is generated. The PRINT statement indicates which variables can be used for graphical output to your screen, and will be send to the output file RES.DAT.

FST has a rerun facility, which enables the model to conduct multiple runs. Before the STOP statement and between two END statements, new parameter values can be given for another run (treatment or so).

2.8 Observed values

```
XWLVG  = AFGEN(XWLVGT, DOY)
XWLVD  = AFGEN(XWLVDT, DOY)
XWST   = AFGEN(XWSTTB, DOY)
XWPA   = AFGEN(XWPATB, DOY)
XWTDM  = AFGEN(XWTDMT, DOY) - XWLVD
XWT    = AFGEN(XWTDMT, DOY)
XNFLV  = AFGEN(XNFLVT, DOY)
```

In this section the observed values of the organ weights and the specific leaf nitrogen (XNFLV) are specified to allow model comparison.

2.9 Functions and parameters for rice

The functions and parameters for rice are specified in Section 9 in the model. Many of these values are general for rice, some are variety specific. This section will be discussed in Chapter 3.

2.10 TERMINAL section

```
TERMINAL
       WGR     = WRR/NOTNUL(NGR)
END
PARAM SWILAI=1.
END
STOP
       (SUBROUTINES .....)
```

In the TERMINAL section of an FST program variables are calculated only once at the end of a simulation run, this section is optional. Hereafter, the possibility is given to make use of the RERUN facility. After the STOP statement the subroutines are invoked.

3 Model parameterization

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This chapter describes how values for the key parameters that are used in the model have been derived. Most parameter values can be used in a general sense for rice, some are variety specific. In the applications chapter we discuss which parameters have to be (re)estimated for specific applications.

```
*** 9.    Functions and Parameters for Rice

**********************************************************************
* Experimental data: Parameters and Functions from: IRRI/APPA, 1992  *
* Oryza sativa cv.IR72, IRRI, Dry Season (M10)       at 225 kg N     *
**********************************************************************
```

The parameters given in this chapter are based on one of the representative yield potential experiments conducted at IRRI in 1992 in the dry season (Kropff et al., 1993).

3.1 Initial conditions

The initial conditions have been discussed in Chapter 2.

3.2 Phenological development of the rice crop

```
* Section 2:
PARAM TBD   = 8.,    TOD   = 30.,    TMD   = 42.
PARAM DVRJ  = 0.000773
PARAM DVRI  = 0.000758
PARAM DVRP  = 0.000784
PARAM DVRR  = 0.001784
PARAM MOPP  = 11.50
PARAM PPSE  = 0.0
```

```
PARAM SHCKD  = 0.4
PARAM DOYS   = 4.
PARAM DOYTR  = 16.
```

For rice, the dimensionless scale for development was used. From experimental data the development rate (DVR, $(^{\circ}Cd)^{-1}$) can be calculated as the inverse of the number of heat units between two phenological events. The values for the cardinal temperatures (TBD, TOD and TMD) have been estimated based on Gao et al., 1992; Summerfield et al., 1992; and unpublished data from Yin et al. and Ingram et al. (IRRI). Four parameters have to be estimated for the effect of temperature in the different stages:

DVRJ for the basic vegetative phase (BVP), from sowing (DVS=0) to the start of the photoperiod-sensitive phase (DVS=0.4).

DVRI for the photoperiod-sensitive phase (PSP), from end of the basic vegetative phase to panicle initiation (DVS=0.65). DVRI is the development rate at optimum photoperiod.

DVRP for the panicle formation phase (PFP), from panicle initiation to first flowering (DVS=1).

DVRR for the grainfilling phase (GFP), from first flowering to physiological maturity (DVS=2).

The variety-specific development rate constant is the inverse of the temperature sum required to complete a specific phase at the optimum photoperiod. Differences between varieties in the total crop duration are usually due to differences in the duration of the BVP (DVRJ) rather than the other phases (Vergara & Chang, 1985).

The photoperiod sensitivity of a variety is indicated with the parameters MOPP (optimum photoperiod) and PPSE, which indicates the decrease in the developmental rate at photoperiods higher than the optimum during the photoperiod sensitive phase (PSP). Most IR varieties are very slightly photoperiod sensitive and therefore the parameter PPSE is set to 0.

The parameter SHCKD indicates the delay in flowering (°Cd) per °Cd of seedling age due to the transplanting shock. The date of sowing (DOYS) and transplanting (DOYTR) are specified here because they are first used in this section.

An interactive program (DRATES, see Appendices 5 and 6) has been developed to calculate the rates of development in the vegetative stage (sowing to flowering) and in the reproductive phase (flowering to physiological maturity). The program asks for dates of seeding, transplanting, panicle initiation (if available), flowering, and physiological maturity. Weather data have to be provided in the standard AB/TPE Weather System format (see Section 2.5 and van Kraalingen et al., 1991). The program DRATES produces an output file (DVS.DAT) which gives estimates of the parameter values for DVRJ, DVRI, DVRP and DVRR, and also the development stages for user-specified days (e.g. sampling dates) during the season. Special care has to be taken with the date of physiological maturity, as that event is difficult to observe visually.

3.3 Daily dry matter production

3.3.1 Daily rate of canopy gross CO_2 assimilation and light absorption by the canopy

```
* Section 3.1:
PARAM SCP     = 0.2
PARAM CO2REF = 340.
PARAM CO2     = 340.
FUNCTION NFLVTB = 0.00,0.54, 0.16,0.54, 0.33,1.53, 0.65,1.22, ...
                  0.79,1.56, 1.00,1.29, 1.46,1.37, 2.04,0.83
FUNCTION REDFTT = -10.,0., 10.,0., 20.,1., 37.,1., 43.,0.
FUNCTION EFFTB  = 10.,0.54, 40.,0.36
FUNCTION KDFTB  = 0.,0.4, 0.65,0.4, 1.,0.6,  2.1,0.6
FUNCTION KNFTB  = 0.,0.4,  2.1,0.4
```

The scattering coefficient (SCP) has the standard value of 0.2, indicating that 20% of the radiation is reflected or transmitted by a single leaf (Goudriaan, cited by Spitters, 1986). This coefficient is used to calculate the extinction coefficients for the different types of radiation. The ambient CO_2 concentrations have been set at 340 ppm. For the evaluation of climate change scenarios the actual CO_2 concentration has to be changed (CO_2).

The average specific leaf N content of the canopy is specified as a function of DVS (NFLVTB). The values used in the model were derived from the 1992 DS experiment with IR72 at high N levels, and can be used for estimates of yield potential. If a specific experiment is analysed by the model, the actual specific leaf N has to be selected using the switch SWINLV.

The function REDFTT quantifies the effect of daytime average temperature on the maximum rate of leaf photosynthesis (after Penning de Vries et al., 1989).

The light extinction coefficient

Values for k_{df} range from 0.4 - 0.7 for monocotyledons (erectophile) and 0.65 - 1.0 for dicotyledons (Monteith, 1969). For rice a value of 0.4 is used until the canopy closes and 0.6 for a closed canopy. This accounts for the clustering of leaves by planting on hills and the very erect stature of the leaves at early stages.

The extinction coefficient k_{df} has to be measured under an overcast sky. Direct radiation has to be avoided as the solar elevation determines the extinction coefficient for direct radiation (Eqn 2.9) (in the morning all direct radiation will be absorbed and scattered in the top layer because of the path length, whereas at noon, direct radiation will penetrate further in the canopy). If measurements have to be taken at a clear sky, a board can be used to shade the light measurement instrument. Otherwise, the average extinction coefficient over the day has to be calculated or the value has to be corrected for the solar elevation. Light extinction can be measured by comparing radiation intensity above and below the canopy using a light-bar (generally a 1 m long tube with PAR (Photosynthetically Active Radiation) light sensors built in). From the LAI and the measured light extinction, the extinction coefficient k_{df} can be calculated using Eqn 2.6. When global radiation is measured, k_{df} for PAR will be about 2/3 of the k calculated for global radiation, because absorption of near infrared radiation by the canopy is less efficient.

An important factor that may confound interpretation of measurements is the light absorption by other organs than leaves. This is accounted for in the model by specifically calculating light absorption by stems and storage organs. In calculating k_{df} of leaves from measurements, this effect should be accounted for.

The current model only accounts for the effective stem area. However, detailed models for light absorption of other organs are available (Kropff & van Laar, 1993). When measuring light extinction in the field, k_{df} of the leaves will be severely overestimated by light absorption of other organs than leaves if the light absorption is related to leaf area only. One option is to include the area of other organs in the calculation; the other option is to remove the flowers and then the leaves after the first light measurements and repeat the light measurements.

CO_2 assimilation-light response of individual leaves

In the model, canopy CO_2 assimilation is calculated on basis of the CO_2 assimilation-light response of individual leaves. This response follows a saturation type of function, characterized by the initial slope (the initial light use efficiency (ε, kg CO_2 ha^{-1} leaf h^{-1} / (J m^{-2} leaf s^{-1})) and the asymptote (A_m, (AMAX) kg CO_2 ha^{-1} leaf h^{-1}) (Eqn 2.18, Figure 3.1).

The initial light use efficiency (ε, EFF) is calculated based on a linear relation with temperature: 0.54 at 10 °C - 0.36 at 40 °C kg CO_2 ha^{-1} leaf h^{-1} / (J m^{-2} leaf s^{-1}). These values are based on data of Ehleringer & Pearcy (1983). They did not observe main differences between C_3 species. In C_3 species, ε decreases slightly with increasing temperature as the affinity of the carboxylating enzyme Rubisco for O_2 increases compared to CO_2. In C_4

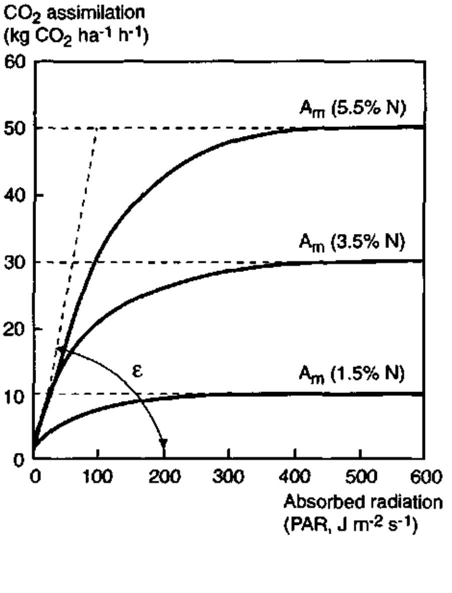

Figure 3.1. The CO_2 assimilation - light response curve of single leaves calculated for three N concentration levels.

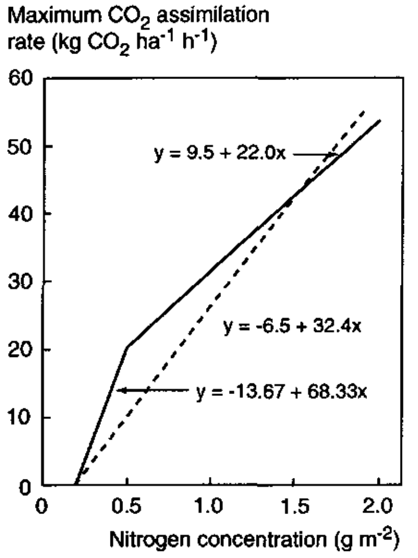

Figure 3.2. The relationship between the maximum rate of CO_2 assimilation of single leaves and the leaf N concentration on a per area basis (g m^{-2}). Dashed line is after van Keulen & Seligman (1987), the solid line above 0.5 g m^{-2} is based on data of Peng et al. (unpublished, IRRI).

species, ε is independent of temperature as these plants have no photo-respiration (which is the reduction CO_2 assimilation by oxygenation of the carboxylating enzyme). This value is assumed not to be affected by the leaf N concentration, as light is the limiting factor in the process.

The light saturated rate of leaf CO_2 assimilation (A_m, AMAX) however, varies considerably, mainly as a function of leaf age and the actual environmental conditions to which the leaf has been exposed in the past. It is also influenced by genotype and plant species. A_m varies between 10 - 50 kg CO_2 ha^{-1} leaf h^{-1} for C_3 species and between 10 - 90 kg CO_2 ha^{-1} leaf h^{-1} for C_4 species, depending on leaf N concentration and temperature (Goudriaan, 1982; van Keulen & Seligman, 1987). A good approximation is to relate A_m to N concentration expressed per leaf area unit because that determines the amount of chlorophyll per unit area. For the relationship between leaf N concentration and the maximum rate of CO_2 assimilation, a combination of two linear relationships is used which is based on data from Peng et al. (IRRI, unpublished data) for leaf N concentrations higher than 0.5 g m^{-2} for which data were available, and the estimate of a base N concentration of 0.2 g m^{-2}. The relationship is slightly different from the relationship given by van Keulen & Seligman (1987) and Penning de Vries et al., 1990) (Figure 3.2). This relationship explains the decrease in A_m later in the growing season when the N concentration in the leaves decreases. Data from phytotron-grown plants generally do not represent photosynthetic characteristics of field-grown plants as the leaves have grown in different environmental conditions, causing differences in SLA and percentage N. If the N concentration is expressed on a per unit of leaf area basis, however, the relationship will be more general. However, the difference between the relationship derived by van Keulen & Seligman (1987) and the data derived by Peng (IRRI) show that more fundamental insight is needed in the relationship between N in the leaf, the amount of Rubisco and the maximum rate of leaf photosynthesis.

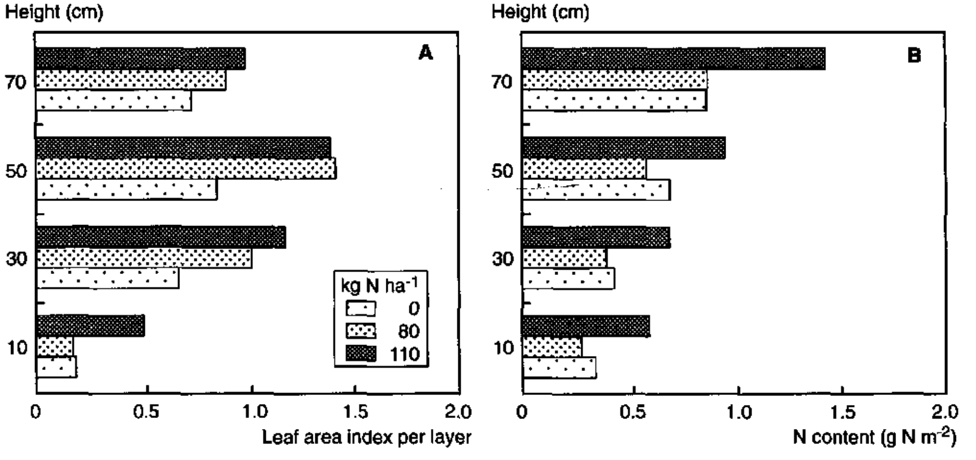

Figure 3.3. Distribution of LAI (A) and the leaf N concentration (B) over height of the canopy of the new line in the wet season of 1991 for three N application treatments at 12 days after flowering.

The N profile in the canopy follows an exponential pattern (Figure 3.3). In the model, this is accounted for by using an extinction coefficient KNF which is specified as a function of developmental stage. The value of 0.4 was based on preliminary measurements in field experiments at IRRI during grainfilling. More data are required to derive this relationship for a wide range of conditions.

3.3.2 Maintenance respiration

```
* Section 3.2:
PARAM MAINLV = 0.02,  MAINST = 0.015
PARAM MAINSO = 0.003, MAINRT = 0.01
PARAM Q10    = 2.,    TREF   = 25.
```

The maintenance requirements are more or less proportional to the biomass to be maintained; For rice leaves, stems and roots, values of 0.02, 0.015 and 0.010 kg CH_2O kg^{-1} dry matter d^{-1}, respectively, are used for rice (Penning de Vries et al., 1989). For storage organs the value can be approximated by calculating maintenance respiration for the active tissue only, representing the envelope of the stored material like the hull in rice, as the biomass stored is biochemically stable and does not require maintenance. For rice we assumed that a percentage of the biomass is inactive which resulted in a low coefficient (0.003). Maintenance requirements decrease with the metabolic activity of the plant. In the model, this is accounted for by assuming plant maintenance respiration to be proportional to the fraction of the accumulated leaf weight that is still green (Spitters et al., 1989).

3.3.3 Growth respiration

```
* Section 3.3:
PARAM CRGLV  = 1.326, CRGST  = 1.326
PARAM CRGSO  = 1.462, CRGRT  = 1.326
PARAM CRGSTR = 1.11
PARAM LRSTR  = 0.947
```

The primary assimilates in excess of the maintenance cost are converted into structural plant material. The amount of structural dry matter produced per unit of available carbohydrates depends on the chemical composition of the dry matter formed. Typical values of the glucose requirements (CR... or Q (see Eqn 2.22)) for various groups of compounds were derived on the basis of their chemical composition by Penning de Vries & van Laar (1982, modified by Penning de Vries et al. (1989)).

3.3.4 Dry matter partitioning

```
* Section 3.4:
FUNCTION FSHTB  = 0.0,0.50, 0.43,0.75, 1.0,1.0 , 2.1,1.
FUNCTION FRTTB  = 0.0,0.50, 0.43,0.25, 1.0,0.0,  2.1,0.
FUNCTION FLVTB  = 0.000,0.545, 0.080,0.545, 0.245,0.559,   ...
                  0.490,0.542, 0.720,0.422, 0.895,0.053,   ...
                  1.230,0.000, 1.730,0.   , 2.1  ,0.
FUNCTION FSTTB  = 0.000,0.455, 0.080,0.455, 0.245,0.441,   ...
                  0.490,0.458, 0.720,0.578, 0.895,0.517,   ...
                  1.230,0.000, 1.730,0.   , 2.1  ,0.
FUNCTION FSOTB  = 0.000,0.000, 0.720,0.000, 0.895,0.430,   ...
                  1.230,1.000, 1.730,1.0  , 2.1  ,1.

PARAM NPLH   = 5.
PARAM NH     = 25.
PARAM NPLSB  = 1000.
```

In the model, the total daily dry matter increment is partitioned to the various plant organ groups according to fractions that are a function of the development stage. These fractions are derived by analysing the fractions of new dry matter production allocated to the plant organs between two subsequent harvests. Important detail is that for stems and leaves the decrease in dry weight cannot be accounted for, so after reaching the maximum weight, this maximum value is used for partitioning calculations when dead leaves are not measured. The relationships used in the model are given in Figure 3.4. The dry matter distribution patterns in the various experiments corresponded well with each other, indicating small seasonal and varietal effects.

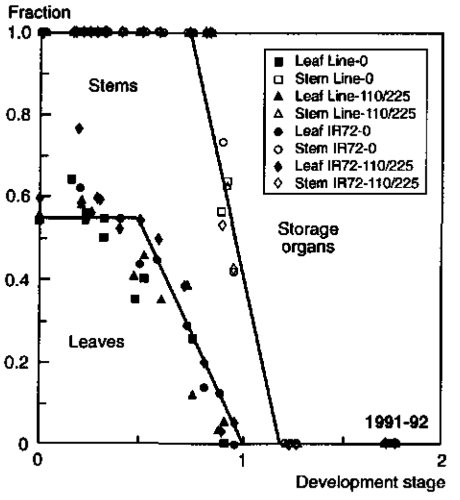

Figure 3.4. Dynamic distribution pattern of dry matter over leaves, stems and panicles for IR72 and the new line (IR58109-113-3-3-2) from experiments in the wet season (WS) of 1991 and the dry season (DS) of 1992 (three N applications).

Procedure to calculate the partitioning tables (FLVTB, FSTTB, FSOTB)

1 Run the program DRATES (see Appendix 6), to calculate DVS for the sampling dates.
2 Make a table including sampling date, development stage (DVS), weight of leaves (WLV), stem (WST), panicles (WPA), totals and difference in weight between two harvests (dGrowth). It is important to use the maximum weight after flowering (*) when the weight decreases, because the model accounts for such decreases in a different way.

Sampling date (d)	DVS	WLV (kg ha^{-1})	WST (kg ha^{-1})	WPA (kg ha^{-1})	Total (kg ha^{-1})	dGrowth (kg ha^{-1})
100	0.8	2000	4000	0	6000	
						3500
120	1.0	2500	6000	1000	9500	
						2000
140	1.2	2500*	6000*	3000	11500	
						2000
160	1.4	2500*	6000*	5000	13500	

In this example, after flowering (DVS = 1) there is no increase in leaves and stem.

3 Calculate the mean DVS for the periods between two harvests and divide the increase in weight per organ by the total increase in weight for the different periods.

DVS	FLV	FST	FSO
0.9	500/3500 = 0.14	2000/3500 = 0.57	1000/3500 = 0.29
1.1	0/2000 = 0.	0/2000 = 0.	2000/2000 = 1.
1.3	0/2000 = 0.	0/2000 = 0.	2000/2000 = 1.

4 Write these fractions in the partitioning tables. The value of 0.5 is estimated here based on other experiments used for the standard parameters.

```
FUNCTION FLVTB = 0.,0.5,     0.9,0.14,    1.1,0., 2.1,0.
FUNCTION FSTTB = 0.,0.5,     0.9,0.57,    1.1,0., 2.1,0.
FUNCTION FSOTB = 0.,0.0,     0.9,0.29,    1.1,1., 2.1,1.
```

Stem reserves

```
PARAM FSTR   = 0.20
PARAM TCLSTR = 10.
```

The fraction of stem reserves (FSTR) can be calculated by the difference between maximum stem weight (at flowering) and the stem weight at final harvest divided by maximum stem weight:

e.g. (5000 – 4000) / 5000 = 0.20
for the following function for the observed stem weight:

```
FUNCTION XWSTTB =  4.,0.,      16.,5.,      34.,109.,    58.,1577., ...
                  68.,2902.,   83.,5000.,   97.,4373.,  114.,4000.
```

This is a relatively rough method, but it gives a first estimate of the net allocation of the stem reserves. Direct measurements of stem reserves and their allocation did not yet lead to quantitative insight in this process. The value of FSTR varies with the N level of the crop (Table 3.1). The time coefficient for stem reserves allocation (TCLSTR) was estimated at 10 days.

The relative death rate of the leaves

```
FUNCTION DRLVT  = 0.0,0., 0.60,0., 1.,0.015, 1.6,0.025, 2.1,0.05
```

The relative death rate of the leaves (RDR (given as a function of DVS in DRLVT), d^{-1}) was calculated in a simplified way from experimental data. For the time interval between two samplings, the relative death rate can be calculated as follows, starting at the time where the leaf dry matter is highest:

$$RDR = (\ln W_t - \ln W_{t+dt}) / dt \quad (3.1)$$

in which t is expressed in days. Using the developmental rate program (DRATES), the development stages at the sampling dates is calculated. To relate the relative death rate to the development stage, the calculated relative death rate is assumed to be the rate at the average development stage between the samplings.

The plant density is defined by the number of hills per m^2 (NH) and the number of plants per hill (NPLH). In the seedbed the plant density is defined by NPLSB.

Table 3.1. Values of the fraction of carbohydrates used for non-structural stem reserves in the stem (FSTR), as determined by the reduction in stem weight.

Year	N appl. (kg ha^{-1})	IR5809.. (%)	IR72 (%)
1992	0	32	39
	180	43	19
	225	38	13
1991	0	48	36
	80	49	23
	110	38	19

Number of grains and spikelets

```
* Section 3.5:
PARAM SPGF    = 64900.
PARAM WGRMX   = 0.0000249
```

The spikelet growth formation factor (SPGF) was derived as the slope of the relationship between spikelet number m^{-2} and the growth of the crop between PI and flowering (Figure 2.7). WGRMX is the maximum individual grain weight (kg grain^{-1}).

The parameters for the calculation of spikelet fertility as a function of temperature are included in the program, subroutine SUBGRN.

3.4 Leaf area development

```
* Section 4:
PARAM TBLV     = 8.
PARAM LAPE     = 0.0001
PARAM RGRL     = 0.0080
PARAM SHCKL    = 0.25
FUNCTION SSGATB = 0.0,0.0003, 0.9,0.0003, 2.1,0.
FUNCTION XLAITB =  4.,0.00,  16.,0.03,  34.,0.46,   58.,5.22, ...
                  68.,5.97,  83.,5.88,  97.,4.82,  114.,2.45
FUNCTION SLATB  = 0.00,0.0045, 0.16,0.0045, 0.33,0.0033, 0.65,0.0028,...
                  0.79,0.0021, 1.00,0.0019, 1.46,0.0017, 2.04,0.0017
```

In the early phases, leaf area growth proceeds more or less exponential, the relative growth rate being approximately linearly related to temperature (Eqn 2.30). When leaf area per plant is plotted on a logarithmic scale versus the temperature sum after emergence, a more or less linear relationship is, therefore, obtained (see Figure 2.10). The slope measures the relative leaf area growth rate (R_l (RGRL), $(°Cd)^{-1}$) and the intercept the apparent leaf area at emergence. In Figure 2.11 the relationships are given for direct-seeded and transplanted rice, showing that the transplanting shock only causes a delay (TSHCKL), but does not affect the slope. The value of 0.008 for RGRL was derived from high N experiments at IRRI (Los Baños, Philippines). For low N treatments, values of 0.005 were measured. A procedure to estimate leaf expansion in relationship to N uptake has to be developed.

Procedure to calculate the relative growth rate of leaf area development (RGRL)

The value of RGRL can best be estimated from the slope of the relationship between ln(LAI) and the temperature sum. When only a limited number of measurements is available the following equation can be used:

$$RGRL = \frac{\ln(\text{leaf area})_{t2} - \ln(\text{leaf area})_{t1}}{\Delta(\text{degree-days})} \qquad (3.2)$$

Example:
The temperature sum can be obtained from the program DRATES (see Appendix 6). The RGRL should be calculated from LAIs in the exponential growth phase (so, LAI<1):

Sampling (nr)	LAI ($m^2\ m^{-2}$)	ln(LAI)	TSUM (°Cd)
t1	0.02	−3.9	0
t2	0.05	−3.0	100
t3	0.12	−2.1	200

RGRL(t2–t1) = (−3.0 −(−3.9)) / 100 = 0.009 $(°Cd)^{-1}$ or
RGRL(t3–t2) = (−3.0 −(−2.1)) / 100 = 0.009 or
RGRL(t3–t1) = (−2.1 −(−3.9)) / 200 = 0.009

Stem area

The table SSGATB gives the specific green stem area as a function of developmental stage (DVS), and XLAITB gives the observed LAI as a function of daynumber (DOY). This table is experiment specific for model comparison.

After the exponential phase leaf area growth is simulated by multiplying the leaf dry weight by the specific leaf area (SLA, m^2 leaf kg^{-1} leaf). SLA is plotted in Figure 3.5 as a function of the development stage expressed in degree-days for several experiments.

3.5 Environmental variables

```
* Section 5:
FUNCTION TMCTB  = 1.,0., 366.,0.
```

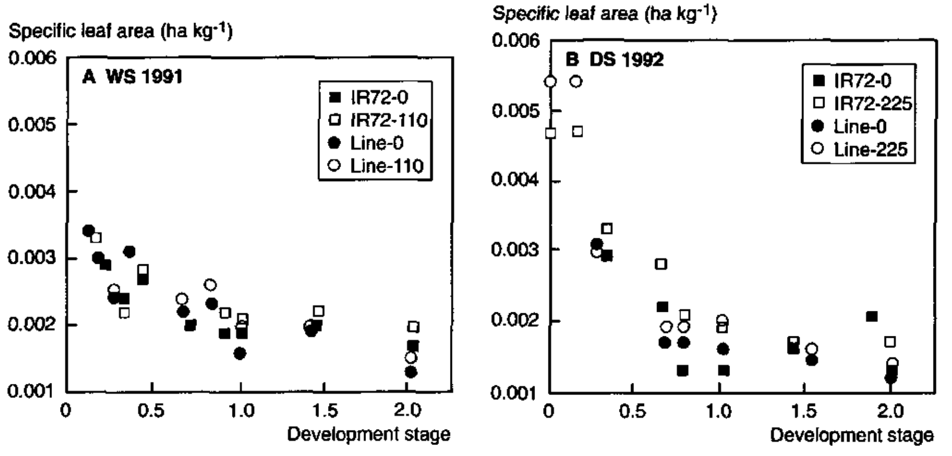

Figure 3.5. Relation between the specific leaf area (SLA, ha leaf kg^{-1}) and development stage (DVS) for two seasons (WS1991 and DS1992) and two varieties (IR72 and IR58109-113-3-3-2) at 0 N and high N applications.

The table TMCTB can be used in the analysis of climate change scenarios when the temperature change is given as a function of daynumber of year (DOY).

3.6 Carbon balance check

```
* Section 6:
PARAM FCLV   = 0.419, FCST   = 0.431
PARAM FCRT   = 0.431, FCSO   = 0.487
PARAM FCSTR  = 0.444
```

The parameters used in Section 6 give the fraction of carbon in dry matter for the different organs (after Penning de Vries et al., 1989).

Observed values

```
* Section 8:
FUNCTION XWLVGT =  4.,0.,     16.,6.,     34.,138.,    58.,1874., ...
                  68.,2840.,  83.,3030.,  97.,2828.,  114.,1432.
FUNCTION XWSTTB =  4.,0.,     16.,5.,     34.,109.,    58.,1577., ...
                  68.,2902.,  83.,4771.,  97.,4373.,  114.,4243.
FUNCTION XWLVDT =  4.,0.,     16.,0.,     34.,0.,      58.,47.,   ...
                  68.,234.,   83.,660.,   97.,1448.,  114.,2269.
FUNCTION XWPATB =  4.,0.,     16.,0.,     34.,0.,      58.,0.0,   ...
                  68.,0.,     83.,1558.,  97.,5932.,  114.,9843.
FUNCTION XWTDMT =  4.,0.,     16.,11.,    34.,247.,    58.,3498., ...
```

```
                   68.,5976.,  83.,10019., 97.,14580.,114.,17787.
FUNCTION XNFLVT =  4.,0.54,    16.,0.54,   34.,1.53,    58.,1.22, ...
                   68.,1.56,   83.,1.29,   97.,1.37,   114.,0.83
```

The tables starting with X give observed data as a function of daynumber to enable comparison of observed and simulated results. In the standard run, the values for the 1992 DS experiment are used.

4 Evaluation of the model ORYZA1

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The current version of the model (Version 1.3, April 1994) was evaluated using 24 data sets collected at IRRI's experimental farm in the 1991 and 1992 wet season (WS) and the 1992 dry season (DS). These experiments were set up to study yield potential in current varieties. The data sets were from three seasons, several varieties that were grown at different N levels. The treatments were as follows:

WS 1991:		Varieties: IR72, IR58109-113-3-3-2
	0	kg N ha^{-1}
	80	kg N ha^{-1} (2 splits before panicle initiation (PI))
	110	kg N ha^{-1} (2 splits before PI and 30 kg N ha^{-1} at flowering).
DS 1992:		Varieties: IR72, IR58109-113-3-3-2
	0	kg N ha^{-1}
	180	kg N ha^{-1} (2 splits before PI)
	225	kg N ha^{-1} (2 splits before PI and 45 kg N ha^{-1} at flowering).
WS 1992:		Varieties: IR72, IR58185-23-3-3-1, IR64616H
	30	kg N ha^{-1} (at flowering)
	110	kg N ha^{-1} (80 basal and 30 at flowering)
	110	kg N ha^{-1} (40 kg basal and mid-tillering, and 30 at flowering).
	110	kg N ha^{-1} (26.7 at basal, mid-tillering and PI, and 30 at flowering).

The crops were grown at the IRRI experimental farm in Los Baños, Laguna, Philippines. Twelve-days-old seedlings grown in trays were used. Treatments were laid out in four replicates in a split plot design with N treatment as the main plots and varieties as subplots. At the major phenological stages and in between, 12 - 14 hills were sampled and analysed for LAI and dry weights of the organs.

The yields obtained at the highest N levels were among the best yields of IR8 in wet and dry seasons in the early 1970s at IRRI's farm. Highest rice yields of IR72 (released in 1987) were about 6 and 9.5 t ha^{-1}, in the wet seasons and the dry seasons, respectively, in a tropical environment with good agronomic management.

Besides the planting date, seeding date and weather data several variety and treatment specific inputs were used:

- Leaf N concentration as a function of time, by N treatment.
- The development rate coefficients by variety.
- The fraction of stem reserves FSTR per variety.
- For the RGRL one value (0.005) was used for all 0 N treatments and another for all other treatments (0.008).

All other coefficients and model inputs were the same for all runs (Figure 4.1). Total biomass as well as panicle dry matter was simulated accurately by the model.

The model explained more than 90% of the considerable variation in observed data on biomass and yield. The results indicate that the model can satisfactorily explain differences in biomass production and yield across N treatments, varieties and environments, given these inputs.

The ORYZA1 model was further evaluated with data from the 1991 WS and the 1992 DS experiments at IRRI and data from Japan and Australia where yield potential is quite different from the tropics as a result of differences in temperature and radiation levels. For the IRRI experiments, the highest N treatments of IR72 were selected (see earlier in this chapter).

For Japan, data from a yield potential experiment conducted by Karoda et al. (unpublished data) with the japonica variety Nipponbare in Kyoto was used. The crop was sown in 1987 on April 10 and harvested on September 10. The yield was 6.8 t ha^{-1}, which is close to the maximum yields observed in similar environments in Japan (T. Horie, unpublished data).

For Australia, data from the 1991/1992 season experiment in Yanco were used (R.L. Williams, unpublished data). The rice variety YRL39 was grown at different N levels, up to 320 kg N ha^{-1} and different splits were applied. The crop was sown on October 21 in 1991 and harvested on April 24 1992 at the Yanco Agricultural Institute, Yanco, Australia. The highest reported yield was 14.7 t ha^{-1} at 320 kg N. Yields of around 14 t ha^{-1} have been regularly observed in the Riverina area, surrounding Yanco.

In this multilocation test, values for IR72 were used for all parameters except for the phenology parameters. They were adapted in such a way that the dates of flowering were simulated accurately. For the time course of leaf N, the data from the 1992 DS experiment were used for all simulations, because such data were not available for the Yanco experiment and to make sure that this would be a real extrapolation.

Measured total biomass ranged from 11.5 to 28.9 t ha^{-1} and yield from 5.7 to 14.7 t ha^{-1} (panicle dry weight) in the different environments. Lowest yields were obtained in the tropical wet season at IRRI and highest yields in Yanco, Australia. The model simulated the wide range in total biomass accumulation, maximum LAI and yield (expressed as panicle dry weight) quite accurately (Table 4.1). However, the yield in the WS at IRRI was overestimated, because the high leaf N content of the DS was used. When the model was run with the measured leaf N content, the results were very close (6.3 t ha^{-1}) to the

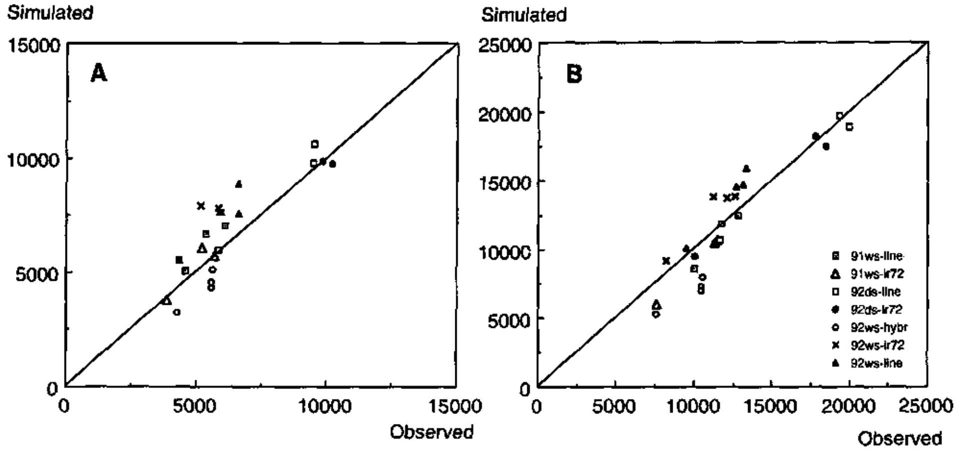

Figure 4.1. Observed versus simulated yield (A) and total biomass (B) at maturity (kg ha^{-1}) of different varieties at different N application levels, see text.

observed. The differences in the duration of the grainfilling period were simulated quite well, although precise comparisons cannot be made because the observations are based on visual interpretations in the field.

The differences in yield potential can be easily understood from the environmental characteristics. The average temperature, which determines the duration of the growth phases was quite different among the environments. In both the wet and dry season at IRRI, the average temperature was about 27 - 28 °C in both the vegetative and grainfilling phase. In Japan, the temperature in the vegetative phase was 23 °C and in the grainfilling phase 26 °C. In Yanco, Australia, the average temperature was 21 °C in the vegetative phase and 23 °C in the grainfilling phase. Radiation levels were highest in Yanco and lowest in Japan (Table 4.1). These results suggest that the combination of temperature and radiation can explain the differences in yield potential. In Yanco, low temperature results in a long duration of grainfilling and the high radiation level in a high growth rate per day resulting in high yields. In Kyoto, the radiation level is very low, but the grainfilling duration is intermediate. In the tropics, the duration is short as a result of the high temperature, but the high radiation in the dry season enables a higher yield than in the wet season.

The light use efficiency was calculated based on the calculated amount of absorbed radiation (model run with observed LAI as input) and observed total biomass accumulation. These results show that the light use efficiency at high radiation levels is lower, but also that the temperature affects the light use efficiency as well. Apparently, the model accounts for these differences in the light use efficiency and a model with a fixed light use efficiency cannot be used across environments. The light use efficiency values in Table 4.1 are based on model results based on the same parameter values for all environments. An aspect that has to be checked in more detail is the varietal differences in characteristics such as the extinction coefficient. Williams et al. (unpublished data) found very low values for the extinction

Table 4.1. Observed and simulated crop characteristics for field experiments on yield potential in rice in different environments (SE between brackets).

	IRRI WS	Japan	IRRI DS	Yanco
Variety	IR72	Nipponbare	IR72	YRL39
Biomass obs. (t ha^{-1})	11.5 (0.6)	12.8 (0.5)	17.8 (0.6)	28.9 (1.1)
Biomass sim. (t ha^{-1})	11.5	13.2	15.4	27.3
Yield obs. (t ha^{-1}, panicle dry wt)	5.7 (0.2)	7.8 (0.5)	9.8 (0.2)	14.7 (0.6)
Yield sim.(t ha^{-1}, panicle dry wt)	7.26	7.41	9.49	14.3
Maximum LAI obs. (m^2 m^{-2})	4.3 (0.4)	5.3 (0.7)	6.0 (0.5)	14.0 (1.0)
Maximum LAI sim. (m^2 m^{-2})	4.9	8.9	6.4	12.8
Crop duration (d)	109	153	110	159
Grainfilling duration obs. (d)	30	41	30	43
Grainfilling duration sim. (d)	29	32	30	39
Mean temperature				
sowing-flowering (°C)	28.1	23.3	26.0	21.3
flowering-maturity (°C)	27.7	25.6	27.9	22.9
Av. daily incoming radiation				
sowing-flowering (MJ m^{-2})	15.2	16.3	17.4	22.9
flowering-maturity	18.9	13.5	21.9	22.6
Absorbed total radiation				
sowing-flowering (MJ m^{-2})	189	195	278	413
flowering-maturity	215	301	371	747
Light use efficiency (g MJ^{-1})	2.8	2.6	2.7	2.5

coefficient of YRL30, a rice variety that has rolled leaves during most of the growing season. If lower values for the extinction coefficient would be used, the absorbed amount of radiation would be lower and thus the light use efficiency higher.

The results suggest that the differences in yield potential as measured in Japan, IRRI and Australia are mainly due to the environmental differences and less to genetic differences. However, the varieties will definitely differ in their ability to overcome specific stresses such as low temperature stress in Yanco and specific diseases in the tropics. More detailed analyses using the same varieties will be useful to further enhance the capacity of the models to predict yield potential in untested environments. These results indicate that the current model for rice yield potential can be used to estimate yield potential in different environments. This is an essential step in determining the yield gap between potential yield and actual research station or farmers yield.

5 Applications of the model

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Several applications of the model already have been indicated in the previous chapters (e.g. input requirements). It can be used as a tool for

(*i*) Prediction of yield potential of a variety in a particular environment as defined by radiation and temperature during the growing season. This is an essential step in defining the yield gap in farmers fields.
(*ii*) Extrapolation of experimental results to other environments.
(*iii*) Detailed analysis of data from field experiments.
(*iv*) The analysis of physiological requirements for increased yield potential.
(*v*) The estimation of the effect of climatic change on rice yield potential.

The model can also be used as a framework in studies that focus on specific agronomic problems. In such studies, (sub)model development is integrated with experimental work. Often new quantitative physiological insight in processes that are not yet included is required and the model may help to guide the direction of the physiological research.

Several applications will be indicated in more detail. The input requirements of the model depend on the type of application of the model and will be indicated as well.

5.1 Estimation of yield potential for a given environment

Yield potential in a given environment (planting date, latitude, radiation, temperature, variety as input) can be simulated by ORYZA1. This can be very useful in exploring the needs for changes in (N) management to obtain potential yields. An example is the work conducted at IRRI to explore options to obtain potential yields.

The first version of the model was evaluated during January 1992 with data from an experiment conducted in the 1991 Wet Season (WS) that was designed to obtain yield potential at the IRRI farm. That version of the model was used to assess the attainable yield of IR72 and the new line under dry season conditions in Los Baños (Table 5.1). Weather data were used from 1987. With similar N concentrations in the leaves as measured in the wet season, yields of 7.0 and 8.2 t ha^{-1} were simulated. Only with a higher N concentration in the leaves, yields of up to 9.3 t ha^{-1} were simulated. These results were later confirmed by the 1992 Dry Season experimental data where leaf N was significantly higher than in the 1991 WS. Another example is the prediction of potential yields of 15 t ha^{-1} in the Australian rice

Table 5.1. Observed and simulated yields (t ha^{-1}) of IR72 and a new line for the 1991 Wet Season (IRRI, Los Baños, Philippines) and simulated effect of a change in season and higher leaf N content. Source: Kropff et al., 1994.

	cv. IR72		New Line	
	Yield (t ha^{-1})	Total duration (d)	Yield (t ha^{-1})	Total duration (d)
Observed:				
Wet Season 1991	5.7	94	6.1	108
Simulation results:				
1 Wet season 1991	5.6	94	6.3	109
2 Dry season 1987	7.0	100	8.2	118
3 As 2 + N conc. 20% higher	7.9	100	9.3	118

growing environment (Yanco), which matched very recent experimental yields.

An important input is the time course of the leaf N content which is can be taken from the highest yielding experiment of which data are available. The recently conducted experiments at IRRI can be used for that purpose.

Input requirements and model settings for estimation yield potential
(the switches SWILAI and SWINLV are set to −1)

A set of physiological and morphological characteristics has to be used. Most parameters are not variety specific according to our current knowledge (see Chapter 3). The parameters for which we found genetic variations are:

- The development rate constants for the different phases: DVRJ, DVRI, DVRP, DVRR. Most variation is found in the parameter DVRJ. The values of these parameters can be estimated using the program DRATES, based on weather data and dates of the key phenological stages. The photoperiod sensitivity parameter PPSE has to be estimated from photoperiod experiments or multilocation experiments. Tools to estimate this parameter from multilocation experiments are in development.
- The fraction of stem reserves that is effectively reallocated (FSTR) is, however, dependent on the N level (Table 3.1) which should be taken into account in detailed analyses. The dry matter distribution pattern is quite similar for most semi-dwarf high yielding varieties (Figure 3.4).

With these sets of characteristics the variety has been defined. If the standard parameter values are used, the yield potential of IR72 is estimated, which is a standard modern HYV.

The input requirements for such predictions are:

- DOYS Date of seeding
- DOYTR Date of transplanting (equals date of seeding for direct-seeded rice)
- NPLSB Number of plants per m^2 in seedbed (roughly)
- NH Number of hills per m^2
- NPLH Number of plants per hill
- Daily radiation as function of the day of year,
- Maximum daily temperature as function of the day of year, and
- Minimum daily temperature as function of the day of year.

For simulation of yield potential, the relative growth rate of leaf area (RGRL, $(°Cd)^{-1}$) has been set at 0.008. A reference time course of N content in the leaves has to be chosen. For simulation of yield potential, the N concentration in leaves of our highest yielding experiment available can be chosen (e.g. IR72, 1992DS, 225 kg N):

```
FUNCTION XNFLVT =  4.,0.578, 16.,0.578, 34.,1.531,  58.,1.028,...
                  68.,1.557, 84.,1.286, 97.,1.373, 114.,0.834
```

5.2 Extrapolation of experimental findings to other environments

Given the N content of the leaves measured throughout the growing season in a specific experiment and the varietal characteristics, attainable yields can be estimated for other environments (planting date, irradiation, temperature).

Input requirements and model settings for extrapolation

Same as in (Section 5.1) but now the leaf N content of the leaves from the experiment has to be used (as a function of development stage, SWINLV=1), as well as an adapted RGRL. Of course, dates and weather data for the new environment have to be included. E.g. for IR72, 1992DS, 225 kg N, the N content in the leaves versus development stage was found to be:

```
FUNCTION NFLVTB = 0.0,0.578, 0.152,0.578, 0.336,1.531, 0.653,1.028,...
                  0.787,1.557, 1.011,1.286, 1.431,1.373, 2.011,0.834
```

5.3 Detailed physiological analysis of field experiments

If detailed measurements on LAI and leaf N content are conducted throughout the growing season, the model can be used for physiological interpretation of treatment effects in terms of differences in LAI development, leaf N content, weather conditions and varietal characteristics.

Example 1

In an air fumigation study, the effect of enhanced SO_2 on yield of *Vicia faba* was analysed. A detailed submodel for the effect of SO_2 on photosynthesis was developed and coupled to a basic model such as ORYZA1. The experimental data from three years were analysed by the model by first evaluating/calibrating the model to the control treatments. The measured LAI was input to the model. Then, the LAI of the fumigated treatment was input to the model. In a next step, the effect of SO_2 on photosynthesis was included. It was found that the yield difference was mainly explained by differences in LAI, as a result of accelerated senescence in the fumigated plots. As a result of this quantitative analysis, further research focused on leaf senescence instead of photosynthesis (Kropff, 1990). Similar studies have been conducted for the effect of blast on rice (Bastiaans, 1993).

Example 2

In experiments on yield potential at IRRI, it was predicted based on wet season data (yield potential of 6 t ha^{-1}) that with 20% higher N in the leaves yields of up to 9.3 t ha^{-1} would be feasible with current varieties (Kropff et al., 1994). In several other countries similar questions can be asked. In Indonesia, for example, wet season yields are often higher than dry season yields. Daradjat & Fagi (1991) used the MACROS L1D model to predict potential yields in the wet and dry season in Indonesia. It appeared that the yield potential is very similar in both seasons. With the current model, such studies can be conducted with realistic measured leaf N concentrations, so that simulated yields for those seasons are realistic.

Example 3

For breeding purposes, it would be useful to characterize the traits that cause differences in yield potential. From detailed field experiments with several varieties, it can be analysed why varieties have a different yield potential.

Example 4

Increasing the yield plateau in rice and the impact of global climate change. The physiological characteristics needed to develop new rice varieties with an increased yield potential have been determined using models in several studies (Penning de Vries, 1991; Dingkuhn et al., 1991; Kropff et al., 1994). Because large changes in photosynthetic efficiency and respiration costs are not to be expected, increased yield potential must come from increased allocation of stem reserves, from a prolonged grainfilling period, from an increased growth rate during grainfilling or from a combination of these sources. Penning de Vries (1991), Dingkuhn et al. (1991) and Kropff et al. (1994) emphasized the lengthening of grainfilling duration as the main option to increase the yield plateau. To achieve 15 t ha^{-1}, 38 days of effective grainfilling would be needed. The yield potential of a rice variety at higher latitudes is greater than in the tropics for the same reason. The grainfilling period is extended as a result of lower average temperature. The ecophysiological model indeed predicts an increase in rice yield potential for Los Baños of 2 t ha^{-1} with a reduction of mean temperature by 3 °C.

A temperature increase of 1 °C and a CO_2 rise of 50 ppm can be expected based on predictions made by Global Circulation Models for the year 2020. The effects of these climate changes were quantified by the simulation model. In the model, temperature affects the rate of photosynthesis, the respiration rate and the rate of phenological development. CO_2 only affects the rate of photosynthesis. The model predicted a yield reduction of 8 - 9% for both varieties in both the DS and the WS as a result of a temperature increase of 1 °C. Increased CO_2 partly reversed this effect resulting in yield reductions of only 3%. A 5% reduction in radiation level resulted in a yield reduction of about 3%. Penning de Vries (1992) simulated yield effects of increased temperatures, assuming that temperature does not affect growth duration. That was based on the assumption that farmers will select varieties with a longer grainfilling duration to compensate for these effects. In preliminary experiments, however, we found large genetic variation in the length of the grainfilling period when expressed on a single panicle basis, but not on a whole crop basis. Research on this aspect of grainfilling duration will have to be intensified.

Input requirements and model settings for detailed data analysis

If detailed experimental data are available, several measured data can be used as input based on the insight of the researcher. Most frequently, LAI will be used as input, Leaf N, phenological parameters, fraction of allocatable stem reserves, RGRL and SLA. The model can then be used to analyse the reasons for differences in yield between treatments.

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Appendix 1 Listing of the model ORYZA1

```
DEFINE_CALL COVER (INPUT,INPUT,INPUT,INPUT,                 OUTPUT)
DEFINE_CALL SUBDD (INPUT,INPUT,INPUT,INPUT,INPUT,           OUTPUT)
DEFINE_CALL SUBCD (INPUT,INPUT,INPUT,INPUT,                 OUTPUT)
DEFINE_CALL SUBCBC(INPUT,INPUT,INPUT,                       OUTPUT)
DEFINE_CALL PHENOL(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
                    INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
                   OUTPUT,OUTPUT)
DEFINE_CALL TOTASP(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
                   INPUT,INPUT,INPUT,                              ...
                    OUTPUT,OUTPUT,OUTPUT,OUTPUT,OUTPUT)
DEFINE_CALL SUBLAI(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
                    INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,     ...
                   OUTPUT,OUTPUT)
DEFINE_CALL SUBGRN(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
                    INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,           ...
                    OUTPUT,OUTPUT,OUTPUT,OUTPUT,OUTPUT)
DEFINE_CALL SUBRTS(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
                    INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
                    INPUT,INPUT,        OUTPUT,OUTPUT,OUTPUT,OUTPUT,...
                    OUTPUT,OUTPUT,OUTPUT,OUTPUT,OUTPUT,OUTPUT)
*----------------------------------------------------------------------*
*                                                                      *
*                              ORYZA1                                  *
*                      A Model for Rice Production                     *
*                                                                      *
*                             April 1994                               *
*                           FST-Version 1.3                            *
*                                                                      *
*                                                                      *
* International Rice Research Institute (IRRI), P.O. Box 933,          *
* 1099 Manila, The Philippines                                         *
*                                                                      *
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*                                                                      *
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* The Netherlands                                                      *
*                                                                      *
* This model is based on the following models:                         *
* - INTERCOM   by Kropff, M.J. et al., 1993. In: Modelling crop-weed   *
*                 interactions. CAB, Wallingford, pp. 201-246.         *
* - MACROS-L1D by Penning de Vries F.W.T. et al., 1989. Simulation of  *
*                 ecophysiological processes of growth in several      *
*                 annual crops. Simulation Monographs 29, Pudoc,       *
*                 Wageningen and IRRI, Los Banos, 271 pp.              *
* - SUCROS     by Laar, H.H. van, J. Goudriaan & H. van Keulen, 1992.  *
*                 Simulation of crop growth for potential and water-   *
*                 limited production situations. Simulation Reports 27,*
*                 CABO-TPE, Wageningen, The Netherlands, 72 pp.        *
*                                                                      *
************************************************************************

*** 1.     Initial Conditions

INITIAL
INCON ZERO       = 0.,    DVSI   = 0.
INCON WLVGI      = 0.,    WSTI   = 0.
INCON WSOI       = 0.,    WRTI   = 0.
```

```
* Switch for leaf area development:
* SWILAI=-1. (LAI measured vs time); SWILAI=1. (LAI is simulated)
PARAM SWILAI      = -1.

* Switch for Leaf Nitrogen:
* SWINLV=-1 (NLV measured vs time); SWINLV=1. (NLV measured vs DVS)
PARAM SWINLV      = -1.

* Switch for GCMs:
* SWITMP=-1. (no temperature change); SWITMP=1. (temperature change)
PARAM SWITMP      = -1.

* Switch for seedbed cover:
* SWICOV=-1 (no cover); SWICOV=1. (cover is used)
PARAM SWICOV      = -1.

* Switch for direct-seeding:
* SWIDS=-1. (=transplanted); SWIDS=1. (=direct seeded).
PARAM SWIDS       = -1.

DYNAMIC

*** 2.     Phenological Development

       CALL SUBDD  (TMAX,TMIN,TBD, TOD,TMD, HU  )
       CALL PHENOL (DVS,DAS,DVRJ,DVRI,DVRP,DVRR, HU,DAYL,MOPP,PPSE, ...
                    TS,SHCKD,DOYTR,DOYS,   DVR,TSHCKD)
       CALL SUBCD  (DOY, DOYTR, TAV,TIME, NCOLD)

       DVS    = INTGRL (DVSI,  DVR)


*** 3.     Daily Dry Matter Production

*** 3.1    Daily Gross Canopy CO2 Assimilation

       CALL TOTASP (DOY,LAT,DTR,SCP,EFF,REDFT,KDF,KNF,ALAI,CO2,NFLV, ...
                   DAYL,AMAX,DTGA,DPAR,DPARI)

       NFLV   = INSW(SWINLV, XNFLV, AFGEN(NFLVTB, DVS))
       REDFT  = AFGEN (REDFTT,TAVD)
       CO2EFF = (1.-EXP(-0.00305*CO2    -0.222))/  ...
                (1.-EXP(-0.00305*CO2REF-0.222))
       EFF    = AFGEN (EFFTB, TAVD) * CO2EFF
       KNF    = AFGEN (KNFTB,  DVS)
       KDF    = AFGEN (KDFTB,  DVS)

       PARCUM = INTGRL(ZERO, DPARI)
       PARI1  = (1.-0.06)*DTR*0.5*(1.-EXP(-KDF*ALAI))/ 1.E6
       PARCM1 = INTGRL(ZERO, PARI1)

*** 3.2    Maintenance and Growth Respiration

       MNDVS  = WLVG/NOTNUL(WLVG+WLVD)
       RMCR   = (WLVG*MAINLV + WST*MAINST + ...
                WSO *MAINSO + WRT*MAINRT) * TEFF * MNDVS
       TEFF   = Q10**((TAV-TREF)/10.)

       CRGCR  = FSH*(CRGLV*FLV  + CRGST *FST *(1.-FSTR) + ...
                                  CRGSTR*FSTR*FST       + ...
                     CRGSO*FSO) + CRGRT *FRT

*** 3.3    Daily Growth Rate from CO2 Assimilation and Respiration Rates

       GCR    = ((DTGA*30./44.) - RMCR +                ...
                 (LSTR*LRSTR*FCSTR*30./12.))/CRGCR
       NGCR   = GCR - LSTR * LRSTR * FCSTR * 30./12.
```

```
*** 3.4    Growth Rates of Plant Organs

      FSH    = AFGEN (FSHTB, DVS)
      FRT    = AFGEN (FRTTB, DVS)
      FLV    = AFGEN (FLVTB, DVS)
      FST    = AFGEN (FSTTB, DVS)
      FSO    = AFGEN (FSOTB, DVS)

      LLV    = WLVG * AFGEN (DRLVT,DVS)
      LSTR   = INSW (DVS-1., 0., WSTR / TCLSTR)
      CALL SUBRTS (DOY,    DOYTR, GCR , FRT,   FSH , FLV, LLV , FST,...
                  FSTR,  LSTR , WLVG, WSTR , WSTS, WRT, NPLH ,NH ,...
                  NPLSB, DELT,                                     ...
                  GLV,   GSTR,  RWLVG,GRT,   RWSTR,GST,            ...
                  RWLVG1,GRT1,  RWSTR1,GST1)
      CALL SUBGRN (GCR ,FSH,FSO ,DOY,DOYS,DOYTR,DVS,WRR,PWRR,      ...
                  SPGF,TAV,TMAX,NSP,TIME,  GRAINF,GSO,GGR,GNSP,GNGR)

*** 3.5    Dry Matter Production and Number of Grains and Spikelets

      WLVG   = INTGRL (WLVGI, RWLVG)
      WLVD   = INTGRL (ZERO ,   LLV)
      WSTS   = INTGRL (WSTI ,   GST)
      WSTR   = INTGRL (ZERO , RWSTR)
      WSO    = INTGRL (WSOI,    GSO)
      WRT    = INTGRL (WRTI,    GRT)
      WST    = WSTS + WSTR
      WAGT   = WLVG + WST + WSO + WLVD
      WAG    = WLVG + WST + WSO
      WRR    = INTGRL (ZERO, GGR)
      WRR14  = 1.14 * WRR

      NGR    = INTGRL (ZERO, GNGR)
      NSP    = INTGRL (ZERO, GNSP)
      PWRR   = NGR * WGRMX


*** 4.     Leaf Area Development

      CALL SUBDD (TMAX,TMIN,TBLV,30.,42., HULV)
      CALL SUBLAI(SWIDS,SWILAI , DAS, DOYS, DOYTR,LAPE,RGRL,TSLV, ...
                 NPLSB , WLVG,  SLA,   NH, NPLH, SHCKL, DVS,    ...
                 LAISIM, TSHCKL)
      LAI    = INSW (SWILAI, XLAI, LAISIM)
      SSGA   = AFGEN(SSGATB, DVS)
      SAI    = SSGA * WST
      SLA    = AFGEN( SLATB, DVS)
      XLAI   = AFGEN(XLAITB, DOY)
      ALAI   = LAI + 0.5 * SAI


*** 5.     Time and Environmental Variables

WEATHER WTRDIR='C:\WEATHER\', CNTR='PHIL', ISTN=1, IYEAR=1992
*  Reading weather data from the weather file:
*  Note:  The radiation will be multiplied by 1000 to get J/m2/d!!!
*  RDD    Daily global radiation        J/m2/d
*  TMMN   Daily minimum temperature     degree C
*  TMMX   Daily maximum temperature     degree C
*  VP     Vapour pressure               kPa
*  WN     Wind speed                    m/s
*  RAIN   Precipitation                 mm
*  LAT    Latitude of the site          degree
*  DOY    Day of year = TIME            d

      TMAXC  = INSW (SWITMP, 0., AFGEN(TMCTB, DOY))
      TMINC  = INSW (SWITMP, 0., TMAXC)
```

```
      CALL COVER (SWICOV, DAS, DOYTR, DOYS, TMPCOV)
      DAS     = INTGRL (ZERO, RDAS)
      RDAS    = 1.

      TAV     = (TMIN + TMAX)/2.
      TAVD    = (TMAX + TAV) /2.
      TS      = INTGRL (ZERO, HU   )
      TSLV    = INTGRL (ZERO, HULV)
      DTR     = RDD
      TMIN    = TMMN + TMINC
      TMAX    = TMMX + TMAXC + TMPCOV


*** 6.    Carbon Balance Check

      CALL SUBCBC (CKCIN,CKCFL,TIME,  CBCHK)
      CKCIN  = (WLVG+WLVD-WLVGI)*FCLV        +       ...
               (WSTS-WSTI)*FCST + WSTR*FCSTR +       ...
               (WRT -WRTI)*FCRT + WSO *FCSO
      CKCFL  = TNASS * (12./44.)
      CTRANS = RWLVG1*FCLV   + GST1*FCST +           ...
               RWSTR1*FCSTR + GRT1*FCRT
      TNASS  = INTGRL(ZERO, RTNASS)
      RTNASS = ((DTGA*30./44. - RMCR)*44./30.) - RGCR -    ...
                 (CTRANS*44./12.)
      RGCR   = (GRT +GRT1)   *CO2RT + (GLV+RWLVG1)*CO2LV + ...
               (GST +GST1)   *CO2ST + GSO*CO2SO          + ...
               (GSTR+RWSTR1)*CO2STR                      + ...
               (1.-LRSTR)*LSTR*FCSTR*44./12.
      CO2RT  = 44./12. * (CRGRT *12./30. -  FCRT)
      CO2LV  = 44./12. * (CRGLV *12./30. -  FCLV)
      CO2ST  = 44./12. * (CRGST *12./30. -  FCST)
      CO2STR = 44./12. * (CRGSTR*12./30. - FCSTR)
      CO2SO  = 44./12. * (CRGSO *12./30. -  FCSO)


*** 7.    Run Control

FINISH DVS        > 2.
FINISH NCOLD      > 3.
FINISH GRAINF     < 0.
TIMER STTIME      = 4., FINTIM = 300., DELT = 1., PRDEL = 5.
TRANSLATION_GENERAL DRIVER='EUDRIV'
PRINT      DOY,DVS,TS,TSLV,XLAI,LAI,ALAI,LAISIM,NFLV,XNFLV,    ...
           GST,GLV,GSO,GSTR,GRT,WRT,WLVG,XWLVG,WLVD,XWLVD,     ...
           WST,XWST,WSO,XWPA,WAG,XWTDM, WAGT,XWT,              ...
           TSHCKD,TSHCKL,WGR,DTGA,WRR14,NGR,DTR,               ...
           AMAX,CBCHK, DPAR, DPARI, PARCUM, PARCM1, PARI1, NGCR


*** 8.    Observed Values

      XWLVG  = AFGEN(XWLVGT, DOY)
      XWLVD  = AFGEN(XWLVDT, DOY)
      XWST   = AFGEN(XWSTTB, DOY)
      XWPA   = AFGEN(XWPATB, DOY)
      XWTDM  = AFGEN(XWTDMT, DOY)  - XWLVD
      XWT    = AFGEN(XWTDMT, DOY)
      XNFLV  = AFGEN(XNFLVT, DOY)


*** 9.    Functions and Parameters for Rice

**********************************************************************
* Experimental data: Parameters and Functions from: IRRI/APPA, 1992  *
* Oryza sativa cv.IR72, IRRI, Dry Season (M10)       at 225 kg N     *
**********************************************************************
```

```
* Section 2:
PARAM TBD    = 8.,     TOD   = 30.,    TMD   = 42.
PARAM DVRJ   = 0.000773
PARAM DVRI   = 0.000758
PARAM DVRP   = 0.000784
PARAM DVRR   = 0.001784
PARAM MOPP   = 11.50
PARAM PPSE   = 0.0
PARAM SHCKD  = 0.4
PARAM DOYS   = 4.
PARAM DOYTR  = 16.

* Section 3.1:
PARAM SCP    = 0.2
PARAM CO2REF = 340.
PARAM CO2    = 340.
FUNCTION NFLVTB = 0.00,0.54, 0.16,0.54, 0.33,1.53, 0.65,1.22, ...
                   0.79,1.56, 1.00,1.29, 1.46,1.37, 2.04,0.83
FUNCTION REDFTT = -10.,0., 10.,0., 20.,1., 37.,1., 43.,0.
FUNCTION EFFTB  = 10.,0.54, 40.,0.36
FUNCTION KDFTB  = 0.,0.4, 0.65,0.4, 1.,0.6,  2.1,0.6
FUNCTION KNFTB  = 0.,0.4,  2.1,0.4

* Section 3.2:
PARAM MAINLV = 0.02,  MAINST = 0.015
PARAM MAINSO = 0.003, MAINRT = 0.01
PARAM Q10    = 2.,    TREF   = 25.

* Section 3.3:
PARAM CRGLV  = 1.326, CRGST  = 1.326
PARAM CRGSO  = 1.462, CRGRT  = 1.326
PARAM CRGSTR = 1.11
PARAM LRSTR  = 0.947

* Section 3.4:
FUNCTION FSHTB  = 0.0,0.50, 0.43,0.75, 1.0,1.0 , 2.1,1.
FUNCTION FRTTB  = 0.0,0.50, 0.43,0.25, 1.0,0.0,  2.1,0.
FUNCTION FLVTB  = 0.000,0.545, 0.080,0.545, 0.245,0.559,   ...
                   0.490,0.542, 0.720,0.422, 0.895,0.053,   ...
                  1.230,0.000, 1.730,0.    , 2.1  ,0.
FUNCTION FSTTB  = 0.000,0.455, 0.080,0.455, 0.245,0.441,   ...
                   0.490,0.458, 0.720,0.578, 0.895,0.517,   ...
                  1.230,0.000, 1.730,0.    , 2.1  ,0.
FUNCTION FSOTB  = 0.000,0.000, 0.720,0.000, 0.895,0.430,   ...
                  1.230,1.000, 1.730,1.0   , 2.1  ,1.
PARAM NPLH    = 5.
PARAM NH      = 25.
PARAM NPLSB   = 1000.
PARAM FSTR    = 0.20
PARAM TCLSTR  = 10.
FUNCTION DRLVT  = 0.0,0., 0.60,0., 1.,0.015, 1.6,0.025, 2.1,0.05

* Section 3.5:
PARAM SPGF    = 64900.
PARAM WGRMX   = 0.0000249

* Section 4:
PARAM TBLV    = 8.
PARAM LAPE    = 0.0001
PARAM RGRL    = 0.0080
PARAM SHCKL   = 0.25
FUNCTION SSGATB = 0.0,0.0003, 0.9,0.0003, 2.1,0.
FUNCTION XLAITB =  4.,0.00,  16.,0.03,  34.,0.46,   58.,5.22, ...
                  68.,5.97,  83.,5.88,  97.,4.82,  114.,2.45
FUNCTION SLATB  = 0.00,0.0045, 0.16,0.0045, 0.33,0.0033, 0.65,0.0028,...
                   0.79,0.0021, 1.00,0.0019, 1.46,0.0017, 2.04,0.0017
```

```
* Section 5:
FUNCTION TMCTB  = 1.,0., 366.,0.

* Section 6:
PARAM FCLV   = 0.419, FCST   = 0.431
PARAM FCRT   = 0.431, FCSO   = 0.487
PARAM FCSTR  = 0.444

* Section 8:
FUNCTION XWLVGT =  4.,0.,      16.,6.,      34.,138.,    58.,1874., ...
                   68.,2840.,  83.,3030.,   97.,2828.,  114.,1432.
FUNCTION XWSTTB =  4.,0.,      16.,5.,      34.,109.,    58.,1577., ...
                   68.,2902.,  83.,4771.,   97.,4373.,  114.,4243.
FUNCTION XWLVDT =  4.,0.,      16.,0.,      34.,0.,      58.,47.,   ...
                   68.,234.,   83.,660.,    97.,1448.,  114.,2269.
FUNCTION XWPATB =  4.,0.,      16.,0.,      34.,0.,      58.,0.0,   ...
                   68.,0.,     83.,1558.,   97.,5932.,  114.,9843.
FUNCTION XWTDMT =  4.,0.,      16.,11.,     34.,247.,    58.,3498., ...
                   68.,5976.,  83.,10019.,  97.,14580.,114.,17787.
FUNCTION XNFLVT =  4.,0.54,    16.,0.54,    34.,1.53,     58.,1.22, ...
                   68.,1.56,   83.,1.29,    97.,1.37,    114.,0.83

TERMINAL
       WGR     = WRR/NOTNUL(NGR)

END
* Rerun LAI is simulated:
PARAM SWILAI = 1.
END
* Rerun observed LAI, and direct-seeded (no transplanting!):
PARAM SWILAI = -1., SWIDS = 1.
PARAM DVRJ   = 0.000661
PARAM DVRI   = 0.000758
PARAM DVRP   = 0.000795
PARAM DVRR   = 0.001784
PARAM NPLH   = 500.
PARAM NH     = 1.
PARAM NPLSB  = 500.
PARAM DOYTR  = 4.
END
* Rerun direct-seeded and LAI simulated:
PARAM SWILAI=1.
END
STOP
```

```
*----------------------------------------------------------------------*
*  SUBROUTINE COVER                                                    *
*  Purpose : In this subroutine a temperature correction is made      *
*            in case a plastic cover is used in the seedbed.           *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)    *
*  name   type meaning                                   units  class *
*  ----   ---- -------                                   -----  ----- *
*  SWICOV  R4  Switch in case a cover is used in seedbed   -      I   *
*  DAS     R4  Days after sowing                           -      I   *
*  DOYTR   R4  Day of transplanting                        d      I   *
*  DOYS    R4  Day of sowing                               d      I   *
*  TMPCOV  R4  Temperature correction if a cover is used   -      O   *
*----------------------------------------------------------------------*
      SUBROUTINE COVER (SWICOV,DAS,DOYTR,DOYS,
     &                  TMPCOV)
      IMPLICIT REAL (A-Z)
      INTEGER IDAS, ISA
      SAVE
      IDAS = INT(DAS)
```

```
      ISA   = INT(DOYTR) - INT(DOYS)
      IF (ISA.LT.0) THEN
          ISA = ISA + 365
        ELSE
          ISA = ISA
      ENDIF

      IF (IDAS.LT.ISA .AND. SWICOV.GT.0.) THEN
        TMPCOV=9.5
      ELSE
        TMPCOV=0.
      ENDIF
      RETURN
      END

*----------------------------------------------------------------------*
*  SUBROUTINE SUBCBC                                                   *
*  Purpose: This subroutine checks the Crop Carbon Balance             *
*           and stops the simulation if the difference between        *
*           CKCIN and CKCFL exceeds 0.1 %                              *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                  units  class *
*  ----   ---- -------                                  -----  ----- *
*  CKCIN   R4  Accumulated C in the crop                kg C/ha  I    *
*  CKCFL   R4  Sum of integrated C fluxes               kg C/ha  I    *
*  TIME    R4  Time of simulation                       d        T    *
*  CBCHK   R4  Carbon balance check, relative value to                *
*              the sums of CKIN and CKCFL               -        O    *
*----------------------------------------------------------------------*
      SUBROUTINE SUBCBC(CKCIN,CKCFL,TIME, CBCHK)
      IMPLICIT REAL (A-Z)
      SAVE

      CBCHK  = 2.0*(CKCIN-CKCFL)/(CKCIN+CKCFL+1.E-10)

      IF (ABS(CBCHK).GT.0.001) THEN
        WRITE (6,10) CBCHK, CKCIN, CKCFL, TIME
 10     FORMAT (/,'* * *Error in Carbon Balance, please check* * *',/,
     &  ' CBCHK=',F8.3,', CKCIN=',F8.2,', CKCFL=',F8.2,' at TIME=',F6.1)
        STOP
      ENDIF

      RETURN
      END

*----------------------------------------------------------------------*
*  SUBROUTINE SUBDD                                                    *
*  Purpose: This subroutine calculates the daily amount of heat units  *
*           for calculation of the phenological development rate and  *
*           early leaf area growth.                                    *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                  units  class *
*  ----   ---- -------                                  -----  ----- *
*  TMAX    R4  Daily maximum temperature                 oC      I    *
*  TMIN    R4  Daily minimum temperature                 oC      I    *
*  TBD     R4  Base temperature for development          oC      I    *
*  TOD     R4  Optimum temperature for development       oC      I    *
*  TMD     R4  Maximum temperature for development       oC      I    *
*  HU      R4  Heat units                                oC      O    *
*----------------------------------------------------------------------*
      SUBROUTINE SUBDD(TMAX,TMIN,TBD,TOD,TMD, HU)
      IMPLICIT REAL (A-Z)
      INTEGER I
      SAVE
```

```
      TM     = (TMAX + TMIN)/2.
      TT     = 0.
      DO 10 I = 1, 24
            TD = TM + 0.5*ABS(TMAX-TMIN)*COS(0.2618*FLOAT(I-14))

         IF ((TD.GT.TBD) .AND. (TD .LT. TMD)) THEN
            IF (TD.GT.TOD) TD = TOD-(TD-TOD)*(TOD-TBD) / (TMD-TOD)
         TT = TT + (TD-TBD)/24.
         ENDIF

   10 CONTINUE
      HU = TT

      RETURN
      END


*----------------------------------------------------------------------*
*  SUBROUTINE SUBCD                                                    *
*  Purpose: This subroutine calculates number of days below a certain  *
*            average temperature (TAV), which is used to terminate the *
*            simulation after a maximum number of cold days the crop   *
*           can survive.                                               *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                    units  class *
*  ----   ---- -------                                    -----  ----- *
*  DOY     R4   Day of year                                 d      T   *
*  DOYTR   R4   Day of transplanting                        d      I   *
*  TAV     R4   Average daily temperature                   oC     I   *
*  TIME    R4   Time of simulation                          d      T   *
*  NCOLD   R4   Number of cold days                         -      O   *
*----------------------------------------------------------------------*
      SUBROUTINE SUBCD(DOY,DOYTR,TAV,TIME,   NCOLD)
      IMPLICIT REAL(A-Z)
      SAVE

      IF(DOY.EQ.DOYTR) NCOLD=0.
      IF(TAV.LT.12.) THEN
         NCOLD = NCOLD + 1.
      ELSE
         NCOLD = 0.
      ENDIF

        IF (NCOLD.GT.3.) THEN
        WRITE (6,10) NCOLD, TIME
 10     FORMAT (/,'* * *Number of cold days (<12 C) exceeded 3* * *',/,
     &  ' NCOLD',F8.3, ' at TIME=',F6.1)
        ENDIF

      RETURN
      END
```

```
*----------------------------------------------------------------------*
*  SUBROUTINE PHENOL                                                   *
*  Purpose: This subroutine calculates the rate of phenological        *
*           development of the crop based on photoperiod and           *
*           temperature.                                               *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                   units  class  *
*  ----   ---- -------                                   -----  -----  *
*  DVS     R4   Development stage of the crop              -      I    *
*  DAS     R4   Days after sowing                          no     I    *
*  DVRJ    R4   Development rate, juvenile phase           1/oCd  I    *
*  DVRI    R4   Development rate, photoperiod-sensitive phase1/oCd I    *
*  DVRP    R4   Development rate, PI phase                 1/oCd  I    *
*  DVRR    R4   Development rate, reproductive phase       1/oCd  I    *
*  HU      R4   Heat units                                 oCd/d  I    *
*  DAYL    R4   Day length                                 h      I    *
*  MOPP    R4   Maximum optimum photoperiod                h      I    *
*  PPSE    R4   Photoperiod sensitivity                    1/h    I    *
*  TS      R4   Temperature sum                            oCd    I    *
*  SHCKD   R4   Delay parameter in phenology              oCd/oCd I    *
*  DOYTR   R4   Transplanting date, day of year            d      I    *
*  DOYS    R4   Sowing date, day of year                   d      I    *
*  DVR     R4   Development rate of the crop               1/d    O    *
*  TSHCKD  R4   Transpl. shock for phenol. development     oCd    O    *
*                                                                      *
*----------------------------------------------------------------------*
      SUBROUTINE PHENOL (DVS,DAS,DVRJ,DVRI,DVRP,DVRR,HU,DAYL,MOPP,PPSE,
     &                   TS,SHCKD,DOYTR,DOYS,
     &                   DVR,TSHCKD)
      IMPLICIT REAL (A-Z)
      INTEGER IDAS, ISA
      SAVE

      IDAS = INT(DAS)
      ISA  = INT(DOYTR) - INT(DOYS)
      IF (ISA.LT.0) THEN
          ISA = ISA + 365
        ELSE
          ISA = ISA
      ENDIF

         IF (DVS.GE.0.   .AND. DVS.LT.0.40) DVR = DVRJ * HU
         IF (DVS.GE.0.40 .AND. DVS.LT.0.65) THEN
            DL = DAYL + 0.9
            IF (DL.LT.MOPP) THEN
               PPFAC = 1.
             ELSE
               PPFAC = 1.-(DL-MOPP)*PPSE
            ENDIF
            PPFAC = MIN(1., MAX(0., PPFAC))
            DVR   = DVRI * HU * PPFAC
         ENDIF
         IF (DVS.GE.0.65 .AND. DVS.LT.1.00) DVR = DVRP * HU
         IF (DVS.GE.1.00)                   DVR = DVRR * HU

         IF (IDAS.EQ.ISA) TSTR   = TS
         TSHCKD = SHCKD * TSTR
         IF (IDAS.GT.ISA .AND. TS.LT.(TSTR+TSHCKD)) DVR = 0.

      RETURN
      END
```

```
*-----------------------------------------------------------------------*
*  SUBROUTINE SUBRTS                                                    *
*  Purpose: This subroutine calculates the growth rates of the organs. *
*           At the day of transplanting it calculates the weight       *
*           losses per area as a result of the change in plant density *
*           when plants are removed from the seedbed and planted in    *
*           the field.                                                 *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                     units  class *
*  ----   ---- -------                                     -----  ----- *
*  DOY    R4   Day of year                                  d       T   *
*  DOYTR  R4   Date of transplanting, daynumber             d       I   *
*  GCR    R4   Growth crop rate                            kg/ha/d I   *
*  FRT    R4   Fraction dry matter allocated to roots       -       I   *
*  FSH    R4   Fraction dry matter allocated to the shoot   -       I   *
*  FLV    R4   Fraction shoot dry matter allocated to leaves-       I   *
*  LLV    R4   Loss rate of leaves                         kg/ha/d I   *
*  FST    R4   Fraction shoot-DM allocated to the stems     -       I   *
*  FSTR   R4   Fraction CH2O allocated to stem reserves    kg/ha/d I   *
*  LSTR   R4   Loss rate of stem reserves                  kg/ha/d I   *
*  WLVG   R4   Weight of green leaves                      kg/ha   I   *
*  WSTR   R4   Weight of stem reserves                     kg/ha   I   *
*  WSTS   R4   Weight of structural stems                  kg/ha   I   *
*  WRT    R4   Weight of the roots                         kg/ha   I   *
*  NPLH   R4   Number of plants per hill                   pl/hill I   *
*  NH     R4   Number of hills                              oCd    I   *
*  NPLSB  R4   Number of plants in seedbed                 pl/m2   I   *
*  DELT   R4   Time step of integration                     d       T   *
*  GLV    R4   Growth rate leaves                         kg/ha/d  O   *
*  GSTR   R4   Growth rate stem reserves                  kg/ha/d  O   *
*  RWLVG  R4   Net growth rate of green leaves            kg/ha/d  O   *
*  GRT    R4   Growth rate of roots                       kg/ha/d  O   *
*  RWSTR  R4   Net growth rate of stem reserves           kg/ha/d  O   *
*  GST    R4   Growth rate of structural stems            kg/ha/d  O   *
*  RWLVG1 R4   RWLVG at transplanting                     kg/ha/d  O   *
*  GRT1   R4   GRT at transplanting                       kg/ha/d  O   *
*  RWSTR1 R4   RWSTR at transplanting                     kg/ha/d  O   *
*  GST1   R4   GST at transplanting                       kg/ha/d  O   *
*-----------------------------------------------------------------------*
      SUBROUTINE SUBRTS(DOY,DOYTR,GCR,FRT,FSH,FLV,LLV,FST,FSTR,LSTR,
     &                  WLVG,WSTR,WSTS,WRT,NPLH,NH,NPLSB,DELT,
     &                  GLV,GSTR,RWLVG,GRT,RWSTR,GST,
     &                  RWLVG1,GRT1,RWSTR1,GST1)

      IMPLICIT REAL (A-Z)
      SAVE

       IF (DOY.EQ.DOYTR) THEN
           PLTR   = NPLH*NH/NPLSB
        ELSE
           PLTR   = 1.
      ENDIF
           RWLVG1 = (WLVG * (1. -PLTR))/DELT
          GST1    = (WSTS * (1. -PLTR))/DELT
          RWSTR1  = (WSTR * (1. -PLTR))/DELT
          GRT1    = (WRT  * (1. -PLTR))/DELT

      GRT    = GCR * FRT                    - GRT1
      GLV    = GCR * FSH * FLV              - RWLVG1
      RWLVG  = GLV - LLV
      GST    = GCR * FSH * FST * (1.-FSTR)  - GST1
      GSTR   = GCR * FSH * FST * FSTR       - RWSTR1
      RWSTR  = GSTR - LSTR

      RETURN
      END
```

```
*---------------------------------------------------------------------*
*  SUBROUTINE SUBGRN                                                  *
*  Purpose: This subroutine calculates spikelet formation rate and    *
*           spikelet fertility as affected by low and high temperature *
*           and the grain growth rate.  Spikelet sterility component  *
*           is according to Horie et al., 1992.                      *
*                                                                     *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)   *
*  name   type meaning                                    units  class *
*  ----   ---- -------                                    -----  ----- *
*  GCR    R4   Growth crop rate                          kg/ha/d I    *
*  FSH    R4   Fraction dry matter allocated to the shoot  -     I    *
*  FSO    R4   Fraction shoot DM allocated to storage organs -   I    *
*  DOY    R4   Day of year                                 d     T    *
*  DOYTR  R4   Date of transplanting, daynumber            d     I    *
*  DVS    R4   Development stage of the crop               -     I    *
*  WRR    R4   Weight of rough rice                      kg/ha   I    *
*  PWRR   R4   Potential weight of rough rice            kg/ha   I    *
*  SPGF   R4   Spikelet growth factor                    no/kg   I    *
*  TAV    R4   Average daily temperature                   oC    I    *
*  TMAX   R4   Daily maximum temperature                   oC    I    *
*  NSP    R4   Number of spikelets                         no    I    *
*  TIME   R4   Time of simulation                          d     T    *
*  GRAINF R4   Sink limitation factor                      -     O    *
*  GSO    R4   Growth rate of storage organs            kg/ha/d  O    *
*  GGR    R4   Rate of increase in grain weight         kg/ha/d  O    *
*  GNSP   R4   Rate of increase in spikelet number      no/ha/d  O    *
*  GNGR   R4   Rate of increase in grain number         no/ha/d  O    *
*---------------------------------------------------------------------*
      SUBROUTINE SUBGRN(GCR,FSH,FSO,DOY,DOYS,DOYTR,DVS,WRR,PWRR,
     &                  SPGF,TAV,TMAX,NSP,TIME,
     &                  GRAINF,GSO,GGR,GNSP,GNGR)
      IMPLICIT REAL(A-Z)
      LOGICAL GRAINS
      SAVE

      GRAINF = 1.
      IF (DOY.EQ.DOYS) GRAINS = .FALSE.

      GSO = GCR * FSH * FSO
      IF (DVS.GT.0.95)  THEN
          GGR = GSO
      ELSE
          GGR = 0.
      ENDIF

      IF (GRAINS) THEN
          IF (WRR .GT. PWRR) GRAINF = -1.
        IF (GRAINF.LT.0.) THEN
          WRITE (6,10) GRAINF, TIME
 10       FORMAT (/,' * * * Sink limitation before DVS=2 !!!! * * *',/,
     &    ' GRAINF',F8.3, ' at TIME=',F6.1)
        ENDIF
      ENDIF

* Grain formation
      DVSPI = 0.65
      DVSF  = 1.
      IF ((DVS.GE.DVSPI) .AND. (DVS.LE.DVSF)) THEN
         GNSP = GCR * SPGF
      ELSE
         GNSP = 0.
      ENDIF

* Grain formation from spikelets (GNGR)
      IF (DOY.EQ.DOYTR) COLDTT = 0.
      IF (DOY.EQ.DOYTR) TFERT  = 0.
```

```
      IF (DOY.EQ.DOYTR) NTFERT = 0.

      IF ((DVS.GE.0.75) .AND. (DVS.LE.1.2)) THEN
         CTT    = MAX(0., 22.-TAV)
         COLDTT = COLDTT + CTT
         ENDIF
      IF ((DVS.GE.0.96) .AND. (DVS.LE.1.2)) THEN
         TFERT  = TFERT  + TMAX
         NTFERT = NTFERT + 1.
      ENDIF

      IF ((DVS.GE.1.2) .AND.(.NOT. GRAINS)) THEN
         GRAINS = .TRUE.
         SF1    = 1. - (4.6+0.054*COLDTT**1.56)/100.
         SF1    = MIN(1., MAX(0.,SF1))
         TFERT  = TFERT/(NTFERT)
         SF2    = 1./(1.+EXP(0.853*(TFERT-36.6)))
         SF2    = MIN(1., MAX(0.,SF2))
         SPFERT = MIN(SF1, SF2)
         GNGR   = NSP*SPFERT
      ELSE
         GNGR   = 0.
      ENDIF
      RETURN
      END

*----------------------------------------------------------------------*
*  SUBROUTINE SUBLAI                                                   *
*  Purpose: This subroutine calculates the leaf area index of the      *
*           crop in the seedbed and after transplanting in the field.  *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                    units  class *
*  ----   ---- -------                                    -----  ----- *
*  SWIDS   R4  Switch for direct-seeding or transplanting   -       I  *
*  SWILAI  R4  Switch for simulated or measured LAI          -       I  *
*  DAS     R4  Days after sowing                             d       I  *
*  DOYS    R4  Sowing date, daynumber of year                d       I  *
*  DOYTR   R4  Day of transplanting                          d       I  *
*  LAPE    R4  Leaf area of the plant at emergence           m2      I  *
*  RGRL    R4  Relative growth rate for leaf development   1/(oCd)   I  *
*  TSLV    R4  Temperature sum for leaf development          oC      I  *
*  NPLSB   R4  Number of plants in seedbed                 pl/m2     I  *
*  WLVG    R4  Weight of the green leaves                  kg/ha     I  *
*  SLA     R4  Specific leaf area                          ha/kg     I  *
*  NH      R4  Number of hills                             hills/m2  I  *
*  NPLH    R4  Number of plants per hill                   pl/hill   I  *
*  SHCKL   R4  Delay parameter in development              oCd/oCd   I  *
*  DVS     R4  Development stage                              -      I  *
*  LAISIM  R4  Simulated leaf area index                    ha/ha    O  *
*  TSHCKL  R4  Transpl. shock for leaf area development     oCd      O  *
*----------------------------------------------------------------------*
      SUBROUTINE SUBLAI(SWIDS,SWILAI,DAS, DOYS, DOYTR,LAPE,RGRL,TSLV,
     &                  NPLSB, WLVG,  SLA,   NH, NPLH, SHCKL, DVS.
     &                  LAISIM, TSHCKL)
      IMPLICIT REAL (A-Z)
      INTEGER IDAS,ISA
      SAVE

      IDAS = INT(DAS)
      IF (SWIDS.LT.0.) THEN
        ISA  = INT(DOYTR) - INT(DOYS)
        IF (ISA.LT.0) THEN
           ISA = ISA + 365
          ELSE
           ISA = ISA
        ENDIF
```

```
      LAIEXS = 0.
      WLVEXS = 0.

            IF (IDAS.LT.ISA) THEN
               IF (LAISIM.LT.1.) THEN
                  LAPI   = LAPE * (EXP(RGRL*TSLV))
                  LAISIM = LAPI * NPLSB
                  WLVEXS = WLVG
                  LAIEXS = LAISIM
               ELSE
                  LAISIM = SLA*(WLVG-WLVEXS)+LAIEXS
               ENDIF
            ELSE
               IF (IDAS.EQ.ISA) THEN
                  LAII   = LAISIM * NH * NPLH / NPLSB
                  TSLVTR = TSLV
                  TSHCKL = SHCKL * TSLVTR
               ENDIF
               IF (TSLV.LT.(TSLVTR+TSHCKL)) THEN
                  LAISIM = LAII
               ELSE
                  IF ((LAISIM.LT.1.0) .AND. (DVS.LT.1.0)) THEN
                     LAISIM = LAII*(EXP(RGRL*(TSLV-TSLVTR-TSHCKL)))
                     WLVEXP = WLVG
                     LAIEXP = LAISIM
                  ELSE
                     LAISIM = LAIEXP+SLA*(WLVG-WLVEXP)
                  ENDIF
               ENDIF
            ENDIF
         ENDIF

      IF (SWIDS.GT.0.) THEN
         IF (IDAS.EQ.0.) LAISIM = NPLSB * LAPE
            IF (LAISIM.LT.1.) THEN
               LAPI   = LAPE * (EXP(RGRL*TSLV))
               LAISIM = LAPI * NPLSB
               WLVEXS = WLVG
               LAIEXS = LAISIM
            ELSE
               LAISIM = SLA * (WLVG-WLVEXS) + LAIEXS
            ENDIF
      ENDIF

      IF (SWILAI.LT.0.) LAISIM = 0.
      RETURN
      END
```

```
*----------------------------------------------------------------------*
*  SUBROUTINE ASTRO                                                    *
*  Purpose: This subroutine calculates astronomic daylength,           *
*           diurnal radiation characteristics such as the daily        *
*           integral of sine of solar elevation and solar constant.    *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                    units  class *
*  ----   ---- -------                                    -----  ----- *
*  DOY     R4  Daynumber (Jan 1st = 1)                      -       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)
      SAVE

*-----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 TOTASP                                                   *
*  Purpose: This subroutine calculates daily total potential gross     *
*           assimilation (DTGA) by performing a Gaussian integration   *
*           over time. At three different times of the day,            *
*           radiation is computed and used to determine assimilation   *
*           whereafter integration takes place.                        *
*                                                                      *
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)     *
*  name   type meaning                                    units  class *
*  ----   ---- -------                                    -----  ----- *
*  DOY     R4  Daynumber (January 1 = 1)                    -      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   *
*  EFF     R4  Initial light use efficiency              kg CO2/J/ I   *
*                                                        ha/h m2 s     *
*  REDFT   R4  Reduction factor, temp. effect on AMAX       -      I   *
*  KDF     R4  Extinction coefficient for diffuse light     -      I   *
*  KNF     R4  Extinction coefficient, N profile in canopy  -      I   *
*  LAI     R4  Apparent leaf area index (incl. stem area)  ha/ha   I   *
*  CO2     R4  Ambient CO2 concentration                    ppm    I   *
*  NFLV    R4  Nitrogen fraction in the leaves              g/m2   I   *
*  DAYL    R4  Astronomic daylength (base = 0 degrees)       h     O   *
*  AMAX    R4  Assimilation rate at light saturation      kg/ha/h  O   *
*  DTGA    R4  Daily total gross Assimilation             kg/ha/d  O   *
*  DPAR    R4  Daily incoming PAR                         MJ/m2/d  O   *
*  DPARI   R4  Intercepted DPAR                           MJ/m2/d  O   *
*                                                                      *
*  SUBROUTINES and FUNCTIONS called : ASTRO, ASSIMP                    *
*----------------------------------------------------------------------*
      SUBROUTINE TOTASP (DOY,  LAT , DTR, SCP, EFF, REDFT, KDF, KNF,
     &                   LAI,  CO2,  NFLV,
     &                   DAYL, AMAX, DTGA, DPAR, DPARI)
      IMPLICIT REAL(A-Z)
      REAL XGAUSS(3), WGAUSS(3)
      INTEGER I1, IGAUSS
      SAVE

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

      PI    = 3.141592654

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

*-----assimilation set to zero and three different times of the day (HOUR)
      DTGA  = 0.
      DPAR  = 0.
      DPARI = 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
      ENDIF
      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 ASSIMP (SCP,EFF,REDFT,KDF,KNF,LAI,SINB,PARDR,PARDF,NFLV,CO2,
     &             AMAX, FGROS, PARINT)

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

10    CONTINUE

      DTGA = DTGA * DAYL

*-----calculation of daily incident PAR and intercepted PAR (MJ/m2/d)
      DPAR  = DPAR  * DAYL * 3600/1.E6
      DPARI = DPARI * DAYL * 3600/1.E6

      RETURN
      END

*----------------------------------------------------------------------*
* SUBROUTINE ASSIMP                                                    *
* Purpose: This subroutine performs a Gaussian integration over       *
*          depth of canopy by selecting three different LAI's and     *
*          computing potential assimilation at these LAI levels. The  *
*          integrated variable is FGROS. The routine accounts for     *
*          an exponential profile of leaf N in the canopy and         *
*          includes the effect of CO2 concentration.                  *
*                                                                      *
* 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  *
* EFF     R4  Initial light use efficiency               kg CO2/J/  I  *
*                                                        ha/h m2 s     *
* REDFT   R4  Reduction factor, temp. effect on AMAX       -       I  *
* KDF     R4  Extinction coefficient for diffuse light     -       I  *
* KNF     R4  Extinction coefficient, N profile in canopy  -       I  *
* LAI     R4  Apparent leaf area index (incl. stem area)  ha/ha    I  *
* SINB    R4  Sine of solar height                         -       I  *
* PARDR   R4  Instantaneous flux of direct radiation (PAR) W/m2    I  *
* PARDF   R4  Instantaneous flux of diffuse radiation(PAR) W/m2    I  *
* NFLV    R4  Nitrogen fraction in the leaves              g/m2    I  *
* CO2     R4  Ambient CO2 concentration                    ppm     I  *
* AMAX    R4  Assimilation rate at light saturation      kg/ha/h   O  *
* FGROS   R4  Instantaneous assimilation rate of         kg CO2/      *
*             whole canopy                               ha soil/h O  *
* PARINT  R4  Intercepted PAR                             J/m2/s   O  *
*----------------------------------------------------------------------*
      SUBROUTINE ASSIMP (SCP,  EFF,   REDFT, KDF,  KNF,  LAI,
     &                   SINB, PARDR, PARDF, NFLV, CO2,
     &                   AMAX, FGROS, PARINT)
      IMPLICIT REAL(A-Z)
      REAL XGAUSS(3), WGAUSS(3)
```

```
      INTEGER I1, I2, IGAUSS
      SAVE

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

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

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

*-----calculate relative effect of CO2 level on AMAX
      CO2AMX = 49.57/34.26 * (1.-EXP(-0.208*(CO2-60.)/49.57))
      CO2AMX = MAX(0., CO2AMX)

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

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

*--------calculate leaf nitrogen for each layer,
*        based on exponential distribution
         IF (LAI.GT.0.01 .AND. KNF.GT.0.) THEN
             SLNI = NFLV * LAI * KNF * EXP(-KNF*LAIC)/(1.-EXP(-KNF*LAI))
         ELSE
             SLNI = NFLV
         ENDIF

*--------calculate actual photosynthesis from SLN, CO2 and temperature
*        calculation of AMAX according to van Keulen & Seligman (1987):
*        AMAX = 32.4 * (SLNI-0.2) * REDFT * CO2AMX
         IF (SLNI .GE. 0.5) THEN
*          according to Shaobing Peng (IRRI, unpublished data):
            AMAX = 9.5 + (22. * SLNI) * REDFT * CO2AMX
         ELSE
            AMAX = MAX(0., 68.33 * (SLNI-0.2) * REDFT * CO2AMX)
         ENDIF

*--------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.
         ENDIF

*--------direct flux absorbed by leaves perpendicular on direct beam and
*        assimilation of sunlit leaf area
         VISPP  = (1.-SCP) * PARDR / SINB
         FGRSUN = 0.
         IASUN  = 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.
            ENDIF
            FGRSUN = FGRSUN +    FGRS * WGAUSS(I2)
            IASUN  = IASUN  + VISSUN * WGAUSS(I2)
20       CONTINUE

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

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

10    CONTINUE
      FGROS = FGROS * LAI

*-----calculation of intercepted PAR (PARINT, J/m2/s)
      PARINT = PARINT * LAI

      RETURN
      END
```

Appendix 2 List of variables

Name	Description	Units
ALAI	Apparent leaf area index (including stem area)	ha ha^{-1}
AMAX	Actual CO_2 assimilation rate at light saturation for individual leaves at a specific height in the canopy (Subroutine ASSIMP)	kg CO_2 ha^{-1} leaf h^{-1}
AOB	Intermediate variable	-
ASIN	Arcsine function (intrinsic FORTRAN function)	-
ASSIMP	Subroutine to calculate FGROS	-
ASTRO	Subroutine to compute e.g. daylength	-
ATMTR	Atmospheric transmission coefficient	-
CBCHK	Difference between carbon added to the crop since initialization and the net total of integrated carbon fluxes, relative to their sum	-
CKCIN	Carbon in the crop accumulated since simulation started	kg C ha^{-1}
CKCFL	Sum of integrated carbon fluxes into and out of the crop	kg C ha^{-1}
CLUSTF	Cluster factor	-
COLDTT	Accumulated cold degree-days	°Cd
COS	Cosine function (intrinsic FORTRAN function)	-
COSLD	Intermediate variable in calculating solar height	-
CO2	Ambient CO_2 concentration	ppm
CO2EFF	Relative effect of CO_2 on initial light use efficiency (EFF)	-
CO2LV	CO_2 production factor for growth of leaves	kg CO_2 kg^{-1} DM
CO2AMX	Relative effect of CO_2 on AMAX	-
CO2REF	Reference level of atmospheric CO_2 (340 ppm)	ppm
CO2RT	CO_2 production factor for growth of roots	kg CO_2 kg^{-1} DM
CO2SO	CO_2 production factor for growth of storage organs	kg CO_2 kg^{-1} DM
CO2ST	CO_2 production factor for growth of stems	kg CO_2 kg^{-1} DM
CO2STR	CO_2 production factor for growth of stem reserves	kg CO_2 kg^{-1} DM
CRGCR	Carbohydrate (CH_2O) requirement for dry matter production	kg CH_2O kg^{-1} DM
CRGLV	Carbohydrate requirement for leaf dry matter production	kg CH_2O kg^{-1} DM leaf
CRGRT	Carbohydrate requirement for root dry matter production	kg CH_2O kg^{-1} DM root
CRGSO	Carbohydrate requirement for stor. organ dry matter production	kg CH_2O kg^{-1} DM stor.organ
CRGST	Carbohydrate requirement for stem dry matter production	kg CH_2O kg^{-1} DM stem
CRGSTR	Carbohydrate requirement for stem reserves production	kg CH_2O kg^{-1} DM
CTRANS	Carbon losses at transplanting	kg C ha^{-1}
DAS	Days after seeding	d
DAYL	Daylength	h
DEC	Declination of the sun	radians
DELT	Time interval of integration (reserved name)	d
DL	Photoperiodic daylength	h
DOY	Daynumber since 1 January (day of year) (reserved variable name)	-
DOYS	Seeding date, daynumber of year	-
DOYTR	Transplanting date, daynumber of year	-
DPAR	Daily incoming PAR	MJ m^{-2} d^{-1}
DPARI	The amount of PAR absorbed on a day by the canopy, calculated in a detailed way based on integration of light absorbed by single leaves over the LAI and over the day	MJ m^{-2} d^{-1}
DRLVT	Table for leaf death coefficient as function of DVS	d^{-1}, -
DS0	Daily extraterrestrial radiation	J m^{-2} d^{-1}
DSINB	Integral of SINB over the day	s d^{-1}
DSINBE	As DSINB, but with a correction for lower atmospheric transmission at lower solar elevations	s d^{-1}

DTGA	Daily total gross CO_2 assimilation of the crop	kg CO_2 ha^{-1} soil d^{-1}
DTR	Daily total global radiation	J m^{-2} d^{-1}
DVR	Development rate of the crop	d^{-1}
DVRI	Development rate during photoperiod-sensitive phase	$(^oCd)^{-1}$
DVRJ	Development rate during juvenile phase	$(^oCd)^{-1}$
DVRP	Development rate during panicle development phase	$(^oCd)^{-1}$
DVRR	Development rate in the reproductive phase (post-anthesis)	$(^oCd)^{-1}$
DVS	Development stage of the crop	-
DVSI	Initial value of development stage of the crop	-
DVSPI	Development stage at panicle initiation	-
DVSF	Development stage at flowering	-
EFF	Initial light use efficiency for individual leaves	kg CO_2 ha^{-1} leaf h^{-1} (J m^{-2} leaf $s^{-1})^{-1}$
EFFTB	*Table of EFF as a function of temperature*	EFF, °C
FCLV	Mass fraction carbon in the leaves	kg C kg^{-1} DM
FCRT	Mass fraction carbon in the roots	kg C kg^{-1} DM
FCSO	Mass fraction carbon in the storage organs	kg C kg^{-1} DM
FCST	Mass fraction carbon in the stems	kg C kg^{-1} DM
FCSTR	Mass fraction carbon in the stem reserves	kg C kg^{-1} DM
FGL	CO_2 assimilation rate at a specific depth in the canopy	kg CO_2 ha^{-1} leaf h^{-1}
FGRAIN	Fraction grain in the panicle	-
FGROS	Instantaneous canopy CO_2 assimilation	kg CO_2 ha^{-1} soil h^{-1}
FGRS	Intermediate variable for calculation of assimilation of sunlit leaves	-
FGRSH	CO_2 assimilation rate at one depth in the canopy for shaded leaves	kg CO_2 ha^{-1} leaf h^{-1}
FGRSUN	CO_2 assimilation rate at one depth in the canopy for sunlit leaves	kg CO_2 ha^{-1} leaf h^{-1}
FINTIM	Finish time, period of simulation (reserved name)	d
FLV	Fraction of shoot dry matter allocated to leaves	-
FLVTB	Table of FLV as function of DVS	-, -
FRDF	Fraction diffuse in incoming radiation	-
FRT	Fraction of total dry matter allocated to roots	-
FRTTB	Table of FRT as function of DVS	-, -
FSH	Fraction of total dry matter allocated to shoots	-
FSHTB	Table of FSH as function of DVS	-, -
FSLLA	Fraction of sunlit leaf area	-
FSO	Fraction of shoot dry matter allocated to storage organs	-
FSOTB	Table of FSO as function of DVS	-, -
FST	Fraction of shoot dry matter allocated to stems	-
FSTTB	Table of FST as function of DVS	-, -
FSTR	Fraction carbohydrates allocated to the stems, that is stored as reserves	-
GCM	General Circulation Model	-
GCR	Gross growth rate of crop dry matter, including translocation	kg DM ha^{-1} soil d^{-1}
GGR	Rate of increase in grain weight	kg DM ha^{-1} soil d^{-1}
GLV	Dry matter growth rate of leaves	kg DM ha^{-1} soil d^{-1}
GNSP	Rate of increase in spikelet number	number ha^{-1} soil d^{-1}
GNGR	Daily increment in grain number	number ha^{-1} soil d^{-1}
GRAINF	Sink limitation factor	-
GRAINS	Fortran logical function whether grains are formed	Boolean
GRT	Dry matter growth rate of roots	kg DM ha^{-1} soil d^{-1}
GRT1	Reduction in root weight per unit area during transplanting from seedbed to field	kg DM ha^{-1} soil
GSO	Dry matter growth rate of storage organs	kg DM ha^{-1} soil d^{-1}

GST	Dry matter growth rate of stems	kg DM ha^{-1} soil d^{-1}
GST1	Reduction in stem weight per unit area during transplanting from seedbed to field	kg DM ha^{-1} soil
GSTR	Dry matter growth rate of the stem reserves	kg DM ha^{-1} soil d^{-1}
HOUR	Selected hour during the day	h
HU	Daily heat units effective for phenological development	(°Cd) d^{-1}
HULV	Daily heat units effective for leaf area development	(°Cd) d^{-1}
I1	Do-loop counter	-
I2	Do-loop counter	-
IDAS	*Integer value of days after sowing*	*d*
IGAUSS	Do-loop counter	-
ISA	Integer value for seedling age	d
KBL	Extinction coefficient for direct component of direct PAR flux	ha soil ha^{-1} leaf
KDF	Extinction coefficient for leaves	ha soil ha^{-1} leaf
KDFTB	Table of KDF as function of development stage (DVS)	-, -
KDRT	Extinction coefficient for total direct PAR flux	ha soil ha^{-1} leaf
KNF	Extinction coefficient of nitrogen profile in the canopy	-
KNFT	Table of KNF as function of development stage (DVS)	-, -
LAPE	Leaf area per plant at emergence	m^2 $plant^{-1}$
LAPI	Leaf area per plant in seedbed	m^2 $plant^{-1}$
LAI	Total area index (leaves + stems)	ha leaf ha^{-1} soil
LAIC	Leaf area index above selected height in canopy	ha leaf ha^{-1} soil
LAIEXP	Leaf area index at end of exponential leaf area growth phase	ha leaf ha^{-1} soil
LAIEXS	Leaf area index at end of exponential leaf area growth phase in seedbed	ha leaf ha^{-1} soil
LAII	Initial leaf area index at tranplanting	ha leaf ha^{-1} soil
LAISIM	Simulated leaf area index	ha leaf ha^{-1} soil
LAT	Latitude of the weather station (reserved variable name from WEATHER)	degrees
LLV	Loss of leaves	kg leaf ha^{-1} d^{-1}
LRSTR	Fraction (1 - 5.3%) of allocated stem reserves that is available for growth (5.3% loss due to membrane passages)	-
LSTR	Loss rate of stem reserves	kg stem res. ha^{-1} d^{-1}
MAINLV	Maintenance respiration coefficient of leaves	kg CH_2O kg^{-1} DM d^{-1}
MAINRT	Maintenance respiration coefficient of roots	kg CH_2O kg^{-1} DM d^{-1}
MAINSO	Maintenance respiration coefficient of storage organs	kg CH_2O kg^{-1} DM d^{-1}
MAINST	Maintenance respiration coefficient of stems	kg CH_2O kg^{-1} DM d^{-1}
MNDVS	Factor accounting for effect of DVS on maintenance respiration	-
MOPP	Maximum optimum photoperiod	h
NCOLD	Number of cold days	d
NH	Number of hills	hills m^{-2}
NFLV	Nitrogen fraction in the leaves	g N m^{-2} leaf
NFLVTB	Table of NFLV as function of development stage (DVS)	-
NGCR	Net growth rate of crop dry matter, including translocation	kg DM ha^{-1} soil d^{-1}
NGR	Number of grains	number ha^{-1}
NPLH	Number of plants per hill	plants $hill^{-1}$
NPLSB	Number of plants in seedbed	plants m^{-2}
NSP	Number of spikelets	number ha^{-1}
NTFERT	Number of days for TFERT	d

PAR	Instantaneous flux of photosynthetically active radiation	J m^{-2} soil s^{-1}
PARCUM	Cumulative amount of radiation absorbed by the canopy based on the detailed calculation of daily absorbed radiation	MJ m^{-2}
PARCM1	Cumulative amount of radiation absorbed by the canopy based on the simple calculation of daily absorbed radiation	MJ m^{-2}
PARDF	Instantaneous diffuse flux of incoming PAR	J m^{-2} soil s^{-1}
PARDR	Instantaneous direct flux of incoming PAR	J m^{-2} soil s^{-1}
PARI1	Amount of PAR absorbed on a day by the canopy, calculated by a single equation using Beer's law	MJ m^{-2} soil d^{-1}
PARINT	Intercepted PAR	J m^{-2} soil s^{-1}
PHENOL	Subroutine to determine the phenology of the crop	-
PI	Ratio of circumference to diameter of circle	-
PLTR	Intermediate variable for change in plant density at transplanting	-
PPFAC	Factor determining photoperiod sensitivity	-
PPSE	Photoperiod sensitivity	h^{-1}
PRDEL	Time interval for tabular printed output (reserved name)	d
PWRR	Potential weight of rough rice (WRR)	kg ha^{-1}
Q10	Factor accounting for increase of maintenance respiration with a 10 °C rise temperature	-
RAD	Factor to convert degrees to radians	radians $degree^{-1}$
RAIN	Precipitation (reserved weather variable name)	mm
RDAS	Rate to calculate days after seeding	d^{-1}
RDD	Daily global radiation (reserved weather variable name)	J m^{-2} d^{-1}
REDFT	Factor accounting for effect of temperature on AMAX	-
REDFTT	Table of REDFT as function of temperature	-, °C
REFH	Reflection coefficient for diffuse PAR	-
REFS	Reflection coefficient for direct PAR	-
RGCR	Growth respiration rate of the crop	kg CO_2 ha^{-1} d^{-1}
RGRL	Relative growth rate of leaf area during exponential growth	$(°Cd)^{-1}$
RMCR	Maintenance respiration rate of the crop	kg CH_2O ha^{-1} d^{-1}
RTNASS	Net rate for integration the total net CO_2 assimilation	kg CO_2 ha^{-1} d^{-1}
RWLVG	Net growth rate of increase in DM of leaves	kg DM ha^{-1} soil d^{-1}
RWLVG1	Reduction in net leaf weight per unit area during transplanting from seedbed to field	kg DM ha^{-1} soil
RWSTR	Net growth rate of increase in DM of the stem reserves	kg DM ha^{-1} soil d^{-1}
RWSTR1	Reduction in net stem reserves weight per unit area during transplanting from seedbed to field	kg DM ha^{-1} soil
SAI	Stem area index	ha ha^{-1}
SC	Solar constant, corrected for varying distances between sun-earth	J m^{-2} s^{-1}
SCP	Scattering coefficient of leaves for PAR	-
SF1	Spikelet fertility due to low temperatures	-
SF2	Spikelet fertility due to high temperatures	-
SHCKD	Parameter indicating relation between seedling age and delay in phenological development	°Cd $(°Cd)^{-1}$
SHCKL	Parameter indicating relation between seedling age and delay in leaf area development	°Cd $(°Cd)^{-1}$
SIN	Sine function (intrinsic FORTRAN function)	-
SINB	Sine of solar elevation	-
SINLD	Intermediate variable in calculating solar declination	-
SLA	Specific leaf area	ha leaf kg^{-1} leaf
SLATB	Table of SLA as function of DVS	-

SNLI	Specific Leaf N at the top of the canopy	kg N ha^{-1} leaf
SPFERT	Spikelet fertility	-
SPGF	Spikelet growth factor	number kg^{-1}
SQV	Intermediate variable in calculation of reflection coefficient	-
SSGA	Specific green stem area	ha kg^{-1} stem
SSGATB	Table of SSGA as function of DVS	-, -
STTIME	Start time of simulation (reserved variable name)	d
SUBCBC	Subroutine for carbon balance check	-
SUBCD	Subroutine to calculate number of cold days	-
SUBDD	Subroutine to calculate daily amounts of heat units	-
SUBGRN	Subroutine to calculate grain growth rate and grain formation rate	-
SUBLAI	Subroutine to calculate the simulated leaf area index	-
SUBRTS	Subroutine to calculate growth rates	-
SWICOV	Switch for temperature correction when cover is used in seedbed	-
SWIDS	Switch for direct-seeded or transplanted rice	-
SWILAI	Switch to use as input in the model measured (-1) or simulated (1) LAI	-
SWINLV	Switch to use as input in the model NFLV vs DVS (-1) or vs DOY (1)	-
SWITMP	Switch to use GCM (General Circulation Model) temperature correction	-
TAV	Daily average temperature	°C
TAVD	Daily average daytime temperature	°C
TBD	Base temperature for development	°C
TBLV	Base temperature for juvenile leaf area growth	°C
TCLSTR	Time coefficient for loss of stem reserves	d^{-1}
TEFF	Factor accounting for effect of temperature on maintenance respiration	-
TFERT	Accumulated temperature for high temperature effect on spikelet fertility	°C
TIME	Time in simulation (reserved variable name)	d
TMAX	Daily maximum temperature	°C
TMAXC	Correction to maximum temperature (GCM)	°C
TMAXT	Table daily maximum temperature as function of day of the year	°C, d
TMCTB	Table for GCM (General Circulation Model) temperature correction	°C, month
TMD	Maximum temperature for development	°C
TMIN	Daily minimum temperature	°C
TMINC	Correction to minimum temperature (GCM)	°C
TMINT	Table daily minimum temperature as function of day of the year	°C, d
TMLV	Maximum temperature for leaf area development	°C
TMMN	Daily minimum temperature (reserved weather variable name)	°C
TMMX	Daily maximum temperature (reserved weather variable name)	°C
TNASS	Total net CO_2 assimilation	kg CO_2 ha^{-1}
TOD	Optimum temperature for development	°C
TOTASP	Subroutine to calculate potential gross CO_2 assimilation of the crop	-
TREF	Reference temperature	°C
TS	Temperature sum for phenological development	°Cd
TSHCKD	Transplanting shock for phenological development	°Cd
TSHCKL	Transplanting shock for leaf area development	°Cd
TSLV	Temperature sum for leaf area development	°Cd
TSLVTR	Temperature sum for leaf area development at tranplanting	°Cd
TSTR	Temperature sum for phenological development at tranplanting	°Cd
VISD	Absorbed direct component of direct flux per unit leaf area (at depth LAIC)	J m^{-2} leaf s^{-1}
VISDF	Absorbed diffuse flux per unit leaf area (at depth LAIC)	J m^{-2} leaf s^{-1}
VISPP	Absorbed light flux by leaves perpendicular on direct beam	J m^{-2} leaf s^{-1}
VISSHD	Total absorbed flux for shaded leaves per unit leaf area (at depth LAIC)	J m^{-2} leaf s^{-1}
VISSUN	Total absorbed flux for sunlit leaves in one of three Gauss point classes	J m^{-2} leaf s^{-1}

VIST	Absorbed total direct flux per unit leaf area (at depth LAIC)	J m^{-2} leaf s^{-1}
VP	Vapour pressure (reserved weather variable name)	kPa
WAG	Total above-ground dry matter	kg DM ha^{-1}
WCR	Total biomass (crop)	kg DM ha^{-1}
WEATHER	Routine from TTUTIL library, call to read external weather data files	-
WGAUSS	Array containing weights to be assigned to Gauss points	-
WGR	Individual grain weight	kg $grain^{-1}$
WGRMX	Maximum individual grain weight	kg $grain^{-1}$
WLVD	Dry weight of dead leaves	kg ha^{-1}
WLVEXP	Weight of leaves at end of exponential leaf growth phase	kg ha^{-1}
WLVEXS	Weight of leaves at end of exponential leaf growth phase in seedbed	kg ha^{-1}
WLVG	Dry weight of green leaves	kg ha^{-1}
WLVGI	Initial dry weight of the leaves	kg ha^{-1}
WN	Wind speed (reserved weather variable name)	m s^{-1}
WRR	Dry weight rough rice (final yield)	kg ha^{-1}
WRR14	Dry weight rough rice (14% moisture)	kg ha^{-1}
WRT	Dry weight of the roots	kg ha^{-1}
WRTI	Initial dry weight of the roots	kg ha^{-1}
WSO	Dry weight of storage organs	kg ha^{-1}
WSOI	Initial dry weight of storage organs	kg ha^{-1}
WST	Dry weight of the stems	kg ha^{-1}
WSTI	Initial dry weight of the stems	kg ha^{-1}
WSTR	Dry weight of stems reserves	kg ha^{-1}
WSTS	Dry weight of structural stems	kg ha^{-1}
XGAUSS	Array containing Gauss points	-
XLAI	Observed values of LAI	ha ha^{-1}
XLAITB	Table of XLAI as function of day of year	-
XNFLV	Observed values of NFLV	g N m^{-2} leaf
XNFLVT	Table of XNFLV as function of day of year	-
XSLA	Observed values of specific leaf area	ha leaf kg^{-1} leaf
XSLATB	Table of XSLA as function of day of year	-
XWLVD	Observed values of WLVD	kg ha^{-1}
XWLVDT	Table of XWLVD as function of day of year	-
XWLVG	Observed values of WLVG	kg ha^{-1}
XWLVGT	Table of XWLVG as function of day of year	-
XWPA	Observed values of WSO	kg ha^{-1}
XWPATB	Table of XWPA af function of day of year	-
XWST	Observed values of WST	kg ha^{-1}
XWSTTB	Table of XWST as function of day of year	-
XWTDM	Observed values of WAG	kg ha^{-1}
XWTDMT	Table of XWTDM as function of day of year	-
ZERO	Initial zero condition for integrals	-

Appendix 3 How to install FST and the FST-Shell on IBM compatible PC's

3.1 Requirements for running the Fortran Simulation Translator (FST)

The following requirements should be met if you want to make full use of FST.

- MS-DOS 5.0 or higher.
- Availability of Microsoft Fortran v 5.1 compiler (installation of the compiler will be explained below).
- A minimum of 640k RAM memory.
- 4 Mb free hard disk space, when Microsoft Fortran is not yet installed, 2 Mb when installed.
- A 80286 or higher processor.
- A EGA or VGA screen.
- A 3.5" floppy drive.
- A mathematical coprocessor is not required but will speed up calculations considerably.

1.2 Contents of the disk

The disk you received is a 3.5" high density disk and has been formatted for IBM-PC's and compatibles. If you are working on another machine and have no way to transfer the source files to your machine, please send a request to obtain the programs in another disk format (do not forget to specify your hardware configuration), for address see below.

The FST disk contains the FST translator and FST link libraries, a user-friendly interface (FST-Shell) to the FST translator and several utility programs to be used in conjunction with the translator and the shell. The contents of the floppy disk is described in the table below:

Directory	File	Contents of the file
A:\SYS\FST	FST.EXE	FST translator program
	FSTS.EXE	Shell to the FST translator
	FSTS.INI	Initialization file describing which editor and lister FSTS should be use
	FSTREC.EXE	Program to recover output after run time error
	Q.EXE	Q editor, (shareware!)
	LIST.COM	Lister, to look at files, (shareware!);
	TTSELECT.EXE	Program to generate graphs on the screen
	HELVB.FON	Font definition file for TTSELECT
	README.TXT	Text file containing version information

A:\SYS\F77	DRIVERS.LIB	DRIVERS object library
	TTUTIL.LIB	TTUTIL 3.3 object library
	WEATHER.LIB	WEATHER version 4 object library
A:\	FST.BAT	Batch file to start translator when working from the command line
	FSTS.BAT	Batch file to start the FST-Shell
	AUTOEXEC.ADD	File to be added to AUTOEXEC. BAT file
A:\EXAMPLES	Several FST files	Example files that can be run with FST or FSTS

As will be explained in more detail below, the FST translator can be used in two different ways, through the FST Shell (FSTS) or from the MS-DOS command line. The installation procedure below describes the installation of both methods.

1.3 General installation of FST and Microsoft FORTRAN 5.1 on IBM-compatibles

This section explains the installation of FST and the installation of MS FORTRAN 5.1.

1) Install the compiler in the directory C:\SYS\F77 on your hard disk. Make sure you have also installed the compiler's library on the directory C:\SYS\F77 as follows: large memory model, floating point emulator, no C and no MS FORTRAN 3.30 compatibility. This library will have the name: LLIBFORE.LIB. The following files should at least be available on the C:\SYS\F77 directory: FL.DEF, F1.ERR, F23.ERR, FL.ERR, F1.EXE, F2.EXE, F3.EXE, F3S.EXE, FL.EXE, LINK.EXE, LLIBFORE.LIB, FL.MSG.
2) Create the directory C:\TMP if this directory does not yet exist (used by the compiler to store temporary files):
```
C:   <Enter>
CD \ <Enter>
MD TMP <Enter>
```
3) Copy the object library files from the A:\SYS\F77 directory to the compilers directory on C: by:
```
COPY A:\SYS\F77\*.*   C:\SYS\F77\*.* <Enter>
```
4) Create the directory C:\SYS\FST and copy files from the A:\SYS\FST directory to the C:\SYS\FST directory by:
```
C: <Enter>
CD \SYS <Enter>
MD FST  <Enter>
COPY A:\SYS\FST\*.*  C:\SYS\FST\*.* <Enter>
```
5) Copy the A:\FST.BAT and A:\FSTS.BAT files to a directory that is in the 'path'. The FST.BAT and FSTS.BAT files are the ones that actually start the FST translator (FST.BAT) or the FST-Shell (FSTS.BAT). An alternative method is to put them in the

directory where you will be doing your work.

```
COPY A:\*.BAT <directory> <Enter>
```

6) Add to the end of your C:\AUTOEXEC.BAT file the contents of the A:\AUTOEXEC.ADD file. This file contains several environment variables necessary for running FST and FSTS.
7) Restart your PC. If somewhere during startup of the PC you get the message "Out of environment space", most likely the above mentioned environment variables will not have been defined and consequently you cannot run FST or FSTS. To solve this problem you should increase the size of the environment at startup. To do this, edit the C:\CONFIG.SYS file and look for a line starting with "SHELL=". (If this line is not available see your MS-DOS manual on how to introduce one). The size of the environment is specified on this line by the switch /E:<number>.

- If no /E:<number> switch exist on this line, type at the end of the line /E:512 (this increases the environment from the default value of 256 bytes to 512 bytes).
- If there is already a /E:<number> switch, increase the specified value with 128.

Restart your PC.

N.B. After this installation the FST-Shell will use the Q-editor (shareware) for program editing and LIST (shareware) for listing files that need only to be shown. By modifying the C:\SYS\FST\FSTS.INI file you can change this and use the editor of your own choice.

Using the FST-Shell to run FST programs

Starting the FST-Shell should be possible after successful installation by typing:

```
FSTS <Enter>
```

Before the FST-Shell shows all kinds of dialogs it will first check the existence of required files and environment variable settings. If no error messages appear, a dialog will appear asking you for the name of the FST file you want to work with. (Cursor, Home and End keys can be used here to fill in this field). Type <Enter> when the file name is correct. The next screen shows a vertical list of different command you can give to the FST-Shell. These commands pertain to the model name you have just typed in. Some commands have a highlighted character and some have not. The commands without a highlighted character are not yet available because you have not yet run a model. The highlighted characters indicate the key to type to carry out that command. Also shown on the screen is the FSTS-Shell version and the name of the FST model.

The meanings of the different keys are:

'E' Starts the Q-editor to make modifications to the model (relevant commands of the Q-editor are shown by pressing F1).

'R' Translates, compiles, links and runs the model if the model source is newer than the model executable, this is most often the case. Otherwise only the executable version of the model is run again.

'L' Lists an FST translation report of the model (relevant commands of the lister are shown by pressing <Alt>H).

'O' Lists the output file of the finished model (relevant commands of the lister are shown by pressing <Alt>H).

'G' Starts the graphing program, type in two or more of the names shown on the screen, (instructions for this program are shown on the screen)

'F' Gives access to viewing/editing/printing of several important files.

'C' To change the name of the model.

'D' Jumps to DOS, but leaving the FST-Shell active.

'A' Shows an 'About' text.

'X' Exits from the FST-Shell.

The usual way to work with this shell is to use 'E' to make modifications to the model, then run the model by pressing 'R'. If translation errors occur, use 'L' to find out what is wrong in the model. If the model has been actually executed, use 'O' to study the tabular output or 'G' to study the graphical output.

Note that example programs are available on the floppy in the A:\EXAMPLES directory. You are advised to run these models first, to verify the installation procedure.

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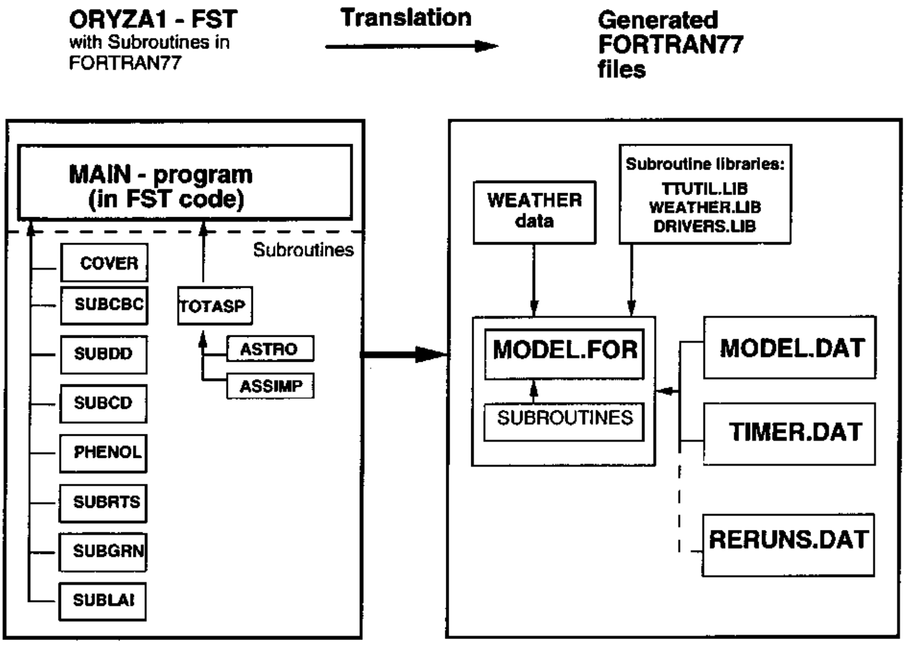
Appendix 4 Simplified structure of the model ORYZA1



Appendix 5   Listing of the program DRATES

```
**********************************************************************
*                                                                    *
*     DRATES Version April 1994                                      *
*     A program to calculate development rates used in ORYZA1        *
*                                                                    *
*     Simulation and Systems Analysis for Rice Production (SARP)     *
*                                                                    *
*     International Rice Research Institute (IRRI, Los Banos)        *
*     Theoretical Production Ecology (TPE-WAU, Wageningen)           *
*     Research Institute for Agrobiology and Soil Fertility (AB-DLO) *
*                                                                    *
*     Program runs with TIMER of TTUTIL 3.1 library                  *
*     Version May 1993, runs for leap years                          *
*     February 1994, adapted: Assuming no photoperiod sensitivity    *
*                                                                    *
**********************************************************************

      PROGRAM  DRATES
      IMPLICIT REAL (A-Z)
      INTEGER  ISTN, ISTAT, IDAY, IYR
      INTEGER  IYRS, IDOYS, IYRTR, IDOYTR, IYRF, IDOYF, IYRM, IDOYM
      INTEGER  IDOYPI,IYRPI
      INTEGER  IHYR(20), IHDAY(20), IDAS, I,NS, ILEN, IL, IDGS
      CHARACTER COUNTR*6, WTRDIR*80, CHOICE*1, Q*1, TMP*80, WSTAT*7
      LOGICAL TERMNL, OUTPUT

      DATA IHYR /20*1993/, IHDAY /20*1/

*     define separator character in WRITE statements
      Q = CHAR (9)

*     Initial defaults
      TBD    = 8.
      TMD    = 42.
      TOD    = 30.
      WTRDIR = 'C:\WEATHER\'
      COUNTR = 'PHIL'
      ISTN   = 1
      IDOYS  = 4
      IYRS   = 1993
      IDOYTR = 20
      IYRTR  = 1993
      IDOYPI = 45
      IYRPI  = 1993
      IDOYF  = 80
      IYRF   = 1993
      IDOYM  = 110
      IYRM   = 1993
      DELT   = 1.
      PRDEL  = DELT
      NS     = 3

      MOPP   = 11.50
      PPSE   = 0.
      CALL FOPENS (40,'DVS.DAT','NEW','UNK')

*     Reads
10    CONTINUE

*     get general information
      CALL ENTDRE ('Base temperature',TBD,TBD)
```

```
      CALL ENTDRE ('Max. temperature for development',TMD,TMD)
      CALL ENTDRE ('Opt. temperature for development',TOD,TOD)
      CALL ENTDCH ('Directory with weather data',WTRDIR,WTRDIR)
      CALL ENTDCH ('Country',COUNTR,COUNTR)
      CALL ENTDIN ('Station number',ISTN,ISTN)

*     get sowing data
      WRITE (*,*) ' '
      CALL ENTDIN ('Sowing date (Day Of Year, DOY)',IDOYS,IDOYS)
      CALL ENTDIN ('Sowing year',IYRS,IYRS)

*     get transplanting data
      WRITE (*,*) ' '
      WRITE (*,'(A)')
     & ' If direct seeded Transplanting date equals Seeding date'
      CALL ENTDIN ('Transplanting date (Day Of Year, DOY)',IDOYTR,
     &              IDOYTR)
      CALL ENTDIN ('Transplanting year',IYRTR,IYRTR)

*     get PI data
      WRITE (*,*) ' '
      WRITE (*,'(A)')
     & ' If PI date is not available type 0 '
      CALL ENTDIN ('PI date (Day Of Year, DOY)',IDOYPI,IDOYPI)
      CALL ENTDIN ('PI year',IYRPI,IYRPI)

*     get flowering data
      WRITE (*,*) ' '
      CALL ENTDIN ('Flowering date (Day Of Year, DOY)',IDOYF,IDOYF)
      CALL ENTDIN ('Flowering year',IYRF,IYRF)

*     get maturity data
      WRITE (*,*) ' '
      CALL ENTDIN ('Physiological maturity date (Day Of Year)',
     &              IDOYM,IDOYM)
      CALL ENTDIN ('Maturity year',IYRM,IYRM)

*     get sampling data
      WRITE (*,*) ' '
      CALL ENTDIN ('Number of sampling dates',NS,NS)

      DO 20 I=1,NS
         WRITE (TMP,'(A,I2)') 'Enter sampling date no.',I
         IL = ILEN (TMP)
         CALL ENTDIN (TMP(1:IL),IHDAY(I),IHDAY(I))
         WRITE (TMP,'(A,I2)') 'Enter sampling year no.',I
         IL = ILEN (TMP)
         CALL ENTDIN (TMP(1:IL),IHYR(I),IHYR(I))
20    CONTINUE

      WRITE (40,'(1X,A6,2(A,A6),A,A4)')
     &      'IYRS',Q,'ISTN',Q,'COUNTR',Q,'TBD'
      WRITE (40,'(1X,I6,A,I6,3A,F4.2,/)')
     &       IYRS,Q,ISTN,Q,COUNTR,Q,TBD

*     Determining developmental rates
*     ===============================

*     initialize timer information
*     calculate number of days in growing season

      IDGS = 0
      DO 25 I=IYRS,IYRM-1
         IF (MOD(I,4).NE.0) THEN
*           normal year
            IDGS = IDGS+365
         ELSE
```

```
*         leap year
          IDGS = IDGS+366
        END IF
25    CONTINUE

      IDGS   = IDGS-IDOYS+IDOYM
      FINTIM = REAL (IDGS)
      IYR    = IYRS

      CALL TIMER (1,REAL (IDOYS),DELT,PRDEL,FINTIM,IYR,
     &            TIME,DAY,IDAY,TERMNL,OUTPUT)

      TS  = 0.
      HU  = 0.

      TERMNL = .FALSE.

30    IF (.NOT.TERMNL) THEN

        TS  = TS+HU*DELT

        CALL STINFO (1111,WTRDIR,' ',COUNTR,ISTN,IYR,
     &               ISTAT,LONG,LAT,ALT,A,B)
        CALL WEATHR (IDAY,ISTAT,RAD,TMIN,TMAX,VAPOUR,WIND,RAIN)

        WRITE (WSTAT,'(I7)') ISTAT
        IF (WSTAT(3:3).EQ.'4'.OR.WSTAT(4:4).EQ.'4'.AND.
     &      IDAY.EQ.366) THEN
          CALL WEATHR (365,ISTAT,RAD,TMIN,TMAX,VAPOUR,WIND,RAIN)
        END IF

        CALL SUBDD(TMAX,TMIN,TBD,TOD,TMD, HU)

        IF (IDAY.EQ.IDOYTR.AND.IYR.EQ.IYRTR) TSTR = TS
        IF (IDAY.EQ.IDOYF .AND.IYR.EQ.IYRF)  TSF  = TS
        IF (IDAY.EQ.IDOYM .AND.IYR.EQ.IYRM)  TSM  = TS
        IF (IDAY.EQ.IDOYPI.AND.IYR.EQ.IYRPI) TSPI = TS

        CALL TIMER (2,REAL (IDOYS),DELT,PRDEL,FINTIM,IYR,
     &              TIME,DAY,IDAY,TERMNL,OUTPUT)

      GOTO 30
      END IF

      SHCKD  = 0.4
      TSHCKD = SHCKD*TSTR

      IF(IDOYPI.EQ.0) THEN
        DVRJ = 0.40/(TSF-330.-440.-TSHCKD)
        DVRI = (0.65-0.40)/330.
        DVRP = (1.-0.65)/440.
      ELSE
        DVRJ = 0.40/(TSPI-330.-TSHCKD)
        DVRI = (0.65-0.40)/330.
        DVRP = (1.-0.65)/(TSF-TSPI)
      ENDIF
      DVRR   = 1./(TSM-TSF)

      WRITE ( *,'(A,F7.6)')  ' DVRJ  = ', DVRJ
      WRITE (40,'(A,F7.6)')  ' DVRJ  = ', DVRJ
      WRITE ( *,'(A,F7.6)')  ' DVRI  = ', DVRI
      WRITE (40,'(A,F7.6)')  ' DVRI  = ', DVRI
      WRITE ( *,'(A,F7.6)')  ' DVRP  = ', DVRP
      WRITE (40,'(A,F7.6)')  ' DVRP  = ', DVRP
      WRITE ( *,'(A,F7.6)')  ' DVRR  = ', DVRR
      WRITE (40,'(A,F7.6)')  ' DVRR  = ', DVRR
      WRITE ( *,'(A,F7.1)')  ' TSTR  = ', TSTR
```

```
      WRITE (40,'(A,F7.1)')  ' TSTR  = ', TSTR
      WRITE ( *,'(A,F7.1)')  ' TSF   = ', TSF
      WRITE (40,'(A,F7.1)')  ' TSF   = ', TSF
      WRITE ( *,'(A,F7.1,/)')' TSM   = ', TSM
      WRITE (40,'(A,F7.1,/)')' TSM   = ', TSM
      WRITE (*,'(1X,A,2(A,A5),3(A,A6))')
     &       'YEAR',Q,'DOY',Q,'DAS',Q,'DVS',Q,'DVR',Q,'TS'
      WRITE (40,'(1X,A,2(A,A5),3(A,A6))')
     &       'YEAR',Q,'DOY',Q,'DAS',Q,'DVS',Q,'DVR',Q,'TS'

*     Calculation of development stages
*     =================================

*     reset timer
      IYR = IYRS
      CALL TIMER (1,REAL (IDOYS),DELT,PRDEL,FINTIM,IYR,
     &            TIME,DAY,IDAY,TERMNL,OUTPUT)

      DVR = 0.
      DVS = 0.
      TS  = 0.
      HU  = 0.

      TERMNL = .FALSE.
40    IF (.NOT.TERMNL) THEN

         TS  = TS +HU *DELT
         DVS = DVS+DVR*DELT

         CALL STINFO (1111,WTRDIR,' ',COUNTR,ISTN,IYR,
     &                ISTAT,LONG,LAT,ALT,A,B)
         CALL WEATHR (IDAY,ISTAT,RAD,TMIN,TMAX,VAPOUR,WIND,RAIN)

         WRITE (WSTAT,'(I7)') ISTAT
         IF (WSTAT(3:3).EQ.'4'.OR.WSTAT(4:4).EQ.'4'.AND.
     &      IDAY.EQ.366) THEN
            CALL WEATHR (365,ISTAT,RAD,TMIN,TMAX,VAPOUR,WIND,RAIN)
         END IF

         CALL SUBDD (TMAX,TMIN,TBD,TOD,TMD, HU)

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

         IF (DVS.GE.0.   .AND. DVS.LT.0.40) DVR = DVRJ * HU
         IF (DVS.GE.0.40 .AND. DVS.LT.0.65) THEN
            DL = DAYL + 0.9
            IF (DL.LT.MOPP) THEN
               PPFAC = 1.
            ELSE
               PPFAC = 1.-(DL-MOPP)*PPSE
            ENDIF
            PPFAC = MIN(1., MAX(0., PPFAC))
            DVR   = DVRI * HU * PPFAC
         ENDIF
         IF (DVS.GE.0.65 .AND. DVS.LT.1.00) DVR = DVRP * HU
         IF (DVS.GE.1.00)                   DVR = DVRR * HU
         IF (IDAY.GT.IDOYTR.AND.IYR.GE.IYRTR.AND.
     &       TS.LT.(TSTR+TSHCKD))           DVR = 0.

         IDAS = NINT (TIME)

         DO 50 I=1,NS
            IF (IDAY.EQ.IHDAY(I).AND.IYR.EQ.IHYR(I)) THEN
               WRITE (*,'(3(I5,A),F6.2,A,F6.4,A,F6.1)')
     &            IYR,Q,IDAY,Q,IDAS,Q,DVS,Q,DVR,Q,TS
               WRITE (40,'(3(I5,A),F6.2,A,F6.4,A,F6.1)')
```

```
     &              IYR,Q,IDAY,Q,IDAS,Q,DVS,Q,DVR,Q,TS
          END IF
50      CONTINUE

          CALL TIMER (2,REAL (IDOYS),DELT,PRDEL,FINTIM,IYR,
     &                 TIME,DAY,IDAY,TERMNL,OUTPUT)

      GOTO 40
      END IF

      CALL ENTDCH ('Again (Y/N) ? ','Y',CHOICE)
      IF (CHOICE.EQ.'Y'.OR.CHOICE.EQ.'y') GO TO 10

      STOP
      END


*-----------------------------------------------------------------*
      SUBROUTINE SUBDD(TMAX,TMIN,TBD,TOD,TMD, HU)
      IMPLICIT REAL (A-Z)
      INTEGER I
      SAVE

      TM    = (TMAX + TMIN)/2.
      TT    = 0.
      DO 10 I = 1, 24
            TD = TM + 0.5*ABS(TMAX-TMIN)*COS(0.2618*FLOAT(I-14))

        IF ((TD.GT.TBD) .AND. (TD .LT. TMD)) THEN
            IF (TD.GT.TOD) TD = TOD-(TD-TOD)*(TOD-TBD) / (TMD-TOD)
        TT = TT + (TD-TBD)/24.
        ENDIF
   10 CONTINUE
      HU = TT

      RETURN
      END

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

*-----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 TIMER (ITASK, DAYB, DELT, PRDEL , FINTIM, IYEAR,
     &                  TIME , DAY , IDAY, TERMNL, OUTPUT)

*     This subroutine updates TIME and related variables
*     each time it is called with ITASK=2. It will set TERMNL to
*     .TRUE. if FINTIM is reached. OUTPUT is flagged when TIME is a
*     multiple of PRDEL. When PRDEL=0, no output is flagged !
*     When IYEAR < 1500, IYEAR will not be increased because in that
*     case climate data are used.
*     The routine should be initialized first by a call
*     with ITASK=1. The first six arguments will then be made local.
*     Leap years are handled correctly.

*     ITASK  - task the routine should carry out (either 1 or 2)      I
*     DAYB   - start day of simulation
*              (1 <= DAY <= 365, 366 in leap years, leap years are
*               not flagged when IYEAR < 1500      )                  I
*     DELT   - time step of simulation (multiple of 1 or
*              1/DELT = integer e.g. 0.25,1/3,0.5,1,2,3)               I
*     PRDEL  - time between successive outputs (must be zero, equal
*              to DELT or multiple of DELT)                            I
*     FINTIM - finish time of simulation (counted from start of
*              simulation !)                                           I
*     IYEAR  - start year with ITASK=1 and current year with
*              ITASK=2, not updated when IYEAR < 1500                I/O
*     TIME   - time from start of simulation (always starts at zero) O
*     DAY    - day number (REAL) of year=IYEAR                         O
*     IDAY   - day number (INTEGER) of year=IYEAR                      O
*     TERMNL - flag that indicates if FINTIM has been reached          O
*     OUTPUT - flag that indicates if TIME is a multiple of PRDEL      O
*
*     Examples:
*     The call:
*     CALL TIMER (1     , DAYB, DELT, PRDEL , FINTIM, IYEAR,
*    &             TIME , DAY , IDAY, TERMNL, OUTPUT)
*     initializes the TIMER, TIME is set to zero, DAY and IDAY are set
*     to DAYB, TERMNL is set .false. and OUTPUT set to .true. (unless
*     the value of PRDEL is zero)
*     With the call:
*     CALL TIMER (2     , DAYB, DELT, PRDEL , FINTIM, IYEAR,
*    &             TIME , DAY , IDAY, TERMNL, OUTPUT)
*     the first time step is made, IYEAR and all variables on the second
*     line are updated. Repeated time steps are made by calls with
*     ITASK = 2, untill FINTIM is reached, TERMNL will then be set to
*     .true.
*
*     Subroutines and/or functions called:
*     - from library TTUTIL: ERROR

*     Author: Daniel van Kraalingen
*     Date  : April 1992
*     TTUTIL Version 3.11

*     formal parameters
      INTEGER ITASK, IYEAR, IDAY
      REAL DAYB, DELT, PRDEL, FINTIM, TIME, DAY
      LOGICAL TERMNL, OUTPUT
```

```
**    local variables
      INTEGER I, ITOLD, ICOUNT, IT, IS, IFINT, IPRINT, ILDAY, ILYEAR
      REAL LDELT, LTIME, TINY, R1
      PARAMETER (TINY=5.E-5)
      LOGICAL PROUT
      SAVE
      DATA ITOLD /4/

      IF (ITASK.EQ.1) THEN

*        test values

         IF (DELT.LE.0.)   CALL ERROR ('TIMER', 'DELT <= 0')
         IF (PRDEL.LT.0.)  THEN
            CALL ERROR ('TIMER', 'PRDEL <= 0')
         ELSE IF (PRDEL.EQ.0.) THEN
*           suppress output when prdel = 0
            PROUT = .FALSE.
         ELSE
            PROUT = .TRUE.
         END IF

         IF (FINTIM.LT.0.) CALL ERROR ('TIMER', 'FINTIM < 0')

         IF (IYEAR.LT.1000 .OR. IYEAR.GT.2100)
     &      CALL ERROR ('TIMER', 'IYEAR < 1000 or IYEAR > 2100')
         IF (DAYB.LT.(1.-TINY) .OR. DAYB.GT.(365.+TINY))
     &      CALL ERROR ('TIMER', 'DAYB < 1 or > 365')

         IF (DELT.GT.0. .AND. DELT.LT.1.) THEN
            R1 = 1./DELT
            IT = NINT (1./DELT)
            IS = 1
         ELSE IF (DELT.GT.1.) THEN
            R1 = DELT
            IT = 1
            IS = NINT (DELT)
         ELSE
            R1 = 1.
            IT = 1
            IS = 1
         END IF

*        check multiples
         IF (ABS (R1-NINT (R1/1.)).GT.TINY) CALL ERROR
     &      ('TIMER', 'DELT incorrect')
         IF (PROUT.AND.ABS (PRDEL-DELT*NINT (PRDEL/DELT)).GT.TINY)
     &      CALL ERROR ('TIMER', 'PRDEL not a multiple of DELT')
         IF (ABS (DAYB-NINT (DAYB/1.)).GT.TINY) CALL ERROR
     &      ('TIMER', 'DAYB not an integer value')
         IF (ABS (FINTIM-DELT*NINT (FINTIM/DELT)).GT.TINY) CALL ERROR
     &      ('TIMER','FINTIM not a multiple of DELT')
         IF (PROUT) IPRINT = NINT (PRDEL/DELT)
         IFINT  = NINT (FINTIM/DELT)
         ICOUNT = 0

*        assign to local variables
         LTIME  = 0.
         LDELT  = DELT
         ILDAY  = NINT (DAYB)
         ILYEAR = IYEAR

*        global variables
         TIME   = 0.
         IDAY   = ILDAY
         DAY    = FLOAT (ILDAY)
         TERMNL = .FALSE.
```

```
      IF (PROUT) THEN
         OUTPUT = .TRUE.
      ELSE
         OUTPUT = .FALSE.
      END IF

   ELSE IF (ITASK.EQ.2) THEN

      IF (ITOLD.EQ.4) CALL ERROR ('TIMER','initialization required')

      IF (TIME.NE.LTIME) CALL ERROR
&        ('TIMER', 'TIME was changed illegally')
      IF (IDAY.NE.ILDAY) CALL ERROR
&        ('TIMER', 'ILDAY was changed illegally')

      IF (ICOUNT.LT.IFINT.AND..NOT.TERMNL) THEN

         ICOUNT = ICOUNT+1
         LTIME  = FLOAT (ICOUNT)*LDELT

         IF (MOD (ICOUNT, IT).EQ.0) THEN
            DO 10 I=1,IS
               ILDAY = ILDAY+1
               IF (ILDAY.EQ.366) THEN
                  IF (ILYEAR.LT.1500) THEN
                     ILDAY  = 1
                  ELSE
                     IF (MOD (ILYEAR,4).NE.0) THEN
                        ILDAY = 1
                        ILYEAR = ILYEAR+1
                     END IF
                  END IF
               ELSE IF (ILDAY.EQ.367) THEN
                  ILYEAR = ILYEAR+1
                  ILDAY  = 1
               END IF
10          CONTINUE
         END IF

         OUTPUT = .FALSE.
         IF (PROUT) THEN
             IF (MOD(ICOUNT,IPRINT).EQ.0.OR.ICOUNT.GE.IFINT)
&                OUTPUT = .TRUE.
         END IF

         TIME  = LTIME
         IDAY  = ILDAY
         DAY   = FLOAT (ILDAY)+MOD (LTIME, 1.)
         IYEAR = ILYEAR
      ELSE
         TERMNL = .TRUE.
         IF (PROUT) OUTPUT = .TRUE.
      END IF

   ELSE
      CALL ERROR ('TIMER','wrong ITASK')
   END IF

   ITOLD = ITASK

   RETURN
   END
```

Appendix 6 Executing the program DRATES

```
C:\USR\DRATES> DRATES

File DVS.DAT already exists
                                    Overwrite (Y/N) [N]:  Y
                                   Base temperature [8]:
              Max. temperature for development [42]:
              Opt. temperature for development [30]:
         Directory with weather data [C:\WEATHER\]:
                                         Country [PHIL]:
                                     Station number [1]:

                 Sowing date (Day Of Year, DOY) [4]:  4
                                 Sowing year [1993]:  1992

If direct seeded Transplanting date equals Seeding date
       Transplanting date (Day Of Year, DOY) [20]:  20
                           Transplanting year [1993]:  1992

If PI date is not available type 0
                     PI date (Day Of Year, DOY) [45]:  40
                                     PI year [1993]:  1992

            Flowering date (Day Of Year, DOY) [80]:  75
                              Flowering year [1993]:  1992

  Physiological maturity date (Day Of Year) [110]:  105
                               Maturity year [1993]:  1992

                       Number of sampling dates [3]:  4
                      Enter sampling date no. 1 [1]:  20
                   Enter sampling year no. 1 [1993]:  1992
                      Enter sampling date no. 2 [1]:  40
                   Enter sampling year no. 2 [1993]:  1992
                      Enter sampling date no. 3 [1]:  75
                   Enter sampling year no. 3 [1993]:  1992
                      Enter sampling date no. 4 [1]:  105
                   Enter sampling year no. 4 [1993]:  1992
```

The default input data are given between square brackets, when using the input data in the example, the following file (DVS.DAT) is generated:

```
  IYRS  ISTN COUNTR  TBD
  1992     1 PHIL   8.00

DVRJ  = .002216
DVRI  = .000758
DVRP  = .000573
DVRR  = .001834
TSTR  =   268.0
TSF   =  1228.3
TSM   =  1773.5

YEAR     DOY     DAS     DVS    DVR      TS
1992      20      16     .48  .0128   268.0
1992      40      36     .66  .0101   617.8
1992      75      71    1.01  .0333  1228.3
1992     105     101    2.01  .0336  1773.5
```