SIMULATION REPORT CABO-TT No. 1

# Actual and Potential Production from Semi-Arid Grasslands - Phase II (APPSAG II)

## FORTRAN version of the simulation model ARID CROP

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Wageningen, 1982

Simulation Reports CABO-TT

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# 1. INTRODUCTION

In the framework of a joint Dutch-Israeli research project on actual and potential production from semi-arid grasslands, a simulation model was developed for the growth of natural pasture under semi-arid conditions (van Keulen, 1975). Subsequently, the model was further developed in the light of new data sets that became available (van Keulen et al., 1981).

The model is written in CSMP (Continuous System Modelling Program), a simulation language developed by IBM for its 360 and 370 series of machines. Other languages developed along the CSSL (Continuous System Simulation Languages) concepts, which are available on other machines are very similar to CSMP and the model can thus be run fairly easily on one of these machines. In many computer centres however, no such language is available and moreover development in computer programming, computer use and the budgets available for research have been such in recent years, that the costs of running a model like "ARID CROP" are prohibitively high for all but a few research institutions. Since that limits the use of the model to a considerable extent, it seemed worthwhile to produce a parallel FORTRAN-version of the model, thus allowing its implementation in a far wider range of computer centres and reducing the running costs to only a fraction of that required for the original model.

Development of the FORTRAN version was carried out on a CDC 6000. No conceptual changes were introduced and it was attempted to retain as much as possible of the original CSMP structure. The results produced by this version are in complete agreement with those obtained by the use of the CSMP-version on an IBM 370-45.

In this report a summary description of the model is given, some details on computer implementation, a complete listing of the FORTRAN model, a dictionary defining the abbreviations used and their dimensions, and a separate list of the parameters and functions applied. Finally, a number of functions, which are available in CSMP and had to be defined as FORTRAN functions are elaborated and their use illustrated.

We hope that the availability of this version of the model ARID CROP may increase its usefulness.

# 2. SUMMARY DESCRIPTION OF THE MODEL

The simulation model ARID CROP calculates the time course of dry matter production of an annual herbaceous vegetation in relation to the amount and distribution of water in the soil below that vegetation. The vegetation is considered as an homogeneous stand uniquely defined in terms of physiological, phenological and physical properties. For vegetations consisting of a mixture of species, as is often the case in natural pastures in semi-arid regions, this is an oversimplification, but since in terms of dry matter production there is generally little difference between species this assumption seems permissible.

The weather is defined in terms of meteorological observations from standard weather stations: daily values of rainfall, total global radiation, minimum and maximum air temperature at screen height, dew point temperature (or dry and wet bulb temperatures) and daily windrun.

## 2.1 Soil physical processes

To simulate soil physical processes, particularly transport processes, the soil is divided into a number of homogeneous compartments of unit area. Both the total number of compartments and their individual thickness can be adapted very easily to suit the need in a particular situation. Detailed simulation models of transport processes in soils are available (de Wit and van Keulen, 1972) but these have not been incorporated in the present model since their small time constants would require very small integration time steps in the simulation.

## Infiltration

Moisture transport is defined therefore especially with emphasis on availability of water to the plants, rather than on its exact distribution in the profile. Transport between soil compartments only takes place during rain or irrigation. The rate of change of water content in a particular compartment is set equal to the water content at "field capacity" and the actual water content, divided by the time interval of integration, provided that the rate of inflow in that compartment is sufficient. The rate of flow out of a compartment and consequently into the next one equals the rate of inflow minus the rate of change in water content in that compartment. This procedure is repeated for the consecutive compartments until all infiltrated water is dissipated or till the remainder has drained below the potential rooting zone. The result after a rainy day is a soil profile, partly or completely at field capacity, with in the former case a sharp boundary with the first "non-filled" compartment.

## Soil evaporation

In medium to deep soils in semi-arid regions, where deep drainage is of minor importance, direct evaporation of water from the soil surface is the major source of non-productive water loss and the overall efficiency of use of precipitation in terms of dry matter production is mainly determined by the ratio of evaporation from the soil surface to transpiration by the vegetation.

In the model potential soil evaporation is calculated from a Penman-type formula. Subsequently, a reduction factor is introduced to account for partial interception of energy by the vegetation cover. The actual rate of soil evaporation is then determined by the moisture content of the upper soil compartment, expressed as a dimensionless number to allow application to different soil types. This total water loss by evaporation is subsequently withdrawn from the various compartments in dependence of the actual moisture distribution in the profile. A Soil-type dependent extinction coefficient, is used, that essentially'mimicks' the recharge of the upper soil compartments from the lower ones as a result of developing potential gradients.

## Soil heat flow

Soil temperature is not calculated in any detail but a ten-day running average of air temperature is used. This seems justified by the fact that the influence of soil temperature on various processes is not known very accurately.

## Water uptake by the roots

The rate of transpiration of a vegetation in a given environment, depends on the distribution and functioning of the root system and on the amount and distribution of water in the profile. Quantitative information on the interrelation between the two, especially under field conditions is scarce. It is obvious however, that when part of the root system is in dry soil and part in wetter soil, the uptake of moisture by the latter will compensate partly the lack of uptake by the former: therefore in the model first an effective rootlength is calculated in each compartment, determined by its moisture content -the lower the moisture content, the lower the efficiency factor-. From the total effective root length and potential transpiration, the potential uptake per unit effective root length is obtained. The actual rate of uptake from each compartment follows then from the potential rate, the moisture content in that compartment and the temperature effect. The latter includes the influence on both root activity and on viscosity of the water.

## 2.2 Growth of the vegetation

### Germination

Since we are dealing with annual vegetation, growth starts from germination each year. The process of germination, which is very complicated is treated in a rather rudimentary fashion in the model, with the result that the prediction of initial biomass - that is the amount of above ground dry matter at emergence of the vegetation - is still a major difficulty with the model. Seeds start germinating after the first rains and the process proceeds as long as the moisture content in the top 10 cm of the profile is above wilting point. Germination is completed when a total temperature sum of 150 day-degrees, above $0^{o}C$ has accumulated, during favourable soil moisture conditions. If the soil dries out before the required temperature sum is reached, the germinating seedlings are killed and a new wave of germination starts after rewetting only.

### Phenological development of the crop

The development pattern of a growing plant is characterized by the rate and order of appearance of vegetative and reproductive organs. The rate of development of plants is partly governed by genetic characteristics and partly by environmental factors, especially temperature and daylength. The genetic characteristics vary among species and among cultivars within the same species (cf. short vs. long duration cultivars). Photoperiodic effects could not be demonstrated for the winter annuals that the model treats. This is in contrast to annuals growing in summer rainfall regions where daylength exerts a very strong influence.

In the model therefore a relation between development rate and temperature is introduced, mainly based on field observations. The relation assumes a threshold temperature of $3.75^{o}C$ and is linear from that value until $25^{o}C$. The development rate (dimension $day^{-1}$) is integrated to yield the dimensionless value of the development stage of the vegetation, which ranges from 0 at emergence to 1. at dead ripeness. The value of the development stage governs primarily the partitioning of assimilates over the various plant organs.

### Growth of the vegetation

After establishment, that is after the temperature requirement for germination has been satisfied, both above ground and below ground biomass are initialized to a pre-set value. (This value varies between seasons, between different fields etc.). Total seasonal dry matter production appears to be rather insensitive to the value of the initial biomass, but the growth curve may be shifted by a period of upto two weeks, which is very important early in the growing season, especially when the vegetation is to be exploited by grazing. A satisfactory solution to this problem has not yet been found, however.

After establishment, calculation of the growth rate of the vegetation is based on determination of the rate of transpiration and on the water use efficiency. The water use efficiency is calculated each day as the ratio between the potential rate of increase in dry weight of the vegetation and the potential rate of transpiration. The former depends on the photosynthetic characteristics of the species, the leaf area index of the vegetation and the prevailing radiation intensity, (which in combination determine the potential rate of gross $CO_2$-assimilation) and the amount of dry matter present,(which determines the maintenance requirement of the vegetation). For the conversion of primary photosynthetic products into structural plant material, a constant conversion efficiency is introduced, based on an average chemical composition of the material being formed. Potential transpiration rate is obtained from the evaporative demand of the atmosphere, characterized by the prevailing radiation intensity, the combined effect of wind speed and air humidity, and the leaf area index of the vegetation.

It is assumed that water use efficiency is independent of the moisture status of the soil and the condition of the vegetation. The former may not be valid in all situations, but the actual amount of water transpired during periods of stress is so low that the difference in terms of dry matter production is very small.

The actual rate of transpiration of the vegetation is calculated from the potential rate, taking into account the moisture distribution and the root distribution in the soil profile. The latter is only defined by its vertical extension, not by a root density function.

When actual transpiration falls short of the potential, a relative transpiration deficit is defined. When the value exceeds 0.4, it is integrated with a time constant of 10 days to yield the cumulative relative transpiration deficit. The value of the latter influences the photosynthetic performance of the vegetation, i.e. prolonged stress leads to deterioration of the photosynthesizing capacity. After removal of the stress, recovery is possible, once growth recommences.

The total increase in dry weight of the vegetation is subsequently calculated by multiplying the actual rate of transpiration by the water use efficiency. In dependence of the development stage, this increment is partitioned between various plant organs. First a part is allocated to the roots, the function being defined in such a way that a progressively smaller proportion of the assimilates contributes to root growth. In the early stages, a considerable proportion of total growth is invested in the root system on which the plant has to rely later on for an adequate supply of water and nutrients. When the plant is under water stress, the proportion diverted to the roots increases in accordance with the functional balance principle. A fixed proportion of the assimilates available for above ground growth is first allocated to the developing seeds, once the development stage for seed fill has been reached. The remainder is partitioned between leaf blades and other vegetative structures (leaf sheaths, stems etc.) Again the proportion of both is a function of the actual value of the development stage. Since plant structures have only a limited life span, there is continuous dying of earlier formed material. Under favourable growth conditions, only a negligible proportion of the standing crop dies. When conditions become more unfavourable, i.e. when the soil dries out or when the vegetation approaches maturity resulting in enhanced translocation of nutrients to the developing seeds and accelerated deterioration of existing structures, the rate of dying increases drastically. The rate of dying due to moisture stress is governed both by the evaporative demand of the atmosphere and the moisture content of the soil. Under high evaporative demands, a situation develops where even complete closure of the stomata cannot prevent dehydration of plant tissue and subsequent death. In the model, the rate of dying is proportional to the difference in potential cuticular water loss (=actual water loss by the vegetation) and the calculated actual transpiration rate of the vegetation (=rate of water uptake from the soil), with a time constant of five days, reflecting the buffering capacity of the vegetation. The death rate due to senescence is calculated independently and the maximum of the two is applied in each situation.

Leaf area growth

The increase in leaf area follows directly from the rate of increase in weight of the leaf blades by the application of a constant specific leaf area ratio. Our understanding of the basic processes governing the morphogenetic characteristics of the plant is too weak at present to permit a more realistic treatment of leaf area development.

Root extension growth

In the model it is assumed that a root "front" is formed without horizontal gradients, so that root density is not a limiting factor for the uptake of water and nutrients. The potential rate of vertical extension of the root system is constant. The actual rate is influenced by soil temperature, and extension growth continues until a dry soil compartment is reached.

## 2.3 Model specifications

The model is executed with time intervals of one day and the simple rectilinear method of integration is used.

# 3. THE FORTRAN MODEL

A complete listing of the FORTRAN text is given in Appendix 1, a dictionary of all variables, with their dimensions is provided in Appendix 2, Appendix 3 gives a list of parameter values applied in the model, and Appendix 4 lists the relevant functions and their numerical values. Structure statistics of the model are provided in Table 1.

## 3.1 Setting up a job and run control.

The control cards needed to run the model are rather specific to installation and operating system. Nevertheless, it may be useful to outline the set-up for a typical batch compilation and execution job as it might be carried out on a CDC CYBER74 operating under NOS/BE operating system.

The following example assumes that the FORTRAN program and the meteorological data file reside on disk. Model output is written on file 'OUTPUT' which is automatically sent for printing at termination of the job.

```
SHAL.                            identification and
USER,467259.                     password of user
ATTACH, ARIDOB, ID=SHAL.         attach file 'ARIDOB' which contains the
                                 FORTRAN code of ARID CROP.
ATTACH, MET80, ID=SHAL.          attach file 'MET80' which contains the
                                 meteorological data for 1980/81.
MNF (I=ARIDOB, D,T,Y,U)          compile the program in 'ARIDOB' using
                                 the MNF compiler with a number of
                                 specified options.
LGO (MET80)                      EXECUTE PROGRAM. Equate file 'MET80'
                                 with the first file defined in the
                                 program card of ARID CROP.

EOR
```

TABLE 1

STRUCTURE OF THE FORTRAN VERSION OF THE MODEL

| SECTION | | TOTAL NUMBER OF STATEMENTS | NUMBER OF NON-COMMENT STATEMENTS | NUMBER OF COMMENT STATEMENTS | NUMBER OF LINES (INCL. CONTINUATIONS) | NO.OF CM WORDS ALLOCATED BY DIMENSION STATEMENTS |
|---|---|---|---|---|---|---|
| MAIN | | 464 | 385 | 79 | 525 | 1567 |
| FUNCTION | RAFGEN | 36 | 23 | 13 | 36 | 100 |
| " | AFGEN | 37 | 25 | 12 | 42 | upto 30 |
| " | DELAYT | 12 | 10 | 2 | 12 | 20 |
| " | LIMIT | 12 | 11 | 1 | 13 | 0 |
| " | INSW | 9 | 8 | 1 | 9 | 0 |
| " | FCNSW | 11 | 10 | 1 | 11 | 0 |
| " | NOT | 9 | 8 | 1 | 9 | 0 |
| " | AND | 9 | 8 | 1 | 9 | 0 |
| " | TWOVAR | 56 | 41 | 15 | 69 | 182 |
| SUBROUTINE | PLOTT | 77 | 69 | 8 | 80 | 230 |
| TOTAL | | 732 | 598 | 134 | 815 | 2129 |

Using FORTRAN instead of CSMP entails a certain loss of flexibility and ease of use. Any 'parameters' must thus appear on the input file in the correct order in the correct format. The input file continues with:

1,210,5,50.,1 input DELT, FINTIM, PRDEL, IBIOM, WANTPL in free-format.

where:

| | |
|---|---|
| DELT = | integration time step (1 should be used) (integer). |
| FINTIM = | number of days simulation is to run. Can be set very large for entire season runs since execution is halted when growth ceases (integer). |
| PRDEL = | time interval between printing of tabular output values. Can be any number larger than zero (integer). |
| IBIOM = | initial pasture biomass (real). |
| WANTPL = | graphic option (integer) 0 - no plotted output required.<br>1 - plotted output required. |

ARID CROP 1980/81 DEMO RUN title card.

This title will appear at the top of each tabular output page and at the top of the graphic output when requested. The title may contain upto and including 80 characters (any characters) and is printed such that column 1 of the title card appears about 20 printing positions across the output page. If no title is wanted, a blank card must be inserted here.

2,3,1,1 input OUTDEL, PLOT, EQLSCL, PVALS in free-format.

This line must appear if WANTPL = 1. One graph may be plotted per run. This line controls the form of the graph, which may contain 1 to 5 curves, all plotted to the same scale, or all with independent scaling and the values of 1 variable or all variables printed alongside the graph.

The variables are defined as follows:

| | |
|---|---|
| OUTDEL = | time interval between graphic output points. Can be any number larger than zero. Needs no coordination with PRDEL (integer). |
| PLOT = | the number of curves to be plotted on the single graph (1-5) (integer). |
| EQLSCL = | scaling option (integer) 0 - all curves to be plotted with independent scaling according to their individual value ranges.<br>1 - all curves to be plotted with the same scaling set according to the highest and lowest values. |
| PVALS = | value printing option (integer) 0 - only one of the plotted variables is to have the plotted values printed on the left-hand side of the graph (alongside TIME values).<br>1 - all of the plotted variables are to have their plotted values printed. One on the left-hand side of the graph and the remainder on the right-hand side. The greater PLOT is, the narrower the graph becomes when PVALS is set to 1 (if PLOT = 5 and PVALS = 1, the graph is about 70 printing positions wide). |

| | |
|---|---|
| 0.,0.<br>85.,0.<br>86.,41.<br>100.,248.<br>113.,495.<br>126.,869.<br>142.,2286.<br>155.,4040.<br>170.,4985.<br>182.,5511.<br>190.,6194.<br>205.,0.<br>208.,0.<br>210.,0. | A set of X,Y coordinate pairs (real) describing the observed biomass growth curve for 1980/81 where X is the running day no. (1=OCT 1) and Y is aboveground biomass (kg DM/ha). The last 3 data points are simply to make up the total number of points to 15 which is the number of input cards for the OBSERT function table read by the program. All these cards are read in free-format. |

EOI

The program uses an additional file ('TAPE40') which is declared in the PROGRAM statement at the beginning and is used for storing data for graphic output during the course of a run. At the end of a simulation run, the program rewinds this file and reads the data for the purpose of constructing the graphic output (when requested). Some installations may require space allocation on disk for this file in the control cards prior to program execution.
Unfortunately, it is cumbersome and inconvenient to write a FORTRAN program that can read the name of a variable and print or plot the value of that variable as calculated during execution. Thus the variables to be printed and/or plotted for output are written into the source program, and any alteration in these lists requires recompilation. Tabular output is provided in CSMP III-style with about 47 variables printed at each requested interval. It is hoped that this list of 47 variables contains all desired outputs since altering the list or extending it is not simple. As far as graphic output is concerned, 5 variables are named in the source program and are ready for graphing.

## 3.2. Central processing (CP) and central memory (CM) requirements.

The actual CM used by a computer in compilation and execution is rather dependent on the particular compiler and installation. It is usually possible to make an approximate calculation of CM requirements if one knows the total number of memory words actually required by DIMENSIONed and non-DIMENSIONed variables which in this case is about 2500 words.

CP requirement is also highly compiler and installation dependent. Using a CDC CYBER74 computer, the range of CP requirements for compilation using different compilers is about 3 - 6 seconds. As with CSMP, the execution time requirement of the FORTRAN version of ARID CROP is highly dependent on the quantity of output requested. Generally, the model is run using a 5 or 10 day interval between tabular outputs (about 50 variables) and something like a 5 day interval between graphic outputs (usually plotting 3 variables). Under such circumstances, the model requires 3 - 5 seconds CP time for execution of a 200 day season using the same computer as above.

## 3.3. Possible language compatibility problems.

The version of FORTRAN used includes features described in the ANSI Standard Fortran 77 as well as a couple of additional features that are accepted by the University of Minnesota FORTRAN Compiler (version 5.4). It is possible that many computer centres have not updated their FORTRAN compilers even to the ANSI 77 set, so a number of potential compatibility problems in the model are listed below to aid the potential user of the model. No claim is made as to the exhaustiveness of this list!

1. PROGRAM statement (line number 1 in the listing)
2. EXTERNAL AND statement (after the DIMENSIONs section)
3. the large number of continuation lines used in entering the ALPHAT matrix data.
4. use of the dollar sign ($) to indicate start of a new statement. This is used in setting the parameters and in the section for preparing the tabular output.
5. input-output statements.
   a) use of free-format (asterisk)
   b) use of comma before I/O list. e.g. WRITE (40,120), TIME
   c) use of Hollerith constants exceeding 10 characters
   d) non-standard column 1 output format such as '1X'.
6. REWIND statement (3rd and 17th line in initialisation section and in SUBROUTINE PLOTIT).
7. IF-type block structures.

```
a) IF (.........) THEN

   ENDIF
b) IF (.........) THEN

   ELSE

   ENDIF

c) IF (.........) THEN

   ELSEIF (.....) THEN

   ELSE

   ENDIF
```

all these block structures are used widely in the model. They can be replaced quite simply with simple IF statements and suitable GOTO statements if necessary.

8. WHILE block structures

```
   WHILE(.........) DO


   ENDWHILE
```

The action of this block is self explanatory and is also very simple to replace with appropriate DO or IF or GOTO combinations.

## 3.4. Functions defined in the model

Most of the functions described below are based on equivalent functions that are used in CSMP. Any details on use of these functions that are not provided here can easily be worked out by looking at the model listing.

AFGEN

The AFGEN function for linear interpolation is set up slightly differently from the CSMP form, though in effect does the same thing. In calling the function 3 parameters need be supplied as opposed to 2 in CSMP. The form of the call is:

R = AFGEN (TABLE, INDVAR, NDP)

where:
- R must be a real variable
- TABLE is the name of the function table
- INDVAR is the independent variable which must be either a real variable or a real constant or number.
- NDP is the number of (x,y) data pairs in the function table. It must be an integer (number or constant).

The function first checks whether INDVAR lies within the coordinate range of the independent variable ("X") supplied for the function table. If it does, linear interpolation between the data pairs given is executed normally. If it does not, an appropriate error message is written on the output file, and the minimum or maximum value for the dependent variable defined in the table is returned to enable continued execution of the program. This is different to CSMP in that no extrapolation takes place in the event of out-of-range "X" values - a zero gradient is assumed at both ends of the inputed curve and thus an "overflow" or "underflow" does not occur.

The function table itself is simply a matrix of 2 rows, the upper row containing the x-coordinates and the lower row the corresponding y-coordinates.

The matrix must of course be DIMENSIONed, the size of the matrix can be larger than the actual number of locations filled with data. If the matrix is to be filled by use of a DATA statement, remember that FORTRAN fills matrices in such a case by column and thus the DATA statement will consist of x,y pairs of numbers (as in CSMP). The x-coordinates must be entered in ascending order only.

e.g.

```
DIMENSION DVRT (2, 50)

DATA DVRT/0., 0., 3.75,0., 16.,0.01, 25., 0.02, 30., 0.001/

DVR = AFGEN (DVRT, TMPA, 5)
```

If changes are to be made to an AFGEN function, check:
1. that the DIMENSION declaration for the function table (in the main program only) is sufficiently large to hold all data points (not all compilers check this).
2. that the NDP parameter in the call statement is adjusted suitably for each and every call of that function table.
3. that the x-coordinates in the function table are entered in ascending order only. Unfortunately, failure to do so will not necessarily result in abnormal termination of execution.

TWOVAR

The differences between the CSMP and the FORTRAN TWOVAR function run parallel to those described for the AFGEN function. In calling the function, 5 parameters need to be supplied as opposed to 3 in CSMP. The form of the call is:

R = TWOVAR (MATRIX, INDVR1, INDVR2, MNDP1, NDP2)

where:

| | |
|---|---|
| R | must be a real variable |
| MATRIX | is the name of the function table. |
| INDVR1 | is the first independent variable which must be either a real variable or a real constant or number. |
| INDVR2 | is the second independent variable which must be either a real variable or a real constant or number. |
| MNDP1 | is the maximum number of x,y data pairs that appear in a single row of the function table. Must be an INTEGER. |
| NDP2 | is the number of second independent variable values that there are in the function table. Must be an INTEGER. |

Whenever called, the function first checks the input value of both independent variables against the corresponding range of values in the matrix. If either of them falls outside its defined range, an error message is printed and the same fixup is taken as described for the AFGEN function.

The function table itself is a 2-dimensional matrix, set up as shown below:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $X2_1$ | $X1_a$ | $Y1_a$ | $X1_b$ | $Y1_b$ | $X1_c$ | $Y1_c$ | $X1_d$ | $Y1_d$ |
| $X2_2$ | X1 | Y1 | X1 | Y1 | X1 | Y1 | | |
| $X2_3$ | X1 | Y1 | X1 | Y1 | | | | |
| $X2_4$ | X1 | Y1 | X1 | Y1 | X1 | Y1 | X1 | Y1 |
| $X2_5$ | X1 | Y1 | X1 | Y1 | | | | |
| $X2_6$ | X1 | Y1 | Y1 | X1 | Y1 | | | |

Column 1 contains the values of INDVR2 in ascending order only. The number of values in this column corresponds to the value of NDP2. The even columns (2,4 etc) contain the various values of INDVR1 for each of the values of INDVR2 defined in column 1. The odd columns (3,5 etc.) contain the values of the dependent variable corresponding to each INDVR1 value. Thus each row of the matrix contains pairs of x, y coordinates which describe the "curve" of dependent variable versus one independent variable (INDVR1) for the particular value of the second independent variable (INDVR2) contained in column 1 of that row. The x values along any row must be in ascending order only.

Not always are there an equal number of data points for each row of the matrix. In such an instance the matrix must be "squared-off" with zeros. (This is because of the way the matrix is filled by FORTRAN when using the DATA statement). Thus every row must contain an NDP2 value followed by 2 * MNDP1 numbers (some of which may be "squaring-off" zeros).

e.g.

DIMENSION FLRT (6, 50)

```
DATA FLRT/X2₁, X2₂, X2₃, X2₄, X2₅, X2₆,
         X1a, X1,  X1,  X1,  X1,  X1,
         Y1a, Y1,  Y1,  Y1,  Y1,  Y1,
         X1b, X1,  X1,  X1,  X1,  X1,
         Y1b, Y1,  Y1,  Y1,  Y1,  Y1,
         X1c, X1,  0.,  X1,  0.,  X1,
         Y1c, Y1,  0.,  Y1   0.,  Y1,
         X1d, 0.,  0.,  X1,  0.,  0.,
         Y1d, 0.,  0.,  Y1,  0.,  0.,/

XFLR = TWOVAR (FLRT, A1, B1, 4, 6)
```

RAFGEN

This is a special purpose function having no equivalent in CSMP. One may wish to investigate the effect of various rainfall distributions and quantities over the season for a given set of other wheather variables. Using the AFGEN function to generate a rainfall bar chart is a most inconvenient method and likewise, creating a special rainfall disk file of the same format as the other meteorological data used by FORTRAN ARIDCROP is tedious, since each day of the season requires an entry even though rain only occurs on a small number of them and most of the data is a series of zeros. The RAFGEN function provides a simple way of representing a seasons rainfall with a minimum of effort. In principle, the data is presented as for a regular AFGEN function, but only rain events appear in the function table; the function carries out no interpolation.

The function table is a matrix of 2 rows, the upper containing the day numbers on which rain events take place (ascending order only), and the lower row containing the corresponding rainfall for each of those days (in mm.). The end of the rains is indicated by a 0.,0. data pair.

The form of the call is:

```
R = RAFGEN (TABLE, INDVAR)
```

where R is a real variable.
TABLE is the name of the function table containing the rainfall events
INDVAR is the day number for which the rainfall is to be returned by the function.
INDVAR is REAL. If time is integer and is used for INDVAR, convert to REAL by adding "+ 0." in the call.

A 2 x 50 matrix is DIMENSION-ed in the routine, thus if there are more than 49 rain events this must be altered accordingly.

On the first RAFGEN call only, the routine finds on which day the last rain occurs. Since many calls to RAFGEN are made after the last rain event, such calls can be dealt with by a simple IF statement and a value of 0 is returned without searching in the actual tabulated function. It is only when a call is made before the end of the rains that the rainfall array is checked through. Failure to find an entry for the input day number results in 0 being returned.

The function resides in the model. A call to the function does not. The call card must be added if it is wished to utilize the RAFGEN function. The call card must be inserted after rain is read off the meteorological data file and will thus override the first value read. Obviously the card must also be inserted before the first time RAIN is used in the model.

DELAYT

Purpose: to store today's average air temperature and return the average air temperature of X days ago.

Call Statement: OLDT = DELAYT (X, NEWT)

Ensure that X never exceeds the size of the storage array DIMENSION-ed in the DELAYT function. X in the model is currently 10, and 20 words are allocated for storage.

LIMIT

Call Statement: Y = LIMIT (P1, P2, X)
ACTION: Y = P1; X < P1
Y = P2; X > P2
Y = X; P1 < X < P2

INSW

Call Statement: Y = INSW (X1, X2, X3)
ACTION: Y = X2; X1 < 0
Y = X3; X1 > 0

FCNSW

Call Statement: Y = FCNSW (X1, X2, X3, X4)
ACTION: Y = X2; X1 < 0
Y = X3; X1 = 0
Y = X4; X1 > 0

NOT

Call Statement: Y = NOT (X)
ACTION: Y = 1; X < 0
Y = 0; X > 0

AND

Call Statement: Y = AND (X1, X2)
ACTION: Y = 1; X1 > 0, X2 > 0
Y = 0; otherwise.

## 3.5. Model initialisation

In its narrowest sense, initialisation refers only to the setting of integrals (state variables) to their appropriate initial conditions prior to the commencement of a simulation run. ARID CROP contains 23 integrals plus those of water content of each soil layer. The number of soil layers is presently set at 10, so the total number of integrals is 33. The version of ARID CROP presented here assumes that all runs commence on 1st October, which is invariably before the first effective rainfall and germination in the Mediterranean region where the model is applied. Thus most of the integrals are initialised to zero and this is done in the initialisation section of the model in a single DATA statement. Of the 33 integrals that are updated each time step in the integration section of the model, the following ones have non-zero initial values:

a) soil moisture content of each soil compartment.
This is set by the following expression:

W(N) = DRF (N) * WLTPT * TCK (N)

where:

W(N) = soil moisture content of the Nth soil compartment (mm)
DRF (N) = dryness factor of Nth soil compartment expressed as a fraction of moisture content at wilting point (-)

WLTPT = wilting point (parameter) ($cm^3/cm^3$)
TCK(N) = thickness of the Nth soil compartment (mm).
The DRF and TCK values for each soil compartment are set in the PARAMETERS section in DATA statements.

b) soil temperature.
This is initialised as the average air temperature on the first day of the simulation. In order to do this, one record of the meteorological data file is read and the file is rewound before the simulation commences.

ARID CROP simulates establishment by updating the (zeroed) integrals of plant part biomass by some initial value on emergence day. These initial values are described by the following variables:

IBIOM = initial aboveground biomass at emergence. This is frequently altered from run to run and is therefore read in from the input file (see Section 3.1). (kg DM/ha)

IRWT = initial root biomass at emergence.
IRWT = IBIOM (kg DM/ha)

WLVSI = initial weight of leaves at emergence.
WLVSI = IBIOM * AFGEN (DISTFT, 0., 5) (kg DM/ha)

WNLVSI = initial weight of aboveground non-leaf material.
WNLVSI = IBIOM - WLVSI (kg DM/ha)

LFI = initial leaf area at emergence.
LFI = WLVSI * LFARR ($m^2$/ha)

The root depth integral is initialised in a similar way:
IRTD = initial root depth.
IRTD = 101. (set in PARAMETERS section) (mm)

Using the term initialisation in its broader sense, the other variables that are set prior to the commencement of the simulation proper are function tables and parameters. Only IBIOM and the observed biomass function table (OBSERT) are read in from the input file in the version presented here, all other function tables and parameter values reside in the model. If one wishes to vary these values from run to run, it might be simpler to adjust the program to read in those variables from the input file instead of having to edit and recompile each time.

Unfortunately, mid-season initialisation cannot be carried out with the same ease as it can with CSMP. The changes required in the model listing are not very extensive, but since the need for such runs is probably minimal, details of the required changes are not presented here.

## 3.6. Meteorological data input

The CSMP version of ARIDCROP imposes 3 main inconveniences in using meteorological data:
1. the data are entered as AFGEN function tables which are both tedious to punch and awkward to check; 2. the computer memory requirement for the 7 data function tables is very large. This is wasteful since each number is required only once each run; 3. the data function tables are printed out each job and this cannot be suppressed. This is quite unnecessary and is wasteful of time, paper and money.

FORTRAN ARIDCROP avoids these problems. The data is structured in an easily read format, it is stored on disk and read sequentially as the simulation progresses and does not appear on the output file unless specifically requested.

The meteorological data files currently read by ARIDCROP were originally generated for a different purpose and include information not required by ARIDCROP. This extra information presents no difficulty and is skipped in the READ instruction in ARIDCROP. The data for each year consists of 210 records, the first being for Oct 1 and the last for April 28. Each record contains:

DATE, RUNNING DAY NUMBER, RAINFALL (mm), CUMULATIVE RAINFALL (mm), MINIMUM TEMP. ($^{o}$C), MAXIMUM TEMP. ($^{o}$C), RADIATION (cal/cm$^{2}$/day), WINDRUN (km/ day) DEWPOINT TEMP. at 800 hrs and 1400 hrs ($^{o}$C), PENMAN EVAPORATION (mm).

For example, the 80th record of the 79/80 data file reads:

1979 DEC 19 80 0.4 106.3 7.9 12.9 223.9 152.0 7.0 7.6 1.0.

ARIDCROP does not require the date, day no., cumulative rainfall or Penman evaporation, and so the following format is used in ARIDCROP in reading the meteorological data files: FORMAT (17X, F6.0, 8X, F5.0, F6.0, F7.0, F6.0, F6.0).

REFERENCES

Keulen, H. van, 1975. Simulation of water use and herbage growth in arid regions. Simulation Monographs, PUDOC, Wageningen.

Keulen, H. van, N.G. Seligman and R.W. Benjamin, 1981. Simulation of water use and herbage growth in arid regions - a reevaluation and further development of the model 'ARID CROP'. Agric. Syst, 6: 159-193.

Wit C.T. de and H. van Keulen, 1972. Simulation of transport processes in soils. Simulation Monographs., Pudoc, Wageningen.

## Appendix 1

```
C
C     **************************   ARIDCROP   **************************
C
C     THIS IS A FORTRAN TRANSLATION OF ARIDCROP - A SIMULATION
C     MODEL OF CROP GROWTH IN ARID ENVIRONMENTS WRITTEN BY
C     HERMAN VAN KEULEN IN THE LANGUAGE CSMP.
C     NO CONCEPTUAL CHANGES HAVE BEEN MADE TO THE MODEL,
C     AND AN ATTEMPT HAS BEEN MADE TO RETAIN MUCH OF
C     THE CSMP STRUCTURE.
C
C     DEFINITIONS OF ALL TERMS USED IN THE MODEL ARE
C     AVAILABLE ON FILE, THUS THERE ARE VERY FEW
C     DEFINING COMMENTS IN THE MODEL LISTING.
C
C     *****************  DIMENSIONS   REALS   INTEGERS   ***************
      DIMENSION  W(20),       F(20),       EB(20),       DRF(20)
      DIMENSION  TCK(20),     TRB(20),     TDB(20),      DRR(20)
      DIMENSION  RTL(20),     VAR(20),     RWFB(20),     SWFB(20)
      DIMENSION  RWRB(20),    ERLB(20),    WRED(20),     EDFTF(20)
      DIMENSION  MWATER(20),  AWATER(20),  ER(20),       TRR(20)
      DIMENSION  DVRT(2,5),   TECT(2,8),   FDMT(2,3),    CSRRT(2,7)
      DIMENSION  RDRDT(2,6),  RDRAT(2,4),  WREDT(2,7),   RADTB(2,14)
      DIMENSION  FLTRT(2,10), FAMSTT(2,5), DISTFT(2,5), REDTTB(2,7)
      DIMENSION  REDFDT(2,10),EDPTFT(2,5), ALPHAT(7,26),RFDVST(2,4)
      DIMENSION  NAME(60),    MAT(60,10),  TITLE(80),    PE(5)
      DIMENSION  MIN(5),      MAX(5),      OBSERT(2,15)
      EXTERNAL AND
      INTEGER TIME,FINTIM,DELT,DAY,STDAY,DAYY,FDAYY,OUTDEL,PRDEL,
     1        NAME,RO,COL,ROW,UPTO,TITLE,WANTPL,EQLSCL,PVALS,PLOT
      REAL    LAT,LHVAP,LFARR,MXRTD,MRESF,LFDV,MNT,MIN,MXT,MAX,
     1        LWR,LAI,INFR,LIMIT,INSW,NOT,IBIOM,IRTD,LRF,LFAREA,
     2        IRWT,LAGRTR,LFI,LMBIOM,MAINT,MWATER,MWRTD,MAT
C
C     ***************  NON-METEOROLOGICAL FUNCTION TABLES  **************
      DATA RFDVST/0.,1.,      .9,1.,     1.,0.,     1.1,0./
      DATA WREDT /0.,0.,      .1,.3,     .15,.45,   .3,.7,     .5,.975,
     1           .75,1.,      1.1,1./
      DATA TECT  /0.,.06,     3.,.29,    10.,.85,   16.,.94,   20.,1.,
     1           31.,.87,     40.,.6,    50.,.3/
      DATA REDFDT/-.01,.05,   0.,.075,   .05,.1,    .1,.2,     .2,.375,
     1           .3,.5,       .4,.725,   .75,.9,    1.,1.,     1.1,1./
      DATA CSRRT /0.,.3,      .1,.4,     .25,.5,    .5,.65,    .75,.75,
     1           1.,.975,     1.1,.975/
      DATA FAMSTT/0.,1.,      .4,1.,     .75,.6,    1.,.5,     1.1,.5/
      DATA RDRDT /0.,0.,      .7,0.,     .71,.005,  .9,.005,   1.,.1,
     1           1.1,.1/
      DATA FLTRT /0.,1.,      .5,.705,   1.,.496,   1.5,.384,  2.,.248,
     1           3.,.134,     5.,.03,    8.,.004,   10.,.001,  15.,.0001/
      DATA REDTTB/5.,.8,      10.,.9,    15.,1.,    20.,.97,   25.,.97,
     1           30.,.97,     50.,.97/
      DATA FDMT  /0.,.1,      1.,.25,    1.1,.25/
      DATA RDRAT /0.,0.,      .5,0.,     1.,.05,    1.1,.05/
      DATA EDPTFT/0.,.15,     .15,.6,    .3,.8,     .5,1.,     1.1,1./
      DATA DISTFT/0.,.9,      .5,.8,     .7,.6,     .9,0.,     1.1,0./
      DATA DVRT  /0.,0.,      3.75,0.,   16.,0.01,  25.,0.0175,40.,0.02/
C
C     ****************  METEOROLOGICAL FUNCTION TABLE  *****************
C     TOTAL DAILY VISIBLE RADIATION AT 31 DEG LAT (NOT DUMMY)
      DATA RADTB /0.,178.9, 15.,185., 46.,239.5, 74.,298.7, 105.,360.6,
     1      135.,399.6, 166.,417.5, 196.,411.2, 227.,382.5, 258.,329.5,
```

```
      2      288.,265.,  319.,204.1, 349.,172.8, 365.,176.9/
C
C     TWOVAR FUNCTION TABLE  -  ALPHAT
      DATA ALPHAT/0.0,  0.2,  2.0,     3.5,     5.0,     10.0,   12.0,
      1       0.0,     0.0,    0.0,     0.0,     0.0,     0.0,    0.0,
      2       1.0,     1.0,    0.0,     0.0,     0.0,     0.0,    0.0,
      3       100.0,   100.0,  10.0,    10.0,    10.0,    10.0,   10.0,
      4       1.0,     1.0,    0.6,     0.425,   0.39,    0.35,   0.334,
      4       0.0,     0.0,    15.0,    15.0,    15.0,    15.0,   15.0,
      5       0.0,     0.0,    0.66,    0.515,   0.455,   0.41,   0.392,
      6       0.0,     0.0,    20.0,    20.0,    20.0,    20.0,   20.0,
      7       0.0,     0.0,    0.715,   0.585,   0.505,   0.45,   0.428,
      8       0.0,     0.0,    25.0,    25.0,    25.0,    25.0,   25.0,
      9       0.0,     0.0,    0.76,    0.64,    0.545,   0.485,  0.461,
      1       0.0,     0.0,    30.0,    30.0,    30.0,    30.0,   30.0,
      2       0.0,     0.0,    0.795,   0.68,    0.58,    0.51,   0.482,
      3       0.0,     0.0,    35.0,    35.0,    35.0,    35.0,   35.0,
      4       0.0,     0.0,    0.835,   0.715,   0.61,    0.53,   0.498,
      5       0.0,     0.0,    40.0,    40.0,    40.0,    40.0,   40.0,
      6       0.0,     0.0,    0.87,    0.745,   0.635,   0.55,   0.516,
      7       0.0,     0.0,    45.0,    45.0,    45.0,    45.0,   45.0,
      8       0.0,     0.0,    0.91,    0.77,    0.66,    0.565,  0.527,
      9       0.0,     0.0,    50.0,    50.0,    50.0,    50.0,   50.0,
      1       0.0,     0.0,    0.94,    0.795,   0.685,   0.585,  0.545,
      2       0.0,     0.0,    60.0,    60.0,    60.0,    60.0,   60.0,
      3       0.0,     0.0,    0.97,    0.845,   0.74,    0.61,   0.558,
      4       0.0,     0.0,    100.,    100.,    100.,    100.,   100.0,
      5       0.0,     0.0,    1.0,     0.875,   0.775,   0.65,   0.6/
C
C     *************************   OUTPUT  LIST   **********************
      DATA NAME/" ","W1","W2","W3","W4","W5","W6","W7","W8","W9","W10",
      1"WTOT",   "TRAIN",  "TMPA",   "TMPSUM", "HRAD",   "EVAP",
      2"TPEVAP", "PEVAP",  "AEVAP",  "TEVAP",  "PCTRAN", "PTRAN",
      3"APTRAN", "TRAN",   "TOTRAN", "AEPER",  "TRANDF", "RTRDEF",
      4"CTRDEF", "RTD",    "ERLBIO", "TRPMN",  "AMAX",   "EFFE",
      5"PDTGAS", "PDTGR",  "WUSEFF", "TGRWTH", "LAI",    "WLVS",
      6"WNLVS",  "WSDS",   "DBIOM",  "TADRW",  "RTWGHT", "TDRWT",
      7"DVS"/
C
C     *****************************   PARAMETERS   *********************
C           ALL THE FOLLOWING PARAMETERS REMAIN CONSTANT
C           THROUGHOUT AN ENTIRE RUN OF THE MODEL.
      AMAXB=40.    $CONFS=0.75  $DGRRT=12.    $DVSSF=0.65  $EFFEB=0.5
      FLDCP=0.23   $FWDB=0.1    $GAMMA=0.49   $IRTD=101.   $LAT=31.
      LFARR=20.    $LHVAP=59.   $MRESF=0.02   $MXRTD=1800. $PI=3.1416
      PROP=15.     $PSCH=0.67   $RC=37.E-5    $REFCF=0.05  $REFT=25.
      RHOCP=2.86E-4$RS=18.5E-6  $TCDPH=10.    $TCDRL=5.    $TCDRNL=5.
      TCRPH=10.    $TSUMG=150.  $WLTPT=0.075 $WCLIM=WLTPT*0.333
      DATA DRF / 0.5,0.75,0.8,0.9,1.0,1.0,1.0,1.2,1.2,1.2,1.0/
      DATA TCK / 20.,30.,50.,100.,100.,300.,300.,300.,300.,300.,1000./
C
C     **************************   RUN  CONTROL   **********************
C
      READ *,DELT,FINTIM,PRDEL,IBIOM,WANTPL
      READ 8,TITLE
    8 FORMAT(80A1)
      IF(WANTPL .EQ. 1)THEN
         READ *,OUTDEL,PLOT,EQLSCL,PVALS
      ENDIF
C     READ IN OBSERVED BIOMASS FUNCTION TABLE
      DO 11 IX=1,15
         READ *,OBSERT(1,IX),OBSERT(2,IX)
   11 CONTINUE
C
C     *********************    INITIALISATION    ***********************
C
```

```
      STDAY=1
      FDAYY=273
      REWIND 40
      LMBIOM=IBIOM*0.5
C     SOIL WATER
      J=10
      DO 1 N=1,J
      W(N)=DRF(N)*WLTPT*TCK(N)
    1 CONTINUE
      DATA TRAIN,TOTINF,TOTRAN,TPEVAP,TEVAP,TMPSUM,TDRAIN,DVS,
     1     LFAREA,WSDS,DBIOM,RTWGHT,RTD,EFFE,CTRDEF,TINTAK,
     2     SLCVR,AMAX,PLBIOM,WLVS,WNLVS,LAI/22*0./
      COL=0
C     SOIL TEMPERATURE INITIALISATION
      READ(50,10)MNT,MXT
   10 FORMAT(31X,F5.0,F6.0)
      REWIND 50
      TS10=5.*(MNT+MXT)
      TS=TS10*0.1
      TSO=TS10
C     INITIAL ABOVEGROUND BIOMASS
      IRWT=IBIOM
      WLVSI=IBIOM*AFGEN(DISTFT,0.,5)
      WNLVSI=IBIOM-WLVSI
      LFI=WLVSI*LFARR
      DO 21 I=1,5
         MAX(I)=-10E200
         MIN(I)=+10E200
   21 CONTINUE
C
C     ************************    MAIN  TIME  LOOP    *****************
C
C     ========================   DYNAMIC SECTION   ==================
      DO 1000 TIME=0,FINTIM,DELT
      DAY=STDAY+TIME
      DAYY=MOD(DAY+FDAYY,365)
C     *********    READ IN ONE DAY OF METEOROLOGICAL DATA    ***********
      READ(50,9)RAIN,MNT,MXT,DTR,WSR,DPT8,DPT2
    9 FORMAT(17X,F6.0,8X,F5.0,F6.0,F7.0,F7.0,F6.0,F6.0)
      DGRCL=2.*AFGEN(RADTB,(DAYY+0.),14)
      DGROV=0.2*DGRCL
      FCL=(DTR-DGROV)/(DGRCL-DGROV+NOT(DGRCL-DGROV))
      FOV=1.-FCL
      LFOV=LIMIT(0.,1.,FOV)
      TMPA=(MNT+MXT)/2.
      DPT=AMIN1((DPT8+DPT2)*0.5,TMPA)
      VPA=4.58*EXP(17.4*DPT/(DPT+239.))
      SVPA=4.58*EXP(17.4*TMPA/(TMPA+239.))
C     RUNON/RUNOFF IGNORED FOR THE MOMENT, THEREFORE...
      INFR=RAIN
      LWR=1.178E-7*(TMPA+273.)**4*(0.58-0.09*SQRT(VPA))*(1.-0.9*LFOV)
      WSM=WSR/1.6
      HZERO=DTR*(1.-REFCF)-LWR
      EA=0.35*(SVPA-VPA)*(0.5+WSM/100.)*LHVAP
      DELTA=17.4*SVPA*(1.-TMPA/(TMPA+239.))/(TMPA+239.)
      EVAP=(HZERO*DELTA/GAMMA+EA)/(1.+DELTA/GAMMA)*1./LHVAP
C     *****************    SOIL    TEMPERATURE    *********************
      DTMPA=DELAYT(10,TMPA)+INSW(TIME-10.,0.1*TSO,0.)
      RCST=(TMPA-DTMPA)/DELT
      WCPR=(W(1)/TCK(1)-WCLIM)/(FLDCP-WCLIM)
      FRLT=AFGEN(FLTRT,SLCVR,10)
      PEVAP=FRLT*EVAP
      REDFD=AFGEN(REDFDT,WCPR,10)
      AEVAP=PEVAP*REDFD
C
C     ***************   DAILY GROSS PHOTOSYNTHESIS   *****************
```

```
      DEC=-23.4*COS(PI*(DAYY+10.173)/182.621)
      RAD=PI/180.
      SSIN=SIN(RAD*LAT)*SIN(RAD*DEC)
      CCOS=COS(RAD*LAT)*COS(RAD*DEC)
      TTE=(-SIN(8.*RAD)+SSIN)/CCOS
      TT=SSIN/CCOS
      ASE=ASIN(TTE)
      AS=ASIN(TT)
      DAYL=12.*(PI+2.*AS)/PI
      EDAYL=12.*(PI+2.*ASE)/PI
      RADC=0.5*DGRCL
      RADO=0.2*RADC
      IF(LAI .GT. 0.)THEN
         SLLAE=SIN((90.+DEC-LAT)*RAD)
         X=0.45*EFFE*RADC/(SLLAE*AMAX)
         P=ALOG(1.+X)
         P=P/(P+1.)
         PS=SLLAE*P*EDAYL*AMAX
         X=0.55*EFFE*RADC/(AMAX*(5.-SLLAE))
         P=ALOG(1.+X)
         P=P/(P+1.)
         DGCC=PS+(5.-SLLAE)*AMAX*EDAYL*P
         DGCCE=0.95*DGCC+20.5
         X=RADO*EFFE/(AMAX*5.)
         P=X/(X+1.)
         DGCO=5.*AMAX*EDAYL*P
         DGCOE=0.9935*DGCO+1.1
            IF(LAI .GE. 5.)THEN
               PDTGAS=(LFOV*DGCO+(1.-LFOV)*DGCC)*30./44.
            ELSE
               FINT=(1.-EXP(-0.8*LAI))
               C1=FINT*DGCCE
               C2=DAYL*LAI*AMAX
               O1=FINT*DGCOE
               O2=C2
                  IF(C1 .LE. C2)THEN
                     C0=C1
                     C1=C2
                     C2=C0
                  ENDIF
               DGCCAE=C2*(1.-EXP(-C1/C2))
                  IF(O1 .LE. O2)THEN
                     O0=O1
                     O1=O2
                     O2=O0
                  ENDIF
               DGCOAE=O2*(1.-EXP(-O1/O2))
               PDTGAS=(LFOV*DGCOAE+(1.-LFOV)*DGCCAE)*30./44.
            ENDIF
      ELSE
         PDTGAS=0.
      ENDIF
C
C     ****************   SOIL WATER DYNAMICS --- PART 1 --- ************
C     PART OF WATER DYNAMICS OF FIRST SOIL COMPARTMENT
      TDB(1)=TCK(1)
      VAR(1)=AMAX1(W(1)/TCK(1)-WCLIM,0.)*EXP(-PROP*0.001*(0.5*TCK(1)))
      SUM10=VAR(1)*TCK(1)
      MWATER(1)=FLDCP*TCK(1)
      AWATER(1)=AMAX1(0.,W(1)-TCK(1)*WLTPT)
      EDPTF(1)=AFGEN(EDPTFT,AWATER(1)/(MWATER(1)-TCK(1)*WLTPT),5)
      RTL(1)=LIMIT(0.,TCK(1),RTD)
      ERLB(1)=RTL(1)*EDPTF(1)
      WCPR=(W(1)/TCK(1)-WCLIM)/(FLDCP-WCLIM)
      WRED(1)=AFGEN(WREDT,AWATER(1)/(MWATER(1)-TCK(1)*WLTPT),7)
      TEC=AFGEN(TECT,TS,8)
```

```
      RWFB(1)=AMAX1(0.,INFR-(MWATER(1)-W(1))/DELT)
      SWP=FCNSW(AWATER(1),0.,0.,AND(RTD,TDB(1)-RTD))
      SWPB(1)=SWP
      DRR(1)=RWFB(1)*AND(MXRTD,TDB(1)-MXRTD+0.5)
C     PART OF WATER DYNAMICS OF OTHER COMPARTMENTS
      DO 3 N=2,J
         TDB(N)=TDB(N-1)+TCK(N)
         VAR(N)=AMAX1(W(N)/TCK(N)-WCLIM,0.)*EXP(-PROP*0.001*(TDB(N-1)
     1     +0.5*TCK(N)))
         SUM10=SUM10+VAR(N)*TCK(N)
         MWATER(N)=FLDCP*TCK(N)
         AWATER(N)=AMAX1(0.,W(N)-TCK(N)*WLTPT)
         EDPTF(N)=AFGEN(EDPTFT,AWATER(N)/(MWATER(N)-TCK(N)*WLTPT),5)
         RTL(N)=LIMIT(0.,TCK(N),RTD-TDB(N-1))
         ERLB(N)=ERLB(N-1)+RTL(N)*EDPTF(N)
         WRED(N)=AFGEN(WREDT,AWATER(N)/(MWATER(N)-TCK(N)*WLTPT),7)
         RWFB(N)=AMAX1(0.,RWFB(N-1)-(MWATER(N)-W(N))/DELT)
         SWP=FCNSW(AWATER(N),0.,0.,AND(RTD-TDB(N-1),TDB(N)-RTD))
         SWPB(N)=SWPB(N-1)+SWP
         DRR(N)=DRR(N-1)+RWFB(N)*AND(MXRTD-TDB(N-1),TDB(N)-MXRTD+0.5)
    3 CONTINUE
C
C     *********   CALCULATION OF POTENTIAL CROP TRANSPIRATION   ********
      VPAM=1.33*VPA
      AVTD=MXT-0.25*(MXT-MNT)
      SVPAM=6.11*EXP(17.4*AVTD/(AVTD+239.))
      WSA=1.333E5*WSR
      RA=3.045E-3*SQRT(1./WSA)+63./WSA
      ELWR=1.175E-7*(AVTD+273.)**4*(0.58-0.09*SQRT(VPA))*
     1        (1.0-0.9*LFOV)*DAYL/24.
      HNOT=0.75*DTR-ELWR
      SLOPE=17.4*SVPAM*(1.-AVTD/(AVTD+239.))/(AVTD+239.)
      S=(RA+RS)/RA
      CC=1./(SLOPE+S*PSCH)
      HRAD=DTR/DAYL
      ALPHA=TWOVAR(ALPHAT,HRAD,LAI,12,7)
      RFDVS=AFGEN(RFDVST,DVS,4)
      PTRAN=CC*((1.-EXP(-0.5*LAI))*HNOT*SLOPE+ALPHA*LAI*
     1        RHOCP/RA*(SVPAM-VPAM)*DAYL/24.)/LHVAP
      APTRAN=PTRAN*RFDVS
      TRPMM=APTRAN/(ERLB(J)+NOT(ERLB(J)))
      MWRTD=RTD*(FLDCP-WLTPT)+NOT(RTD)
C
C     ****************   SOIL WATER DYNAMICS --- PART 2 --- ************
C     REST OF WATER DYNAMICS OF FIRST COMPARTMENT
      F(1)=TCK(1)*VAR(1)/(SUM10+NOT(SUM10))
      ER(1)=AMIN1(W(1)-WCLIM*TCK(1),F(1)*AEVAP)
      EB(1)=ER(1)
      TRR(1)=TRPMM*RTL(1)*EDPTF(1)*TEC*WRED(1)
      TRB(1)=TRR(1)
      RAWR=RTL(1)/TCK(1)*AWATER(1)/MWRTD
      RWRB(1)=RAWR
C     REST OF WATER DYNAMICS OF OTHER COMPARTMENTS
      DO 2 N=2,J
         F(N)=TCK(N)*VAR(N)/(SUM10+NOT(SUM10))
         ER(N)=AMIN1(W(N)-WCLIM*TCK(N),F(N)*AEVAP)
         EB(N)=EB(N-1)+ER(N)
         TRR(N)=TRPMM*RTL(N)*EDPTF(N)*TEC*WRED(N)
         TRB(N)=TRB(N-1)+TRR(N)
         RAWR=RTL(N)/TCK(N)*AWATER(N)/MWRTD
         RWRB(N)=RWRB(N-1)+RAWR
    2 CONTINUE
      WTOT=0.
      DO 7 N=1,J
      WTOT=WTOT+W(N)
    7 CONTINUE
```

```
      SW=W(1)+W(2)+W(3)-WLTPT*TDB(3)
C
C     **************   REST OF POT. CROP TRANSPIRATION   ***************
      TRAN=TRB(J)
      RTRDEF=(PTRAN-TRAN)/(PTRAN+NOT(PTRAN))
      S1=(RA+RC)/RA
      CC1=1./(SLOPE+S1*PSCH)
      PCTRAN=PTRAN*CC1/CC
      TRANDF=(PCTRAN-TRAN)*DELT
      FDV=INSW(TRANDF,1.,-1.)
C
C     *************************   GERMINATION   ************************
      ENGR=INSW(TSUMG-TMPSUM,0.,INSW(SW,TMPSUM/DELT,0.))
      PUSHD=AND(PLBIOM-LMBIOM,LMBIOM-(WLVS+WNLVS))
C     PLBIOM IS YESTERDAYS ABOVEGROUND BIOMASS
      PLBIOM=WLVS+WNLVS
      PUSHG=AND(TMPSUM-TSUMG,0.5*IBIOM-(WLVS+WNLVS))
     1      *INSW(TIME-180.,1.,0.)*(1.-PUSHD)
C     AEPER=RATIO OF ACTUAL AND POTENTIAL EVAPOTRANSPIRATION
      AEPER=(TRB(J)+EB(J))/(PEVAP+PTRAN+NOT(PEVAP+PTRAN))
C
C     ************************   CROP PRODUCTION   **********************
      TADRW=WLVS+WNLVS+WSDS+DBIOM
      DVR=AFGEN(DVRT,TMPA,5)*INSW((WLVS+WNLVS)-LMBIOM,0.,1.)
     1       *(1.-PUSHD)*INSW(DVS-1.,1.,0.)
      TVEGM=WLVS+WNLVS
      FDM=AFGEN(FDMT,DVS,3)
      RDLVSX=TRANDF*1.E4/((1.-FDM-FWDB)/FDM)*WLVS/(TVEGM+NOT(TVEGM))
      RDNLVX=TRANDF*1.E4/((1.-FDM-FWDB)/FDM)*WNLVS/(TVEGM+NOT(TVEGM))
      RDRD=AFGEN(RDRDT,DVS,6)
      RDLVSA=RDLVSX/TCDRL
      RDNLVA=RDNLVX/TCDRNL
      RDLVS2=RDRD*WLVS*(1.-PUSHD)
      RDNLV2=RDRD*WNLVS*(1.-PUSHD)
      RDLVS1=AMIN1(RDLVSA/DELT,WLVS/DELT)
      RDNLV1=AMIN1(RDNLVA/DELT,WNLVS/DELT)
      RDLVS=INSW(FDV,RDLVS1,RDLVS2)*(1.-PUSHD)
      RDNLVS=INSW(FDV,RDNLV1,RDNLV2)*(1.-PUSHD)
      RINTAK=0.
      TPPR=TINTAK+TADRW
      CRNLVS=RINTAK*WNLVS/(TVEGM+NOT(TVEGM))
      CRLVS=RINTAK*WLVS/(TVEGM+NOT(TVEGM))
      AVLAR=LFAREA/(WLVS+NOT(WLVS))
      RDLFA=AVLAR*RDLVS
      CRLFAR=CRLVS*AVLAR
      TDRWT=TADRW+RTWGHT
      TEFR=10.**((TMPA-REFT)*ALOG10(2.)/10.)
      MAINT=(TDRWT-DBIOM)*MRESF*TEFR
      PDTGR=(PDTGAS-MAINT)*CONFS
      WUSEFF=PDTGR/(PTRAN+NOT(PTRAN))
      TGRWTH=TRAN*WUSEFF
      FAMST=AFGEN(FAMSTT,RTRDEF,5)
      CSRR=AFGEN(CSRRT,DVS,7)*FAMST
      GRRWT=TGRWTH*(1.-CSRR)*(1.-PUSHD)
      GROWTR=TGRWTH*CSRR*(1.-PUSHD)
      FRTS=INSW(DVS-DVSSF,0.,0.3)*INSW(GROWTR,0.,1.)
      GRSDS=GROWTR*FRTS
      DISTF=AFGEN(DISTFT,DVS,5)
      GROWTV=GROWTR*(1.-FRTS)
      GRLVS=GROWTV*DISTF
      GRNLV=GROWTV*(1.-DISTF)
      LAGRTR=GRLVS*LFARR
      RFRGT=AFGEN(REDTTB,TS,7)
      GRRT=SWPB(J)*DGRRT*RFRGT*INSW((WLVS+WNLVS)-IBIOM,0.,1.)*
     1      INSW(RTD-MXRTD,1.,0.)*INSW(DVS-1.,1.,0.)
      TCREC=TVEGM/(GRNLV+GRLVS+NOT(GRNLV+GRLVS))
```

```
      RITDF=(1.-CTRDEF)*INSW(RTRDEF-0.4,0.,RTRDEF/TCDPH)
      RDTDF=CTRDEF/TCRPH*INSW(RTRDEF-0.4,1.,0.)
      RDRA=AFGEN(RDRAT,CTRDEF,4)
      RDEFFE=INSW(RTRDEF-0.4,0.,RDRA*EFFE)*(1.-PUSHD)
      RDAMAX=INSW(RTRDEF-0.4,0.,RDRA*AMAX)*(1.-PUSHD)
      RREFFE=(EFFEB-EFFE)/(TCREC+NOT(TCREC))*INSW(CTRDEF-0.5,1.,0.)
     1        *INSW(-TVEGM,1.,0.)
      RRAMAX=(AMAXB-AMAX)/(TCREC+NOT(TCREC))*INSW(CTRDEF-0.5,1.,0.)
     1        *INSW(-TVEGM,1.,0.)
      ENGRS=AND(TIME-200.,LMBIOM-(WLVS+WNLVS))
C
C     *****************************************************************
C     ********************    OUTPUT SECTION    ************************
C     *****************************************************************
C
      IF(   (TIME+0.)/PRDEL .EQ. (TIME/PRDEL)+0.
     1      .OR. DVS .GT. 1.   .OR. ENGRS .GT. 0.9 ) THEN
C          =========   ENTER VALUES INTO OUTPUT MATRIX   ===========
         COL=COL+1
         MAT(1,COL)=TIME+0.
         DO 4 RO=2,11
            MAT(RO,COL)=W(RO-1)
    4    CONTINUE
         RO=11
         RO=RO+1 $ MAT(RO,COL)=WTOT    $ RO=RO+1 $ MAT(RO,COL)=TRAIN
         RO=RO+1 $ MAT(RO,COL)=TMPA    $ RO=RO+1 $ MAT(RO,COL)=TMPSUM
         RO=RO+1 $ MAT(RO,COL)=HRAD    $ RO=RO+1 $ MAT(RO,COL)=EVAP
         RO=RO+1 $ MAT(RO,COL)=TPEVAP  $ RO=RO+1 $ MAT(RO,COL)=PEVAP
         RO=RO+1 $ MAT(RO,COL)=AEVAP   $ RO=RO+1 $ MAT(RO,COL)=TEVAP
         RO=RO+1 $ MAT(RO,COL)=PCTRAN  $ RO=RO+1 $ MAT(RO,COL)=PTRAN
         RO=RO+1 $ MAT(RO,COL)=APTRAN  $ RO=RO+1 $ MAT(RO,COL)=TRAN
         RO=RO+1 $ MAT(RO,COL)=TOTRAN  $ RO=RO+1 $ MAT(RO,COL)=AEPER
         RO=RO+1 $ MAT(RO,COL)=TRANDF  $ RO=RO+1 $ MAT(RO,COL)=RTRDEF
         RO=RO+1 $ MAT(RO,COL)=CTRDEF  $ RO=RO+1 $ MAT(RO,COL)=RTD
         RO=RO+1 $ MAT(RO,COL)=ERLB(10)$ RO=RO+1 $ MAT(RO,COL)=TRPMM
         RO=RO+1 $ MAT(RO,COL)=AMAX    $ RO=RO+1 $ MAT(RO,COL)=EFFE
         RO=RO+1 $ MAT(RO,COL)=PDTGAS  $ RO=RO+1 $ MAT(RO,COL)=PDTGR
         RO=RO+1 $ MAT(RO,COL)=WUSEFF  $ RO=RO+1 $ MAT(RO,COL)=TGRWTH
         RO=RO+1 $ MAT(RO,COL)=LAI     $ RO=RO+1 $ MAT(RO,COL)=WLVS
         RO=RO+1 $ MAT(RO,COL)=WNLVS   $ RO=RO+1 $ MAT(RO,COL)=WSDS
         RO=RO+1 $ MAT(RO,COL)=DBIOM   $ RO=RO+1 $ MAT(RO,COL)=TADRW
         RO=RO+1 $ MAT(RO,COL)=RTWGHT  $ RO=RO+1 $ MAT(RO,COL)=TDRWT
         RO=RO+1 $ MAT(RO,COL)=DVS
            IF ( COL .EQ. 10  .OR.  DVS .GT. 1.  .OR.
     1        ENGRS .GT. 0.9  .OR.  TIME .EQ. FINTIM ) THEN
C          ==========   PRINT OUT OUTPUT MATRIX  =============
              PRINT 90,TITLE
   90         FORMAT("1",/20X,80A1,//)
              PRINT 100,(MAT(1,UPTO),UPTO=1,10)
  100         FORMAT(" ","TIME",  10(F10.0,2X),"    TIME",/)
              DO 5 ROW=2,RO
               PRINT 110,NAME(ROW),(MAT(ROW,UPTO),UPTO=1,10),NAME(ROW)
  110          FORMAT(1X,A7,10(1PG12.4),1X,A8)
    5         CONTINUE
              COL=0
              DO 6 RO=1,60
              DO 6 COL=1,10
                 MAT(RO,COL)=0.
    6         CONTINUE
           ENDIF
      ENDIF
C     ********   PREPARE GRAPH DATA SET    ***************
      IF ( WANTPL .EQ. 1  .AND.
     1     ( (TIME + 0.)/OUTDEL .EQ. (TIME/OUTDEL)+0.  .OR.
     2      DVS .GT. 1.   .OR.   ENGRS .GT. 0.9        .OR.
     3      TIME .EQ. FINTIM )                            ) THEN
```

```
            PE(1)=AFGEN(OBSERT,DAY+0.,15)
            PE(2)=TADRW
            PE(3)=WLVS
            PE(4)=WSDS
            PE(5)=DBIOM
            WRITE(40,120),TIME
 120        FORMAT(I5)
            DO 20 IJK=1,PLOT
               IF(PE(IJK) .GT. MAX(IJK)) MAX(IJK)=PE(IJK)
               IF(PE(IJK) .LT. MIN(IJK)) MIN(IJK)=PE(IJK)
               WRITE(40,130), PE(IJK)
 130           FORMAT(F20.8)
 20         CONTINUE
         ENDIF
         IF ( DVS .GE. 1.0 ) THEN
            PRINT *,"FINISH CONDITION ... DVS=",DVS,"   SIMULATION HALTED"
            IF (WANTPL .EQ. 1) CALL PLOTIT(TITLE,PVALS,PLOT,EQLSCL,MIN,MAX)
            STOP
         ENDIF
         IF ( ENGRS .GT. 0.1 ) THEN
            PRINT *,"FINISH CONDITION ... ENGRS ... SIMULATION HALTED"
            IF (WANTPL .EQ. 1) CALL PLOTIT(TITLE,PVALS,PLOT,EQLSCL,MIN,MAX)
            STOP
         ENDIF
         IF ( TIME .EQ. FINTIM ) THEN
            PRINT *,"FINISH CONDITION ... FINTIM (=",FINTIM,") REACHED."
            IF (WANTPL .EQ.1) CALL PLOTIT(TITLE,PVALS,PLOT,EQLSCL,MIN,MAX)
            STOP
         ENDIF
C
C        **********************    INTEGRATION     ***********************
C
         TRAIN=TRAIN+RAIN*DELT
         TOTINF=TOTINF+INFR*DELT
         TPEVAP=TPEVAP+EVAP*DELT
         TMPSUM=TMPSUM+((TS-ENGR-TMPSUM*PUSHD/DELT)*DELT)
         TOTRAN=TOTRAN+TRAN*DELT
         W(1)=W(1)+((INFR-RWFB(1)-TRR(1)-ER(1))*DELT)
         DO 27 N=2,J
            W(N)=W(N)+((RWFB(N-1)-RWFB(N)-TRR(N)-ER(N))*DELT)
 27      CONTINUE
         TEVAP=TEVAP+EB(J)*DELT
         TDRAIN=TDRAIN+DRR(J)*DELT
         DBIOM=DBIOM+(RDLVS+RDNLVS+(WLVS+WNLVS)*PUSHD/DELT)*DELT
         WLVS=WLVS+(PUSHG/DELT*WLVSI+GRLVS-RDLVS-PUSHD/DELT
     1        *WLVS-CRLVS)*DELT
         WNLVS=WNLVS+(PUSHG/DELT*WNLVSI+GRNLV-RDNLVS-PUSHD/DELT
     1        *WNLVS-CRNLVS)*DELT
         WSDS=WSDS+(GRSDS-WSDS*PUSHD/DELT)*DELT
         LFAREA=LFAREA+(LAGRTR-RDLFA+LFI*PUSHG/DELT-LFAREA*PUSHD/DELT
     1        -CRLFAR)*DELT
         LAI=1.E-4*LFAREA
         DVS=DVS+(DVR-DVS*PUSHD/DELT)*DELT
         RTWGHT=RTWGHT+(GRRWT+IRWT*PUSHG/DELT-RTWGHT*PUSHD/DELT)*DELT
         RTD=RTD+(GRRT+IRTD*PUSHG/DELT-RTD*PUSHD/DELT)*DELT
         EFFE=EFFE+(EFFEB/DELT*PUSHG-EFFE/DELT*PUSHD-RDEFFE+RREFFE)*DELT
         CTRDEF=CTRDEF+(RITDF-RDTDF)*DELT
         TINTAK=TINTAK+RINTAK*DELT
         AMAX=AMAX+(AMAXB/DELT*PUSHG-AMAX/DELT*PUSHD-RDAMAX+RRAMAX)*DELT
         SLCVR=SLCVR+(LAGRTR+LFI*PUSHG/DELT-SLCVR*PUSHD/DELT)*1.E-4*DELT
C        TS=SOIL TEMPERATURE = TEN DAY RUNNING AVE OF AIR TEMP.
         TS=0.1*(TS10+RCST*DELT)
         TS10=TS10+RCST*DELT
 1000 CONTINUE
         STOP
         END
```

```
C
C     *****************************************************************
      FUNCTION RAFGEN(TABLE,INDVAR)
C     TABLE=MATRIX OF X,Y COORDINATES.X=NO OF DAYS FROM OCT 1(X=1=OCT 1)
C     X VALUES MUST BE IN INCREASING ORDER. Y=RAINFALL ON THAT DAY (MM)
C     END OF RAINS INDICATED BY 0.,0.
C     INDVAR=INDEPENDENT VARIABLE VALUE (DAY NO)
      REAL INDVAR
      DIMENSION TABLE(2,50)
         LOGICAL DONE
         DATA DONE/.FALSE./
C     SINCE MANY CALLS TO RAFGEN ARE MADE AFTER LAST RAIN EVENT, CHECK
C     IF INDVAR IS AFTER LAST RAIN EVENT. IF SO, RETURN VALUE OF 0.
C     ELSE, CHECK THROUGH X VALUES FOR INDVAR VALUE. IF OCCURS,
C     RETURN CORRESPONDING Y VALUE, ELSE RETURN VALUE OF 0.
C        INITIALISE RAFGEN
         RAFGEN=0.
         IF(.NOT. DONE)THEN
C           FIND WHAT DAY LAST RAIN OCCURS ON (I.E. FIND THE 0.,0.)
            NDP=1
            WHILE(TABLE(1,NDP) .NE. 0.)DO
            NDP=NDP+1
            ENDWHILE
            NDP=NDP-1
            DONE=.TRUE.
         ENDIF
      IF(INDVAR .GT. TABLE(1,NDP))THEN
C        AFTER END OF RAINS
         RAFGEN=0.
      ELSE
C        INDVAR MIGHT BE A RAINY DAY
         DO 1 N=1,NDP
         IF(INDVAR .EQ. TABLE(1,N))RAFGEN=TABLE(2,N)
    1    CONTINUE
      ENDIF
      RETURN
      END
C     *****************************************************************
      FUNCTION AFGEN(TABLE,INDVAR,NDP)
C     TABLE=MATRIX OF X,Y COORDINATES, 2 ROWS, NDP COLUMNS LONG.
C     X VALUES MUST BE IN INCREASING ORDER.
C     INDVAR=INDEPENDENT VARIABLE VALUE
C     NDP=NO OF DATA PAIRS IN THE FUNCTION TABLE
      REAL INDVAR
      DIMENSION TABLE(2,NDP)
C     (MORE EFFICIENT TO SET INDVAR TO LOCAL VARIABLE...)
      ENDVAR=INDVAR
         IF(ENDVAR .LT. TABLE(1,1))THEN
C           X COORDINATE BELOW RANGE. ASSUME GRADIENT BELOW 1ST POINT=0
            AFGEN=TABLE(2,1)
            PRINT 1,ENDVAR,NDP
    1       FORMAT(1X,"AFGEN CHECK. INDEP VARIABLE ",F10.4,
     1      " IS BELOW RANGE. VALUE CORRESP TO LOWEST X VALUE",
     2      " RETURNED. FUNCTION HAS ",I3," DATA PAIRS.")
         ELSEIF(ENDVAR .GT. TABLE(1,NDP))THEN
C           X COORDINATE ABOVE RANGE. ASSUME GRADIENT ABOVE LAST POINT=0
            AFGEN=TABLE(2,NDP)
            PRINT 2,ENDVAR,NDP
    2       FORMAT(1X,"AFGEN CHECK. INDEP VARIABLE ",F10.4,
     1      " IS ABOVE RANGE. VALUE CORRESP TO HIGHEST X VALUE",
     2      " RETURNED. FUNCTION HAS ",I3," DATA PAIRS.")
         ELSE
C           X COORDINATE IS WITHIN TABLE RANGE
C           LOCATE X COORDINATE IN TABLE EITHER SIDE OF ENDVAR VALUE
            N=1
            WHILE(ENDVAR .GT. TABLE(1,N))DO
```

```
            N=N+1
            ENDWHILE
               IF(N .EQ. 1)THEN
                  AFGEN=TABLE(2,1)
                  RETURN
               ENDIF
C        ENDVAR LIES BETWEEN TABLE(1,N-1) AND TABLE(1,N)
C        LINEAR INTERPOLATION
            AFGEN=((ENDVAR-TABLE(1,N-1))*((TABLE(2,N)-TABLE(2,N-1))
     1           /(TABLE(1,N)-TABLE(1,N-1))))+TABLE(2,N-1)
         ENDIF
      RETURN
      END
C     *******************************************************************
      FUNCTION DELAYT(NUMBER,PRESENT)
C     FUNCTION TO RETURN AVE AIR TEMP OF "NUMBER" DAYS AGO
      DIMENSION TEMP(20)
      DATA TEMP/ 20*0./
      DELAYT=TEMP(1)
      DO 1 N=1,NUMBER-1
      TEMP(N)=TEMP(N+1)
    1 CONTINUE
      TEMP(NUMBER)=PRESENT
      RETURN
      END
C     *******************************************************************
      REAL FUNCTION LIMIT(P1,P2,X)
         IF(P1 .GE. P2)PRINT *,"LIMIT FUNCTION CHECK.
     1      P1 IS .GE. P2 ... P1=",P1,"   P2=",P2
         IF(X .LT. P1)THEN
            LIMIT=P1
         ELSEIF(X .GT. P2)THEN
            LIMIT=P2
         ELSE
            LIMIT=X
         ENDIF
      RETURN
      END
C     *******************************************************************
      REAL FUNCTION INSW(X1,X2,X3)
         IF(X1 .LT. 0.)THEN
            INSW=X2
         ELSE
            INSW=X3
         ENDIF
      RETURN
      END
C     *******************************************************************
      FUNCTION FCNSW(X1,X2,X3,X4)
         IF(X1 .LT. 0.)THEN
            FCNSW=X2
         ELSEIF(X1 .EQ. 0.)THEN
            FCNSW=X3
         ELSE
            FCNSW=X4
         ENDIF
      RETURN
      END
C     *******************************************************************
      REAL FUNCTION NOT(X)
         IF(X .LE. 0.)THEN
            NOT=1.
         ELSE
            NOT=0.
         ENDIF
      RETURN
```

```
      END
C     ******************************************************************
      FUNCTION AND(X1,X2)
         IF(X1 .GT. 0. .AND. X2 .GT. 0.)THEN
            AND=1.
         ELSE
            AND=0.
         ENDIF
      RETURN
      END
C     ******************************************************************
      FUNCTION TWOVAR(MATRIX,INDVR1,INDVR2,MNDP1,NDP2)
      REAL MATRIX,INDVR1,INDVR2
      DIMENSION MATRIX(NDP2,26)
C        MATRIX=NAME OF FUNCTION TABLE
C        INDVR1=NAME OF FIRST INDEPENDENT VARIABLE.ASCENDING ORDER ONLY
C        INDVR2=          SECOND
C         MNDP1=MAX NO OF SECOND INDEPENDENT VARIABLE VALUES
C          NDP2=NO OF SECOND INDEPENDENT VARIABLE VALUES
C     MORE EFFICIENT TO SET INDVR1 AND INDVR2 TO LOCAL VARIABLES...
      ENDVR1=INDVR1
      ENDVR2=INDVR2
C     CHECK ENDVR2 WITHIN ENDVR2 MATRIX RANGE
      IF(ENDVR2 .LT. MATRIX(1,1))THEN
         PRINT *,"TWOVAR CHECK...ENDVR2",ENDVR2,"  BELOW RANGE. LOWEST
     1      ENDVR2 AND LOWEST ENDVR1 VALUES ASSUMED AND APPROPRIATE
     2      DEPENDENT VARIABLE VALUE RETURNED."
         TWOVAR=MATRIX(1,3)
      ELSEIF(ENDVR2 .GT. MATRIX(NDP2,1))THEN
         PRINT *,"TWOVAR CHECK...ENDVR2",ENDVR2,"  ABOVE RANGE.
     1      HIGHEST ENDVR2 AND LOWEST ENDVR1 VALUES ASSUMED
     2      AND APPROPRIATE DEPENDENT VARIABLE VALUE RETURNED."
         TWOVAR=MATRIX(NDP2,3)
      ELSE
C     ENDVR2 WITHIN BOUNDS. LOCATE DEM BOUNDS..
         N=1
         WHILE(ENDVR2 .GE. MATRIX(N,1))DO
         N=N+1
         ENDWHILE
C        N=UPPER BOUND ROW
C     CHECK ENDVR1 IS WITHIN ENDVR1 RANGE OF BOUNDING ROWS...
      DO 1 M=N-1,N
         L=2
         WHILE(ENDVR1 .GE. MATRIX(M,L) .AND. L .LT. 2*MNDP1)DO
         L=L+2
         ENDWHILE
            IF(L .EQ. 2)THEN
C           ENDVR1 IS BELOW RANGE
               PRINT *,"ENDVR2 WITHIN RANGE, BUT ENDVR1",ENDVR1,
     1         "  BELOW RANGE. MINIMUM ENDVR1 FOR LOWER/UPPER
     2         BOUND ENDVR2 VALUE IS ASSUMED AND APPROPRIATE
     3         DEPENDENT VARIABLE VALUE RETURNED."
            TWOVAR=MATRIX(M,L)
            RETURN
         ELSEIF(L .EQ. 2*MNDP1 .AND. MATRIX(M,L) .LT. ENDVR1)THEN
C           ENDVR1 IS ABOVE RANGE
            PRINT *,"ENDVR2 WITHIN RANGE, BUT ENDVR1",ENDVR1,
     1      "  ABOVE RANGE.MAXIMUM ENDVR1 FOR LOWER/UPPER
     2      BOUND ENDVR2 VALUE IS ASSUMED AND APPROPRIATE
     3      DEPENDENT VARIABLE VALUE RETURNED."
            TWOVAR=MATRIX(M,L)
            RETURN
         ELSE
C        ENDVR1 IS WITHIN RANGE OF BOUNDING ROWS. INTERPOLATE...
            IF(M .EQ. N-1)THEN
               APROX1=(((MATRIX(M,L+1)-MATRIX(M,L-1))/(MATRIX(M,L)-
```

```
     1        MATRIX(M,L-2)))*(ENDVR1-MATRIX(M,L-2)))+MATRIX(M,L-1)
            ELSE
              APROX2=(((MATRIX(M,L+1)-MATRIX(M,L-1))/(MATRIX(M,L)-
     1        MATRIX(M,L-2)))*(ENDVR1-MATRIX(M,L-2)))+MATRIX(M,L-1)
            ENDIF
          ENDIF
    1 CONTINUE
C     FINAL INTERPOLATION FOR ENDVR2...
      TWOVAR=(((APROX2-APROX1)/(MATRIX(N,1)-MATRIX(N-1,1)))
     1        *(ENDVR2-MATRIX(N-1,1)))+APROX1
      ENDIF
      RETURN
      END
C     ****************************************************************
      SUBROUTINE PLOTIT ( TITLE, PVALS, PLOT, EQLSCL, MIN, MAX )
      DIMENSION  TITLE(80),   MIN(5),   MAX(5),   ROEPP(5)
      DIMENSION  LEN(120),    PE(5),    SYMBOL(5),LETTER(5)
      REAL      INSW, MIN, MAX, MINALL, MAXALL, ROEPP, NOPP
      INTEGER  TITLE, PVALS, PLOT,PLOTT, EQLSCL, SYMBOL, LEN, TIME
      DATA SYMBOL/"*","+","$","&","#"/
      DATA LETTER/"A","B","C","D","E"/
C     MORE EFFICIENT TO SET PLOT TO LOCAL VARIABLE...
      PLOTT=PLOT
            PRINT 10,TITLE
   10       FORMAT("1",/,20X,80A1,//)
            REWIND 40
C           NUMBER OF PLOT POSITIONS
            NOPP=INSW ( PVALS-1., 117., 129.-(PLOTT * 12.) )
            IF (EQLSCL .EQ. 1) THEN
              MINALL=+10E200
              MAXALL=-10E200
              DO 20 IJK=1,PLOTT
                IF (MIN(IJK) .LT. MINALL) MINALL=MIN(IJK)
                IF (MAX(IJK) .GT. MAXALL) MAXALL=MAX(IJK)
   20         CONTINUE
C             RANGE OF EACH PRINTING POSITION
              DO 30 IJK=1,PLOTT
                ROEPP(IJK)=(MAXALL-MINALL)/(NOPP-1)
                MIN(IJK)=MINALL
                MAX(IJK)=MAXALL
   30         CONTINUE
            ELSE
              DO 40 IJK=1,PLOTT
                ROEPP(IJK)=(MAX(IJK)-MIN(IJK))/(NOPP-1)
   40         CONTINUE
            ENDIF
C           HEADINGS
            DO 50 I=1,PLOTT
              PRINT 60,SYMBOL(I),LETTER(I),MIN(I),MAX(I),ROEPP(I)
   60         FORMAT(" ",32X,A1," = ",A1,",    MINIMUM = ",
     1               F8.2,",MAXIMUM = ",F8.2,",  RANGE OF",
     2               " EACH PLOT POSITION = ",F6.2)
   50       CONTINUE
            PRINT 70
   70       FORMAT(" ",//)
  150       READ(40,160,END=300)TIME
  160       FORMAT(I5)
C           INITIALISE PLOT ARRAY
            NOP=INT(NOPP)
            DO 80 I=1,NOP
              LEN(I)=" "
   80       CONTINUE
C           END MARKERS
            LEN(1)="I"
            LEN(NOP)="I"
            DO 90 IJK=1,PLOTT
```

```
            READ(40,100),PE(IJK)
  100       FORMAT(F20.8)
 C          PRINTING POSITION
            PP=(PE(IJK)-MIN(IJK))/ROEPP(IJK)
            NPP=INT(PP+0.5)+1
            LEN(NPP)=SYMBOL(IJK)
  90     CONTINUE
         IF(PLOTT .EQ. 1 .OR. PVALS .EQ. 0) THEN
            PRINT 180,TIME,PE(1),(LEN(N),N=1,NOP)
  180       FORMAT(1X,I4,1PG12.4,2X,117A1)
         ELSEIF(PLOTT .EQ. 2) THEN
            PRINT 190,TIME,PE(1),(LEN(N),N=1,105),PE(2)
  190       FORMAT(1X,I4,1PG12.4,2X,105A1,1PG12.4)
         ELSEIF(PLOTT .EQ. 3) THEN
            PRINT 200,TIME,PE(1),(LEN(N),N=1,93),PE(2),PE(3)
  200       FORMAT(1X,I4,1PG12.4,2X,93A1,2(1PG12.4))
         ELSEIF(PLOTT .EQ. 4) THEN
            PRINT 210,TIME,PE(1),(LEN(N),N=1,81),PE(2),PE(3),PE(4)
  210       FORMAT(1X,I4,1PG12.4,2X,81A1,3(1PG12.4))
         ELSE
            PRINT 220,TIME,PE(1),(LEN(N),N=1,69),PE(2),PE(3),PE(4)
     1            ,PE(5)
  220       FORMAT(1X,I4,1PG12.4,2X,69A1,4(1PG12.4))
         ENDIF
         GOTO 150
  300    RETURN
      END
 C    *********************************************************************
```

Appendix 2

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*****************************************************************************
*****************************************************************************
                    ARIDCROP  DEFINITIONS
*****************************************************************************
*****************************************************************************
        THIS IS AN ALPHABETICALLY ARRANGED DEFINITIONS
        LIST OF TERMS APPEARING IN THE MODEL ARID CROP
        WRITTEN BY HERMAN VAN KEULEN IN THE SIMULATION
        LANGUAGE CSMP III
=============================================================================
VARIABLE          DEFINITION                                    UNITS
=============================================================================
*****************************************************************************
                                 A
*****************************************************************************
AEPER   RATIO OF ACTUAL AND POTENTIAL EVAPOTRANSPIRATION
AEVAP   ACTUAL RATE OF SOIL EVAPORATION(=EB10)                  MM/DAY
AINT    FORTRAN TRUNCATION FUNCTION
ALPHA   PROPORTIONALITY FACTOR (=F(LAI,RADIATION INTENSITY))
ALPHAT  ALPHA FUNCTION TABLE
AMAX    ACTUAL LIGHT SATURATED LEVEL OF PHOTOSYNTHESIS
           LIGHT CURVE (SINGLE LEAF)                            KGCO2/HA LEAF/HR
AMAXB   POTENTIAL LIGHT SATURATED LEVEL OF GROSS CO2
           ASSIMILATION (PARAMETER)                             KGCO2/HA LEAF/HR
APTRAN  ACTUAL POTENTIAL TRANSPIRATION, CORRECTED FOR
           DEVELOPMENT STAGE                                    MM/DAY
AS      ARCSIN OF TT
ASE     ARCSIN OF TTE
ASIN    FORTRAN ARCSIN FUNCTION
AVLAR   RATIO BETWEEN TOTAL LEAF AREA AND TOTAL LEAF WEIGHT
AVTD    AVERAGE TEMPERATURE DURING DAYTIME                      DEGREE C
AWATER  MACRO DUMMY VARIABLE FOR AVAILABLE WATER PER COMP       MM
*****************************************************************************
                                 B
*****************************************************************************
*****************************************************************************
                                 C
*****************************************************************************
C0      INTERMEDIATE VARIABLE
C1,C2   INTERMEDIATE VARIABLE, LIMITS TO DGCC
CC      INTERMEDIATE VARIABLE
CC1     INTERMEDIATE VARIABLE
CCOS    PRODUCT OF COSINES OF LATITUDE AND DECLINATION
COMP    MACRO NAME
CONFS   CONVERSION EFFICIENCY OF PRIMARY PHOTOSYNTHATE TO
           STRUCTURAL PLANT MATERIAL (PARAMETER)                KG DM/KG CH2O
CRLFAR  CONSUMPTION RATE OF LEAF AREA                           M2/DAY
CRLVS   CONSUMPTION RATE OF LEAF MATERIAL                       KG DM/HA/DAY
CRNLVS  CONSUMPTION RATE OF NON-LEAF MATERIAL                   KG DM/HA/DAY
CSRR    CURRENT SHOOT TO ROOT RATIO, I.E. DIVISION OF NEW MATERIAL
           BETWEEN ABOVE AND BELOW GROUND PLANT PARTS
CSRRT   TABLE FOR CSRR FUNCTION OF DEVELOPMENT STAGE
CTRDEF  CUMULATIVE RELATIVE TRANSPIRATION DEFICIT
*****************************************************************************
                                 D
*****************************************************************************
DAY     DAY NO. FROM START OF RUN = DAY NO.FROM OCT.1
DAYL    ASTRONOMICAL DAYLENGTH                                  HOURS
DAYY    NUMBER OF CALENDAR DAY SINCE JAN.1
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DBIOM    BIOMASS OF DEAD PLANT MATERIAL                          KG DM/HA
DEC      DECLINATION OF SUN WITH RESPECT TO EQUATOR              DEGREE
DELT     INTEGRATION TIME STEP                                   DAYS
DELTA    SLOPE OF SATURATED VAPOUR PRESSURE CURVE AT AIR TEMP.   MM HG/DEGREE C
DGCC     DAILY GROSS CO2 ASSIMILATION ON A CLEAR DAY             KG CO2/HA/DAY
DGCCAE   INTERMEDIATE VARIABLE
DGCCE    INTERMEDIATE VARIABLE
DGCO     DAILY GROSS CO2 ASSIMILATION ON AN OVERCAST DAY         KG CO2/HA/DAY
DGCOAE   INTERMEDIATE VARIABLE
DGCOE    INTERMEDIATE VARIABLE
DGRCL    DAILY TOTAL GLOBAL RADIATION WITH CLEAR SKY             CAL/CM2
DGROV    DAILY TOTAL GLOBAL RADIATION WITH OVERCAST SKY          CAL/CM2
DISTF    DISTRIBUTION FACTOR FOR PARTITIONING BETWEEN
            LEAVES AND STEM
DISTFT   FUNCTION TABLE
DGRRT    DAILY EXTENSION RATE OF THE ROOTS
            UNDER OPTIMAL CONDITIONS                             MM/DAY
DPT2     DEW POINT TEMPERATURE AT 2 IN THE AFTERNOON             DEGREE C
DP2T     FUNCTION TABLE
DPT8     DEW POINT TEMPERATURE AT 8 IN THE MORNING               DEGREE C
DP8T     FUNCTION TABLE
DPT      AVERAGE DEW POINT TEMPERATURE                           DEGREE C
DRR1-N   CUMULATIVE DEEP DRAINAGE BEYOND POTENTIAL ROOTING ZONE MM/DAY
DRF1-N   INITIAL DRYNESS FACTOR OF CONSECUTIVE COMPARTMENTS
            AS A FRACTION OF MOISTURE CONTENT AT WILTING POINT
DRF      MACRO DUMMY VARIABLE FOR INITIAL DRYNESS FACTOR
DRRB     MACRO DUMMY VARIABLE FOR DRR2-N+1
DRRT     MACRO DUMMY VARIABLE FOR DRR1-N
DTMPA    AIR TEMPERATURE 10 DAYS AGO                             DEGREE C
DTR      DAILY TOTAL RADIATION                                   CAL/CM2
DTRT     FUNCTION TABLE
DVS      DEVELOPMENT STAGE OF VEGETATION AS A FRACTION.
            DVS=1. IS FULL MATURITY
DVSSF    DEVELOPMENT STAGE AT WHICH SEED FILL STARTS (PARAMETER)
DVR      DEVELOPMENT RATE                                        /DAY
DVRT     FUNCTION TABLE. DVR=F(TEMP)
********************************************************************************
                                      E
********************************************************************************
EA       CONTRIBUTION OF DRYING POWER OF THE ATMOSPHERE TO
            EVAPORATIVE DEMAND                                   CAL/CM2/DAY
EB       MACRO DUMMY VARIABLE FOR EB1-10
EB1-10   CUMULATIVE EVAPORATION OVER COMPARTMENTS                MM/DAY
EDAYL    EFFECTIVE DAYLENGTH                                     HOURS
EDPTF    FACTOR DEFINING EFFECTIVINESS OF ROOTS
EDPTFT   FUNCTION TABLE. RELATION BETWEEN SOIL MOISTURE
            AND EFFECTIVENESS OF ROOTS
EFFE     ACTUAL INITIAL EFFICIENCY OF THE PHOTOSYNTHESIS
            LIGHT CURVE FOR INDIVIDUAL LEAVES           KG CO2/HA/HR/J/M2/S
EFFEB    BASIC POTENTIAL EFFE (PARAMETER)               KG CO2/HA/HR/J/M2/S
ELWR     BRUNT'S ESTIMATION OF LONG-WAVE RADIATION LOSS
ENGR     RATE OF EMPTYING OF TEMPERATURE SUM WHEN
            NO SEEDS ARE GERMINATING
ENGRS    SWITCH PARAMETER TO INDICATE END OF GROWING SEASON
ER       EVAPORATION RATE FROM A COMPARTMENT                     MM/DAY
ERLB     MACRO DUMMY VARIABLE FOR ERLB1-10
ERLB1-10 CUMULATIVE EFFECTIVE ROOT LENGTH                        MM
ERLT     MACRO DUMMY VARIABLE FOR ERLB1-9
ET       MACRO DUMMY VARIABLE FOR EB1-9
EVAP     PENMAN EVAPORATION (POTENTIAL SOIL EVAPORATION)         MM/DAY
********************************************************************************
                                      F
********************************************************************************
F        MACRO DUMMY VARIABLE FOR F1-10
F1-10    SOIL EVAPORATIVE LOSS DISTRIBUTION FACTOR
FAMST    EFFECT OF WATER SHORTAGE ON CURRENT SHOOT TO ROOT RATIO
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| | | |
|---|---|---|
| FAMSTT | FUNCTION TABLE | |
| FCL | FRACTION OF THE DAY THAT IS CLEAR | |
| FDAYY | FIRST DAY OF SIMULATION IN DAYS FROM 1 JAN | |
| FDM | FRACTION OF DRY MATTER IN THE CANOPY (1-FRACTION OF WATER) | |
| FDMT | FUNCTION TABLE.( FDM=F(DVS) ) | |
| FDV | INTERMEDIATE VARIABLE | |
| FINT | FRACTION OF RADIATION INTERCEPTED BY THE CROP CANOPY | |
| FLDCP | FIELD CAPACITY (PARAMETER) | CM3/CM3 |
| FLTRT | FUNCTION TABLE. FRACTION OF ENERGY REACHING THE SOIL =F(LEAF AREA INDEX) | |
| FOV | FRACTION OF THE DAY THAT IS OVERCAST | |
| FRLT | FRACTION OF LIGHT TRANSMITTED THROUGH VEGETATION | |
| FRTS | FRACTION OF PHOTOSYNTHATE ACTUALLY TRANSLOCATED TO SEEDS | |
| FTRS | FRACTION OF PHOTOSYNTHATE ALLOCATED TO SEEDS (PARAMETER) | |
| FWDB | FRACTION OF WATER IN DEAD BIOMASS (PARAMETER) | |

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G

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| | | |
|---|---|---|
| GAMMA | PSYCHROMETER CONSTANT (PARAMETER) | MM HG/DEGREE C |
| GRLVS | GROWTH RATE OF LEAVES | KG DM/HA/DAY |
| GRNLV | GROWTH RATE OF NON-LEAF MATERIAL | KG DM/HA/DAY |
| GROWTR | TOTAL GROWTH RATE OF ABOVE GROUND BIOMASS | KG DM/HA/DAY |
| GROWTV | GROWTH RATE OF ABOVEGROUND VEGETATIVE BIOMASS | KG DM/HA/DAY |
| GRRT | RATE OF VERTICAL EXTENSION OF THE ROOT SYSTEM | MM/DAY |
| GRSDS | GROWTH RATE OF THE SEEDS | KG DM/HA/DAY |
| GRRWT | GROWTH RATE OF THE ROOTS | KG DM/HA/DAY |

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H

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| | | |
|---|---|---|
| HNOT | ABSORBED SHORT WAVE RADIATION BY VEGETATION | CAL/CM2/DAY |
| HRAD | AVERAGE HOURLY RADIATION INTENSITY | CAL/CM2/HR |
| HZERO | ABSORBED SHORT WAVE RADIATION BY SOIL | CAL/CM2/DAY |

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I

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| | | |
|---|---|---|
| IBIOM | INITIAL BIOMASS (PARAMETER) | KG DM/HA |
| INFR | RATE OF INFILTRATION OF WATER INTO THE SOIL | MM/DAY |
| IRTD | INITIAL ROOTING DEPTH (PARAMETER) | MM |
| IRWT | INITIAL WEIGHT OF THE ROOTS, SET EQUAL TO INITIAL ABOVEGROUND BIOMASS | KG DM/HA |

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J

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K

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L

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| | | |
|---|---|---|
| LAGRTR | RATE OF LEAF AREA GROWTH | M2/HA/DAY |
| LAI | LEAF AREA INDEX | HA/HA |
| LAT | LATITUDE OF LOCATION (PARAMETER) | DEGREES |
| LFAREA | LEAF AREA | M2/HA |
| LFARR | LEAF AREA PER UNIT LEAF WEIGHT (PARAMETER) | M2/KG |
| LFI | INITIAL LEAF AREA | M2/HA |
| LFOV | FOV RESTRAINED BETWEEN 0 AND 1 (USING LIMIT FUNCTION) | |
| LHVAP | HEAT OF VAPORISATION OF WATER (PARAMETER) | CAL/10**-4 KG |
| LMBIOM | LIMITING BIOMASS TO BE CONSIDERED | KG DM/HA |
| LWR | OUTGOING LONG-WAVE RADIATION | CAL/CM2/DAY |

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M

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| | | |
|---|---|---|
| MAINT | MAINTENANCE RESPIRATION ASSIMILATE REQUIREMENT | KG CH2O/HA/DAY |
| MNT | MINIMUM DAILY TEMPERATURE | DEGREE C |
| MNTT | FUNCTION TABLE | |
| MRESF | MAINTENANCE RESPIRATION FACTOR (PARAMETER) | KG CH2O/KGDM/DAY |

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MWATER   MAXIMUM AMOUNT OF WATER THAT CAN BE HELD
            IN A SOIL COMPARTMENT                              MM
MWRTD    MAXIMUM  AMOUNT OF WATER THAT CAN BE STORED
            IN ROOTED DEPTH                                    MM
MXRTD    MAXIMUM ROOTING DEPTH (PARAMETER)                     MM
MXT      MAXIMUM DAILY TEMPERATURE                             DEGREE C
MXTT     FUNCTION TABLE
*************************************************************************
                                  N
*************************************************************************
*************************************************************************
                                  O
*************************************************************************
O1       INTERMEDIATE VARIABLE
O2       INTERMEDIATE VARIABLE
OO       INTERMEDIATE VARIABLE
*************************************************************************
                                  P
*************************************************************************
P        INTERMEDIATE VARIABLE
PCTRAN   POTENTIAL CUTICULAR TRANSPIRATION                     MM/DAY
PDTGAS   POTENTIAL DAILY TOTAL GROSS ASSIMILATION              KG CH2O/HA
PDTGR    POTENTIAL DAILY TOTAL GROWTH RATE                     KG DM/HA/DAY
PEVAP    POTENTIAL EVAPORATION AS A FUNCTION OF SOIL COVER     MM/DAY
PHOTPR   PROCEDURE DUMMY NAME
PI       3.1416 (PARAMETER)
PLBIOM   LIVING BIOMASS ONE TIME STEP AGO                      KG DM/HA
PROP     PROPORTIONALITY FACTOR FOR DIVISION OF SOIL WATER
            EVAPORATION OVER VARIOUS COMPARTMENTS (PARAMETER)
PS       PHOTOSYNTHETIC RATE OF SUNLIT LEAF AREA               KG CH2O/HA/DAY
PSCH     PSYCHROMETRIC CONSTANT (PARAMETER)                    MBAR/DEGREE C
PTRAN    POTENTIAL TRANSPIRATION RATE                          MM/DAY
PUSHD    SWITCH TO KILL THE VEGETATION AFTER DROUGHT PERIOD
PUSHG    SWITCH TO INITIALISE BIOMASS AT MOMENT OF ESTABLISHMENT
*************************************************************************
                                  Q
*************************************************************************
*************************************************************************
                                  R
*************************************************************************
RA       HEAT RESISTANCE OF LEAF BOUNDARY LAYER                DAY/CM
RAD      VALUE OF A RADIAN
RADC     PHOTOSYNTHETICALLY ACTIVE RADIATION ON A CLEAR DAY    J/M2/SEC
RADO     PHOTOSYNTHETICALLY ACTIVE RADIATION ON AN OVERCAST DAY J/M2/SEC
RADTB    FUNCTION TABLE (TOTAL DAILY VISIBLE RADIATION)
RAIN     RAINFALL INTENSITY                                    MM/DAY
RAINTB   FUNCTION TABLE
RAWR     RELATIVE AMOUNT OF WATER AVAILABLE FOR THE ROOTS
RAWRB    MACRO DUMMY VARIABLE FOR RWRB1-10
RAWRT    MACRO DUMMY VARIABLE FOR RWRB1-9
RC       CUTICULAR RESISTANCE (PARAMETER)                      DAY/CM
RCST     RATE OF CHANGE OF SOIL TEMPERATURE                    DEGREE C/DAY
RDAMAX   RATE OF DECLINE IN LIGHT SATURATED LEVEL OF
            PHOTOSYNTHESIS LIGHT CURVE FOR INDIVIDUAL LEAVES   KG CO2/HA/HR/DAY
RDEFFE   RATE OF DECLINE IN INITIAL EFFICIENCY OF
            PHOTOSYNTHESIS LIGHT CURVE FOR INDIVIDUAL LEAVES
                                                   KG CO2/HA/HR/J/M2/S/DAY
RDLFA    RATE OF REDUCTION OF LIVE LEAF AREA DUE TO LEAF DEATH M2/HA/DAY
RDLVS    ACTUAL RATE OF DYING OF LEAF MATERIAL                 KG DM/HA/DAY
RDLVS1   RATE OF DYING OF LEAVES DUE TO WATER SHORTAGE         KG DM/HA/DAY
RDLVS2   RATE OF DYING OF LEAVES DUE TO SENESCENCE             KG DM/HA/DAY
RDLVSA   INTERMEDIATE VARIABLE
RDLVSX   INTERMEDIATE VARIABLE
RDNLV1   RATE OF DYING OF NON-LEAF MATERIAL DUE TO H20 SHORTAGE KG DM/HA/DAY
RDNLV2   RATE OF DYING OF NON-LEAF MATERIAL DUE TO SENESCENCE  KG DM/HA/DAY
RDNLVA   INTERMEDIATE VARIABLE
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| | | |
|---|---|---|
| RDNLVS | ACTUAL RATE OF DYING OF NON-LEAF MATERIAL | KG DM/HA/DAY |
| RDNLVX | INTERMEDIATE VARIABLE | |
| RDRA | RELATIVE RATE OF DECLINE IN AMAX AND EFFE | /DAY |
| RDRAT | FUNCTION TABLE. RDRA=F(CUMULATIVE TRANSPIRATION DEFICIT) | |
| RDRD | RELATIVE DEATH RATE CAUSED BY COMPLETION OF DEVELOPMENT /DAY | |
| RDRDT | FUNCTION TABLE. RDRD=F(DVS) | |
| ~~RDTDF~~ | ~~RATE OF DECREASE IN TRANSPIRATION DEFICIT~~ | ~~MM/DAY~~ |
| REDFD | REDUCTION FACTOR FOR EVAPORATION DUE TO DRYING OF THE SOIL | |
| REDFDT | FUNCTION TABLE. FRACTION OF POTENTIAL EVAPORATION= F(DIMENSIONLESS WATER CONTENT OF TOP SOIL COMPARTMENT) | |
| REDTTB | FUNCTION TABLE. REDUCTION FACTOR FOR ROOT GROWTH= F(SOIL TEMPERATURE) | |
| REFCF | REFLECTION COEFFICIENT OF WATER (PARAMETER) | |
| REFT | REFERENCE TEMPERATURE FOR CALCULATION OF MAINTENANCE RESPIRATION (PARAMETER) | |
| RFDVS | REDUCTION FACTOR FOR TRANSPIRATION DUE TO SENESCENCE | |
| RFDVST | FUNCTION TABLE | |
| RFRGT | REDUCTION FACTOR FOR ROOT GROWTH DUE TO TEMPERATURE | |
| RHOCP | VOLUMETRIC HEAT CAPACITY OF THE AIR (PARAMETER) | CAL/CM3/DEGREE C |
| RINTAK | RATE OF GRAZING INTAKE | KG DM/HA/DAY |
| RITDF | RATE OF INCREASE IN TRANSPIRATION DEFICIT | MM/DAY |
| RRAMAX | RATE OF RECOVERY OF LIGHT SATURATED LEVEL OF PHOTOSYNTHESIS LIGHT CURVE FOR INDIVIDUAL LEAVES | KG CO2/HA/HR/DAY |
| RREFFE | RATE OF RECOVERY OF INITIAL EFFICIENCY OF PHOTOSYNTHESIS LIGHT CURVE FOR INDIVIDUAL LEAVES | KG CO2/HA/HR/J/M2/S/DAY |
| RRNOFF | RATE OF RUN-OFF | MM/DAY |
| RS | MINIMUM STOMATAL RESISTANCE (PARAMETER) | DAY/CM |
| RTD | ROOTING DEPTH | MM |
| RTL | VERTICAL ROOTING LENGTH IN A COMPARTMENT | MM |
| RTRDEF | RELATIVE TRANSPIRATION DEFICIT | |
| RTWGHT | WEIGHT OF ROOTS | KG DM/HA |
| RWFB | MACRO DUMMY VARIABLE FOR RWFB1-10 | |
| RWFB1-10 | RATE OF WATER FLOW THROUGH BOTTOM OF PREVIOUS SOIL COMPARTMENT | MM/DAY |
| RWFT | MACRO DUMMY VARIABLE FOR RWFB1-9 | |
| RWRB1-10 | CUMULATIVE RELATIVE AMOUNT OF WATER AVAILABLE FOR THE ROOTS | |

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S

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| | | |
|---|---|---|
| S | INTERMEDIATE VARIABLE TO CALCULATE CC | |
| ~~S1~~ | ~~INTERMEDIATE VARIABLE TO CALCULATE "S" FOR CUTICLE~~ | |
| SLCVR | SOIL COVER USED IN CALCULATION OF LIGHT TRANSMISSION | M2/HA |
| SLLAE | SUNLIT LEAF AREA (AS PROPORTION OF TOTAL LEAF AREA) | |
| SLOPE | SLOPE OF SVP CURVE AT AIR TEMPERATURE | MBAR/DEGREE C |
| SSIN | PRODUCTS OF SINES OF LATITUDE AND DECLINATION OF SUN | |
| STDAY | DAY NUMBER OF START OF RUN AS DAYS FROM OCT 1 | |
| SUM10 | CUMULATIVE "VAR" * COMPARTMENT THICKNESS | |
| SUMB | MACRO DUMMY VARIABLE FOR SUM1-10 | |
| SUMT | MACRO DUMMY VARIABLE FOR SUM1-9 | |
| SVPA | AVERAGE SATURATED VAPOUR PRESSURE OF THE AIR | MM HG |
| SVPAM | SATURATED VAPOUR PRESSURE OF THE AIR | MBAR |
| SW | AMOUNT OF AVAILABLE WATER IN UPPER 10 CM OF SOIL | MM |
| SWP | SWITCH PARAMETER FOR ROOT GROWTH | |
| SWPB | MACRO DUMMY VARIABLE FOR SWPB1-10 | |
| SWPB1-10 | CUMULATIVE ROOT GROWTH SWITCH PARAMETER | |
| SWPT | MACRO DUMMY VARIABLE FOR SWPB1-9 | |

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T

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| | | |
|---|---|---|
| TADRW | TOTAL ABOVE GROUND BIOMASS | KG DM/HA |
| TCDPH | TIME CONSTANT FOR BUILD-UP OF CUMULATIVE TRANSPIRATION DEFICIT (PARAMETER) | DAY |
| TCDRL | TIME CONSTANT FOR DYING OF LEAF MATERIAL AS A RESULT OF WATER SHORTAGE (PARAMETER) | DAY |

| | | |
|---|---|---|
| TCDRNL | TIME CONSTANT FOR DYING OF NON-LEAF MATERIAL AS A RESULT OF WATER SHORTAGE (PARAMETER) | DAY |
| TCK1-11 | THICKNESS OF CONSECUTIVE COMPARTMENTS | MM |
| TCREC | TIME CONSTANT FOR RECOVERY OF AMAX AND EFFE | DAY |
| TCRPH | TIME CONSTANT FOR DECLINE IN CUMULATIVE TRANSPIRATION DEFICIT (PARAMETER) | DAY |
| TDB | MACRO DUMMY VARIABLE FOR TDB1-10 | |
| TDB1-10 | TOTAL DEPTH TO THE BOTTOM OF A SOIL COMPARTMENT | MM |
| TDRAIN | WATER LOST BY DEEP DRAINAGE BELOW DEPTH OF 180 CM | MM |
| TDRWT | TOTAL BIOMASS | KG DM/HA |
| TDT | MACRO DUMMY VARIABLE FOR TDB1-9 | |
| TEC | ROOT CONDUCTIVITY REDUCTION FACTOR DUE TO TEMPERATURE | |
| TECT | FUNCTION TABLE. ROOT CONDUCTIVITY=F(SOIL TEMP) | |
| TEFR | TEMPERATURE EFFECT ON MAINTENENCE RESPIRATION | |
| TEVAP | CUMULATIVE SOIL EVAPORATIVE LOSS OVER SEASON | MM |
| TGRWTH | ACTUAL RATE OF DRY MATTER PRODUCTION | KG DM/HA/DAY |
| THCKN | MACRO DUMMY VARIABLE FOR TCK1-10 | |
| TINTAK | TOTAL RATE OF INTAKE BY GRAZING ANIMALS | KG DM/HA/DAY |
| TMPA | AVERAGE DAILY AIR TEMPERATURE | DEGREE C |
| TMPSMI | INITIAL VALUE OF THE TEMPERATURE SUM EXPERIENCED BY THE VEGETATION | DEGREE C*DAYS |
| TMPSUM | TEMPERATURE SUM FROM THE ONSET OF GERMINATION | DEGREE C*DAYS |
| TOTINF | CUMULATIVE SOIL WATER INFILTRATION | MM |
| TOTRAN | CUMULATIVE TRANSPIRATION OVER GROWING SEASON | MM |
| TPEVAP | CUMULATIVE POTENTIAL SOIL EVAPORATIVE LOSS (PENMAN) OVER GROWING SEASON | MM |
| TPPR | TOTAL PRIMARY PRODUCTION | KG DM/HA |
| TRAIN | CUMULATIVE SEASONAL RAINFALL | MM |
| TRAN | ACTUAL RATE OF TRANSPIRATION | MM/DAY |
| TRANDF | DIFFERENCE BETWEEN POTENTIAL CUTICULAR TRANSPIRATION AND ACTUAL SOIL WATER UPTAKE | MM |
| TRB | MACRO DUMMY VARIABLE FOR TRB1-10 | |
| TRB1-10 | TRANSPIRATION LOSS SUMMED OVER COMPARTMENTS | MM |
| ~~TRPMM~~ | ~~POTENTIAL TRANSPIRATION RATE PER MM ROOT LENGTH~~ IN WET SOIL | MM/DAY |
| TRR | TRANSPIRATION RATE FROM A SINGLE SOIL COMPARTMENT | MM/DAY |
| TRT | MACRO DUMMY VARIABLE FOR TRB1-9 | |
| TS | AVERAGE SOIL TEMPERATURE (=10 DAY RUNNING AVERAGE OF AIR TEMPERATURE) | DEGREE C |
| TSI | INITIAL VALUE OF SOIL TEMPERATURE | DEGREE C |
| TSUMG | TEMPERATURE SUM REQUIRED FOR GERMINATION (PARAMETER) | DEGREE C*DAYS |
| TT | INTERMEDIATE VARIABLE | |
| TTE | INTERMEDIATE VARIABLE | |
| TVEGM | TOTAL VEGETATIVE BIOMASS (LEAF + NON-LEAF MATERIAL) | KG DM/HA |

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U

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V

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| | | |
|---|---|---|
| VAR | SOIL MOISTURE REDISTRIBUTION FACTOR INTERMEDIARY VARIABLE | |
| VPA | AVERAGE VAPOUR PRESSURE OF THE AIR | MM HG |
| VPAM | ACTUAL VAPOUR PRESSURE OF THE AIR | MBAR |

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W

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| | | |
|---|---|---|
| W1-10 | AMOUNT OF WATER IN A SOIL COMPARTMENT | MM |
| WATER | MACRO DUMMY VARIABLE FOR W1-10 | |
| WCLIM | AIR DRY WATER CONTENT OF A SOIL COMPARTMENT | CM3/CM3 |
| WCPR | DIMENSIONLESS WATER CONTENT OF THE TOP SOIL COMPARTMENT | |
| WLTPT | WILTING POINT (PARAMETER) | CM3/CM3 |
| WLVS | LEAF BIOMASS | KG DM/HA |
| WLVSI | INITIAL LEAF BIOMASS | KG DM/HA |
| WNLVS | NON-LEAF BIOMASS | KG DM/HA |
| WNLVSI | INITIAL NON-LEAF BIOMASS | KG DM/HA |
| WRED | REDUCTION FACTOR FOR ROOT WATER UPTAKE | |

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          DUE TO LOW SOIL MOISTURE CONTENT
WREDT     FUNCTION TABLE. REDUCTION IN ROOT WATER UPTAKE=
          F(SOIL MOISTURE CONTENT)
WSA       AVERAGE DAYTIME WINDSPEED                        CM/DAY
WSDS      SEED BIOMASS                                     KG DM/HA
WSM       DAILY WINDRUN                                    MILES
WSR       MEASURED DAILY WINDRUN                           KM
WSTB      FUNCTION TABLE
WTOT      TOTAL AMOUNT OF WATER IN THE SOIL PROFILE        MM
WUSEFF    WATER USE EFFICIENCY OF THE VEGETATION           KG DM/MM H2O
***************************************************************************************
                                    X
***************************************************************************************
X         INTERMEDIATE VARIABLE
***************************************************************************************
***************************************************************************************
                                    Y
***************************************************************************************
***************************************************************************************
                                    Z
***************************************************************************************
***************************************************************************************
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## Appendix 3

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                     ARIDCROP  PARAMETER LIST
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*****************************************************************************
        THIS IS AN ALPHABETICALLY ORDERED LIST OF
        PARAMETERS OF THE MODEL ARID CROP
=============================================================================
PARAMETER          VALUE          DEFINITION                      UNITS
=============================================================================
*****************************************************************************
AMAXB               40.     POTENTIAL LIGHT SATURATED LEVEL OF
                            GROSS CO2 ASSIMILATION           KGCO2/HA LEAF/HR
CONFS                0.70   CONVERSION EFFICIENCY OF PRIMARY
                            PHOTOSYNTHATES INTO
                            STRUCTURAL PLANT MATERIAL        KG DM/KG CH2O
DGRRT               12.     DAILY EXTENSION RATE OF THE ROOTS
                            UNDER OPTIMAL CONDITIONS          MM/DAY
DVSSF                0.65   DEVELOPMENT STAGE AT WHICH SEED FILL STARTS
EFFEB                0.5    POTENTIAL INITIAL                 KG CO2/HA/HR
                            LIGHT USE EFFICIENCY              PER J/M2/S
FDAYY                       FIRST DAY OF SIMULATION IN DAYS FROM 1 JAN
FLDCP                0.23   FIELD CAPACITY                    CM3/CM3
FTRS                 0.3    FRACTION OF PHOTOSYNTHATE TRANSLOCATED
                            TO SEEDS ONCE SEED-FILL DVS IS REACHED
FWDB                 0.1    FRACTION OF WATER IN DEAD BIOMASS
GAMMA                0.49   PSYCHROMETER CONSTANT             MM HG/DEGREE C
IBIOM                       INITIAL BIOMASS                   KG DM/HA
IRTD               101.     INITIAL ROOTING DEPTH             MM
LAT                         LATITUDE OF LOCATION              DEGREES
LFARR               20.     LEAF AREA PER UNIT LEAF WEIGHT    M2/KG
LHVAP               59.     HEAT OF VAPORISATION OF WATER     CAL/10**-4 KG
MRESF                0.15   MAINTENANCE RESPIRATION FACTOR    KG CH2O/KGDM/DAY
MXRTD             1800.     MAXIMUM ROOTING DEPTH             MM
PI                  3.1416
PROP                15.     PROPORTIONALITY FACTOR FOR PARTITIONING
                            OF SOIL EVAPORATION OVER VARIOUS COMPARTMENTS
PSCH                 0.67   PSYCHROMETRIC CONSTANT            MBAR/DEGREE C
RC                  37.E-5  CUTICULAR RESISTANCE              DAY/CM
REFCF                0.05   REFLECTION COEFFICIENT OF WATER
REFT                25.     REFERENCE TEMPERATURE FOR CALCULATION OF
                            MAINTENANCE RESPIRATION
RHOCP                2.86E-4VOLUMETRIC HEAT CAPACITY OF AIR  CAL/CM3/DEGREE C
RS                  18.5E-6 STOMATAL RESISTANCE               DAY/CM
STDAY                       DAY NUMBER OF START OF RUN AS DAYS FROM OCT 1
TCDPH               10.     TIME CONSTANT FOR BUILD-UP OF
                            CUMULATIVE TRANSPIRATION DEFICIT DAY
TCDRL                5.     TIME CONSTANT FOR DYING OF LEAF
                            MATERIAL DUE TO WATER SHORTAGE   DAY
TCDRNL               5.     TIME CONSTANT FOR DYING OF
                            NON-LEAF MATERIAL DUE TO WATER
                            SHORTAGE                         DAY
TCREC                5.     TIME CONSTANT FOR RECOVERY OF
                            AMAX AND EFFE                    DAY
TCRPH               10.     TIME CONSTANT FOR DECLINE IN
                            CUMULATIVE TRANSPIRATION DEFICIT DAY
TSUMG              150.     TEMPERATURE SUM REQUIRED
                            FOR GERMINATION                  DEGREE C*DAYS
WLTPT                0.075  WILTING POINT                    CM3/CM3
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## Appendix 4

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              THIS IS A LIST OF ALL FUNCTIONS, CONTAINED IN
              THE MODEL ARID CROP, EXCEPT FOR THE TABLES
              DEFINING WEATHER CONDITIONS
*********************************************************************************
1.  FUNCTION ALPHAT
        REDUCTION FACTOR FOR DRYING POWER TERM IN TRANSPIRATION
        CALCULATION, FUNCTION OF LEAF AREA INDEX AND HOURLY RADIATION
        INTENSITY
    HRAD         0.  10.  15.  20.  25.  30.  35.  40.  45.  50.  60.  100.
          LAI/ALPHA
          0.2  1.0                                                     1.0
          2.0  0.0  .600 .660 .715 .760 .795 .835 .870 .910 .940 1.00 1.00
          3.5  0.0  .425 .515 .585 .640 .680 .715 .745 .770 .795 .845 1.00
          5.0  0.0  .390 .455 .505 .545 .580 .610 .635 .660 .685 .740 .775
         10.0  0.0  .350 .410 .450 .485 .510 .530 .550 .565 .585 .610 .650

2.  FUNCTION CSRRT
        PARTITIONING OF ASSIMILATE BETWEEN SHOOT AND ROOT
        CURRENT FRACTION TO SHOOT AS A FUNCTION OF DEVELOPMENT STAGE
    DVS   0.    0.10  0.25  0.50  0.75  1.00  1.10
    CSRR  0.30  0.40  0.50  0.65  0.75  1.00  1.00

3.  FUNCTION DISTFT
        PARTITIONING OF ASSIMILATE BETWEEN LEAF BLADES AND STEM/SHEATHS
        CURRENT FRACTION TO LEAF BLADES AS FUNCTION OF DEVELOPMENT STAGE
    DVS   0.    0.50  0.70  0.90  1.10
    DISTF 0.90  0.80  0.60  0.00  0.00

4.  FUNCTION DVRT
        DEVELOPMENT RATE OF THE VEGETATION AS A FUNCTION OF AIR TEMPERATURE
    TMPA  0.    3.75  16.0   25.0   40.0
    DVR   0.    0.0    0.01   0.0175 0.02

5.  FUNCTION EDPTFT
        RELATIVE EFFECTIVINESS OF THE ROOTS AS A FUNCTION OF THE
        FRACTION AVAILABLE WATER PER COMPARTMENT
    FAWAT 0.    0.15  0.30  0.50  1.10
    EDPTF 0.15  0.60  0.80  1.00  1.00

6.  FUNCTION FAMSTT
        SHIFT IN CURRENT SHOOT TO ROOT RATIO AS A FUNCTION OF RELATIVE
        TRANSPIRATION DEFICIT
    RTRDEF  0.    0.40  0.75  1.00  1.10
    FAMST   1.00  1.00  0.60  0.50  0.50

7.  FUNCTION FDMT
        FRACTION DRY MATTER IN LIVE BIOMASS AS A FUNCTION OF
        DEVELOPMENT STAGE OF THE VEGETATION
    DVS     0.    1.00  1.10
    FDM     0.10  0.25  0.25

8.  FUNCTION ELTRT
        FRACTION OF ENERGY REACHING THE SOIL SURFACE AS A FUNCTION
        OF TOTAL FOLIAGE AREA INDEX
    SLCVR  0.    0.50  1.00  1.50  2.00  3.00  5.00  8.00   10.00  15.00
    FRLT   1.00  0.705 0.496 0.384 0.248 0.134 0.03  0.004  0.001  0.0001

9.  FUNCTION RADTB
        DAILY TOTAL VISIBLE RADIATION ON COMPLETELY CLEAR DAYS AS A FUNCTION
        OF LATITUDE AND DAY OF THE YEAR, EXAMPLE GIVEN HERE REFERS ONLY TO
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     LATITUDE OF 30 DEGREES N.L.
 DAYY     0.  15.  46.  74. 105. 135. 166. 196. 227. 258. 288. 319. 349. 365.
 DTVRAD 185. 191. 245. 303. 363. 400. 417. 411. 384. 333. 270. 210. 179. 183.

10. FUNCTION RDRAT
     RELATIVE RATE OF DECLINE IN PHOTOSYNTHETIC CAPACITY AS A FUNCTION
     OF CUMULATIVE RELATIVE TRANSPIRATION DEFICIT
 CTRDEF 0.     0.50  1.00  1.10
 RDRA   0.     0.    0.05  0.05

11. FUNCTION RDRDT
     RELATIVE DEATH RATE OF THE VEGETATION DUE TO SENESCENCE AS A FUNCTION
     OF DEVELOPMENT STAGE OF THE VEGETATION
 DVS    0.     0.70  0.71  0.90  1.00  1.10
 RDRD   0.     0.    0.005 0.005 0.10  0.10

12. FUNCTION REDFDT
     FRACTION OF POTENTIAL SOIL EVAPORATION REALIZED AS A FUNCTION
     OF DIMENSIONLESS WATER CONTENT OF TOP SOIL COMPARTMENT
 WCPR    -0.10  0.     0.05  0.10  0.20  0.30  0.40  0.75  1.00  1.10
 REDFD    0.05  0.075  0.10  0.20  0.375 0.50  0.725 0.90  1.00  1.00

13. FUNCTION REDTTB
     REDUCTION FACTOR FOR ROOT GROWTH AS A FUNCTION OF SOIL TEMPERATURE
 TS       5.     10.    15.    20.    25.    30.    50.
 RFRGT   0.80   0.90   1.00   0.97   0.97   0.97   0.97

14. FUNCTION RFDVST
     REDUCTION FACTOR FOR POTENTIAL TRANSPIRATION AS A FUNCTION
     OF DEVELOPMENT STAGE OF THE VEGETATION
 DVS     0.     0.90  1.00  1.10
 RFDVS   1.00   1.00  0.00  0.00

15. FUNCTION TECT
     REDUCTION FACTOR FOR ROOT CONDUCTIVITY AS A
     FUNCTION OF SOIL TEMPERATURE
 TS      0.     3.    10.    16.    20.    31.    40.    50.
 TEC     0.06   0.29   0.85   0.94   1.00   0.87   0.60   0.30

16. FUNCTION WREDT
     REDUCTION FACTOR FOR ROOT WATER UPTAKE AS A FUNCTION OF
     FRACTION AVAILABLE WATER IN A COMPARTMENT
 FAWAT   0.     0.10  0.15  0.30  0.50  0.75  1.10
 WRED    0.     0.30  0.45  0.70  0.975 1.00  1.00
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