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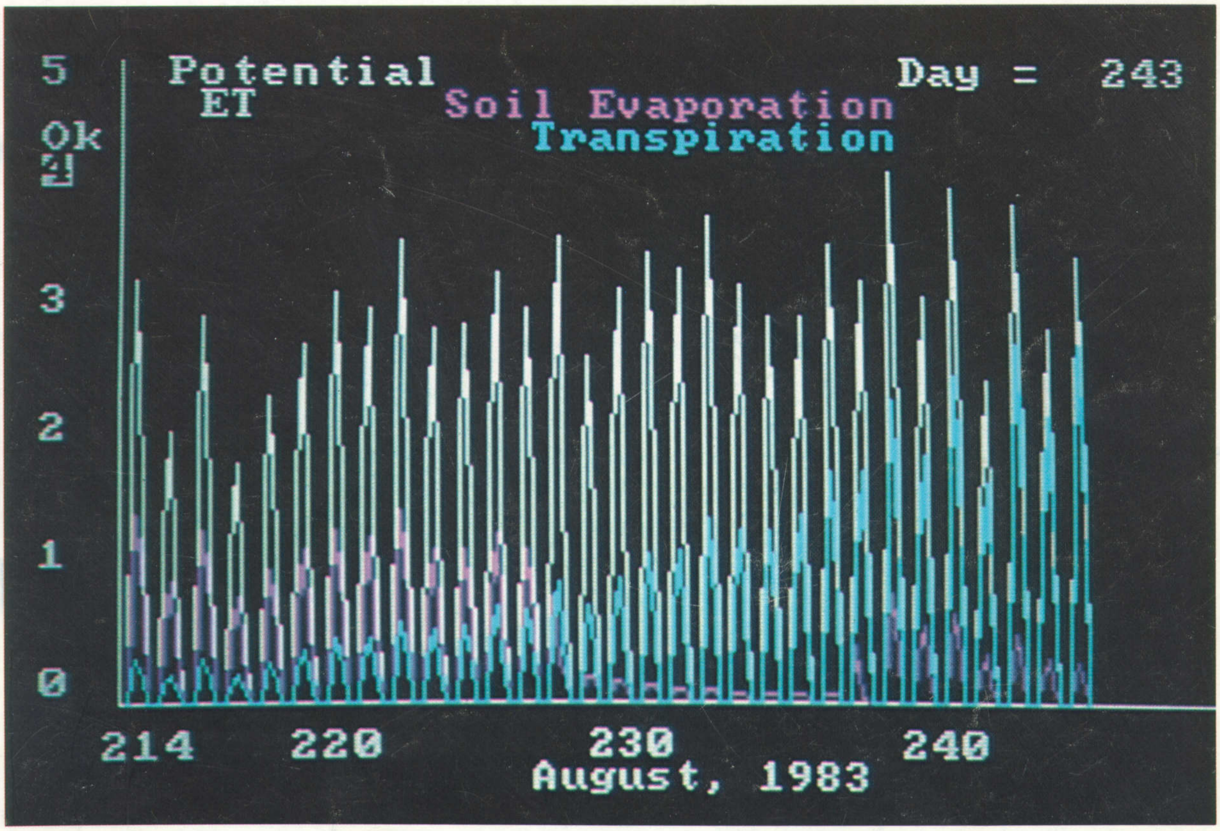
A dynamic simulation of root growth, water uptake, and biomass partitioning in a soil-plant-atmosphere continuum: update and documentation



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INTERPRETIVE SUMMARY

ROOTSIMU is a computer simulation model which describes the complex of interactions between the shoot and root systems of a crop growing vegetatively in a soil-plant-atmosphere continuum. The model contains both a carbon-balance algorithm to account for many fundamental plant processes and a water-balance algorithm to account for water movement through both the plant and bulk soil. Maintenance of a functional balance between shoot and root size is facilitated by partitioning growth between new root and shoot tissue according to plant water potential. Readers are referred to Huck and Hillel (*21*) for additional, detailed discussions of the model logic. The model was originally developed on a mainframe computer, but versions are now available for mini- and micro-computers.

ROOTSIMU V4.0

A Dynamic Simulation of Root Growth, Water Uptake, and Biomass Partitioning in a Soil-Plant-Atmosphere Continuum: Update and Documentation[1]

GERRIT HOOGENBOOM and M.G. HUCK[2,3]

INTRODUCTION

AN EARLY VERSION of the model ROOTSIMU (version 1.5) has been described by Huck and Hillel (*21*). They explained their underlying assumptions and presented examples based on the use of a sine-function as the driver for the calculation of air and soil temperature and radiation intercepted by the canopy. The original version of the model permitted testing the plausibility of assumptions, but its predictions could not be tested against measured data because no provision for input of climatic data was included in the code. ROOTSIMU version 1.5 of the model was developed in Continuous System Modeling Program, an IBM computer simulation language referred to as CSMP3 (*24,36*). CSMP contains integration and plotting subroutines and several other special functions and, therefore, it facilitates easy modifications and expansions of the source code.

A modification of the model is presented which permits the use of measured climatic data as driving functions. Arbitrary functions are generated by interpolation between known data points as described earlier (*21*). This new revision of the model (ROOTSIMU version 4.0) permits a comparison of predictions from the computer run under simulated conditions with experimentally determined data. The discrete daily input data, which are used to simulate the continuous weather conditions, are almost identical with those observed in actual experiments from which measurement data were obtained. However, the daily summation of each input variable is now adjusted to match observed values. Sections of the model which calculate photosynthesis and shoot and root growth also were revised.

The primary purpose of this publication is to incorporate the real weather capability into the model ROOTSIMU and to describe further modifications in other sections of the model. It includes a listing of the model ROOTSIMU version 4.0 in CSMP and FORTRAN and instructions to run the model on either a mainframe, mini-, or micro-computer.

Examples comparing predicted soybean root growth and water movement with actual experimental data from the 1981 growing season will be published by Hoogenboom et al. (*17*). Presented herein are some examples of soybean plant growth data predicted by the simulation model for the 1983 growing season. Soybean (*Glycine max* [L.] Merr.) shoot and root growth as measured under experimental conditions during the 1983 growing season will be published elsewhere (*18,23*). In the following examples, data recorded by a standard Class "A" weather station during the summer of 1983 (*1*) and summarized on a daily basis were used as a driver for the climate sections of the model.

MODEL DESCRIPTION

The quantitative model ROOTSIMU, Appendix A-C, is a set of equations which describes the complex of interactions between the shoot and root systems of a crop growing vegetatively in a one dimensional soil profile, arbitrarily divided

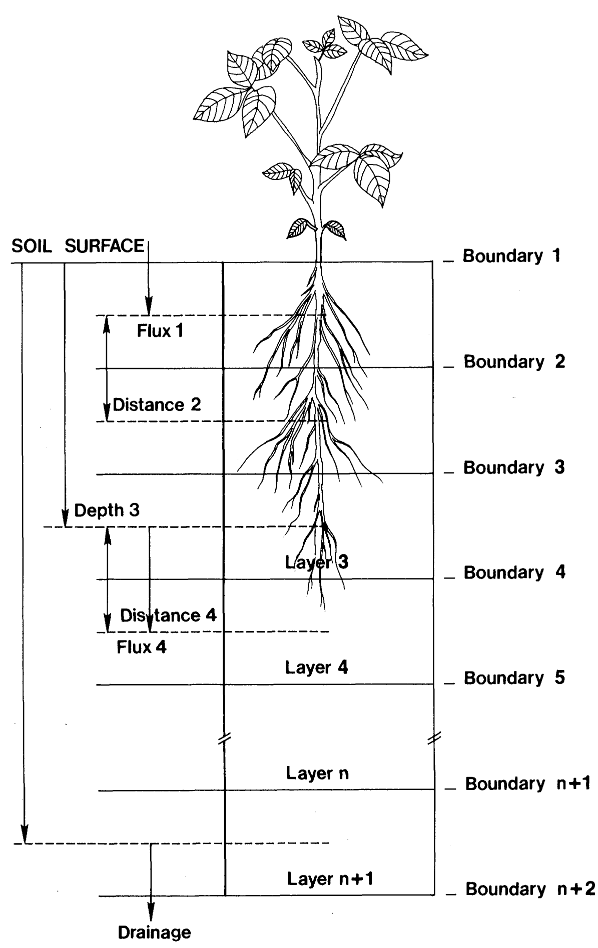

FIG. 1. Hypothetical soybean plant growing in a one-dimensional layered soil consisting of uniform layers in the horizontal direction.

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[3]Mention of a trade name is solely for the convenience of the reader and does not imply endorsement of that product to the exclusion of others by the U.S. Department of Agriculture or by Auburn University or its employees.

into discrete layers, figure 1 (*20*). The model contains both carbon-balance and water-balance algorithms to describe such fundamental processes as photosynthesis, respiration, vegetative growth of shoot and root tissues (computed independently), transpiration and soil water uptake by roots, and water movement through bulk soil including effects of irrigation, rainfall, and drainage.

The carbon-balance section computes a photosynthetic rate per unit leaf area from regression-based temperature and photosynthetic active radiation (PAR) functions. Self-shading, when the leaf area index (LAI) is greater than 1, and stomatal closure, induced by low plant water potentials (ψ_{plant}), reduce photosynthesis. Soluble carbohydrates derived from photosynthesis accumulate in a labile pool accessible to each organ. The soluble carbohydrates are withdrawn from this pool and are used in growth and respiratory processes at independently computed rates for each process. Maintenance respiration depends only on temperature and tissue mass, but growth respiration also depends upon the size of the reserve-carbohydrate pool, figure 2. Shoot tissue necrosis is a function of leaf age and LAI, because at an LAI greater than 1 the lower leaves on the canopy are shaded by the upper leaves. Root death rate is a function of root age and carbohydrate reserve level. Maintenance of a functional balance between shoot and root size is facilitated by partitioning growth between new root and shoot tissue according to ψ_{plant} (computed from tissue relative water content). As ψ_{plant} plant declines with depletion of stored soil water reserves, root growth increases and shoot growth declines. Roots grow more rapidly in wetter parts of the soil profile than in the drier parts of the soil profile, so younger roots with higher tissue conductivity form in wet soil, while older, non-functioning roots die in dry soil.

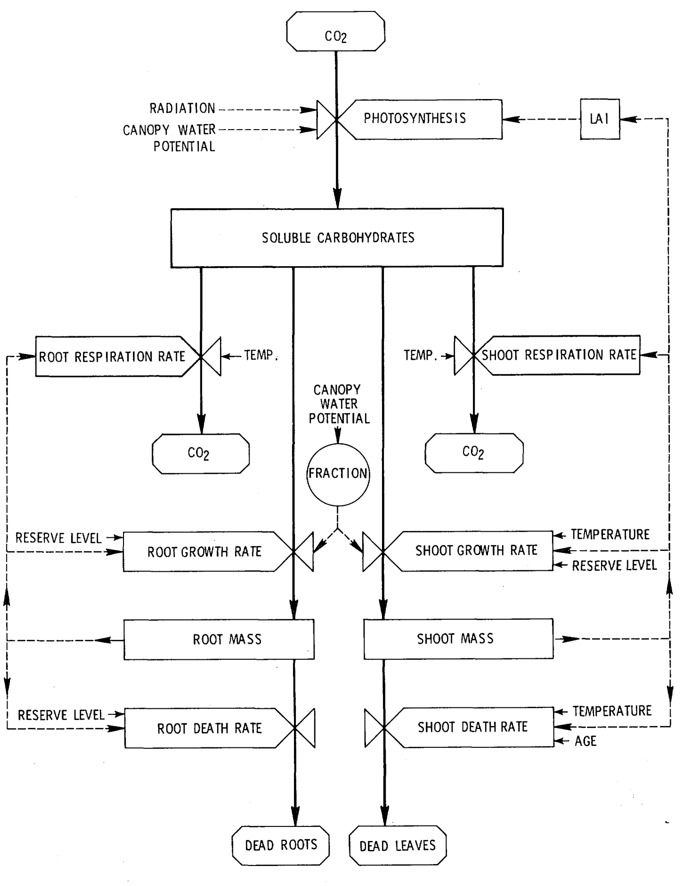

FIG. 2. Forrester flow diagram for carbon balance algorithm.

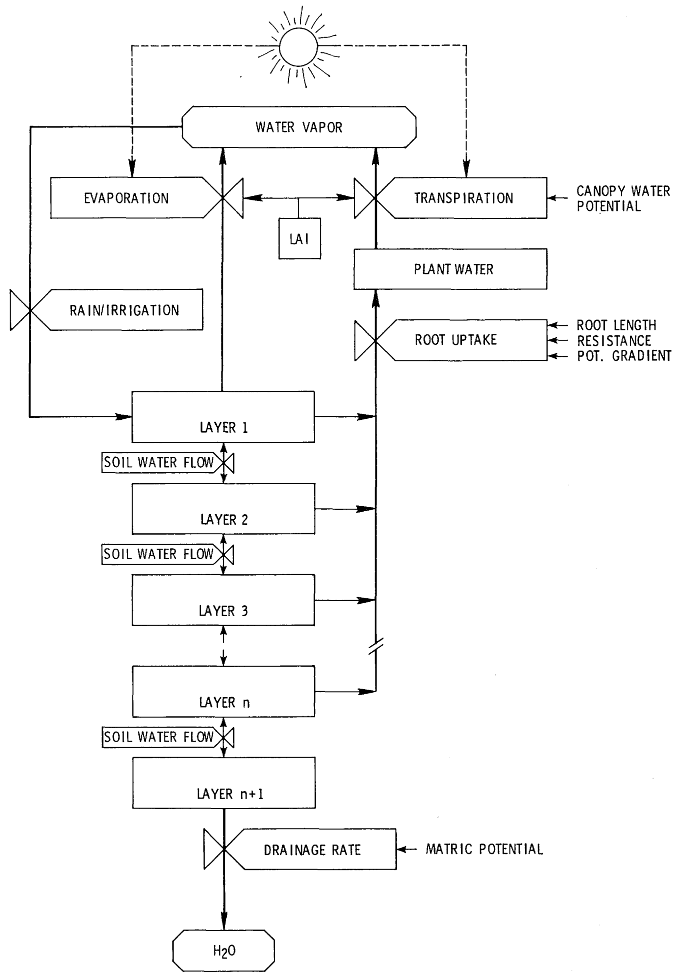

FIG. 3. Forrester flow diagram for water balance algorithm.

The water-balance section computes evaporative demand from incoming solar radiation and partitions water loss between transpiration and soil surface evaporation, according to LAI (soil shading) and hydraulic conductivity of the soil surface layer (a function of its water content). Internal water redistribution and sub-surface drainage are computed from ψ gradients in bulk soil, while soil water uptake by roots is a catenary function of ψ differences between leaves, root surface, and the water held in each soil layer, figure 3. A more detailed description of the basic logic of the carbon-balance and water-balance section of the model is given by Huck and Hillel (*21*).

MODEL MODIFICATIONS

The descriptions and code of the aboveground (shoot) portions of the model have been extensively revised to include recorded weather data for driving the model. Modules were taken from the published work of de Wit et al. (*40*) and Goudriaan and van Laar (*11*) and revised to fit this model, Appendix A. The automatic sort algorithm, which is a feature of CSMP, facilitated revisions to the CSMP simulation language source code (*41*). The UPDATE subroutine generated by the

CSMP translator was kept, modified, and stored as FORTRAN code.

This version of the model will run on a wide variety of mainframe, mini-, and micro-computers as an independent FORTRAN language program, Appendix B. Machine-readable copies of either source code are available from the authors on a 5.25-inch diskette or by direct transmission electronic mail. An earlier version of the model (ROOTSIMU version 1.5) is available in Advanced Continuous Simulation Language identified as ACSL, Mitchell and Gauthier Assoc. (*28*), Appendix C. Basically, the simulation languages ACSL and CSMP are similar. However, in contrast to the simulation language CSMP which can only run on an IBM mainframe computer, the simulation language ACSL is available on a broader range of computers, including micro-computers.[4]

Weather Data

In many applications when soil water relations and associated crop performance are simulated, the only long-term weather data available are those collected by a conventional meteorological observation station. Therefore, this model was written to include sections for interpolating between the discrete points (usually recorded at daily intervals) obtained from standard weather observations. The CSMP interpolation functions AFGEN and NLFGEN were used to generate continuous data between measured data points. A macro (macro is the equivalent of a subroutine) named WAVE, proposed by de Wit et al. (*40*), has been incorporated into the CSMP version of our model, Appendix A. This produces a continuous sine curve connecting maximum and minimum temperature values. Floyd and Braddock (*8*) reported that use of sine curve fitting can be an accurate way to model diurnal temperature curves. The FORTRAN version of the model, Appendix B, includes a homologous subroutine named WAVE which produces continuous-function output of the form required by the defining equations used in the model.

Interpolation schemes for solar radiation, rainfall (and/or irrigation events), open-pan evaporation, and air and soil temperature are included in the versions of the model illustrated here. Rainfall was assumed to infiltrate the surface at a constant rate over the full 24-hour day when it was recorded. The instantaneous potential evapotranspiration (ET) rate was interpolated from daily total pan evaporation measurements and proportioned according to the instantaneous radiation. Shaw and Laing (*34*) reported that, at full canopy, the evapotranspiration rate of soybeans is 90 percent of open-pan evaporation. Similar observations were reported by Hanks (*13*) and Mason et al. (*27*). Alternative methods for computing ET rate, such as the energy-balance method of Penman (*30*), can be substituted by the user if adequate measurement data to support the desired computation method are available.

Length of the daily light period (LSNHS), height of the sun (SNHSS), and the time of sunrise (RISE) are computed each day from geometrical calculations based on latitude (LAT) and season (declination of the sun [DEC]). Daily totals for maximum and minimum solar radiation, for a completely clear day (DRC, DRCP) or for a completely overcast day (DRO, DROP), respectively, are estimated as a function of sun height, based on the assumptions of de Wit et al. (*40*). These computed daily solar radiation totals are then compared with the measured solar radiation (DTRR, DTR) observed for that day, and the ratios between measured radiation and that expected for a clear day or for an overcast day are computed (LFCL, LFOV). Finally, an instantaneous rate for solar radiation (RADIAT) is computed along a half-sine curve using the proportions of diffuse and clear-sky radiation computed earlier. The net effect of these computations defines a continuous function, figure 4, which resembles figure 3 of Huck and Hillel (*21*) except that each day's total radiation is now adjusted to match that observed by the meteorological instrumentation.

Linear interpolation between successive daily minimum and maximum air temperatures (MINTMP, MAXTMP) provides a variable-width band, figure 5, within which WAVE generates a sinusoidal air temperature function with periodicity determined by the length of the daily light period. The same WAVE function is used to generate instantaneous soil temperatures between successive daily minimum and maximum soil temperatures (MNSTMP, MXSTMP). It is assumed that the daily minimum and maximum soil temperatures occur with a delay of 3 hours, compared to the minimum and

[4]A new version of CSMP called PCSMP has become available for application on micro-computers.

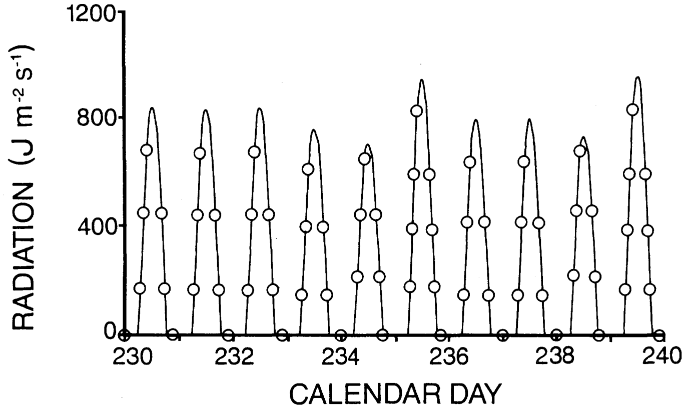

FIG. 4. Simulated rate of instantaneous global radiation from day 230 to day 240, computed by WAVE algorithm.

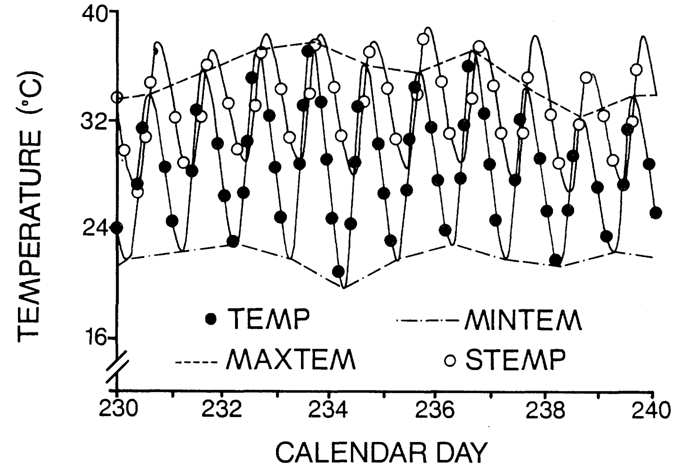

FIG. 5. Simulated air (TEMP) and soil temperatures (STEMP) during days 230 to 240. Both temperatures are calculated by forcing a sine function through the daily maximum air (MAXTEM) and soil temperatures and daily minimum air (MINTEM) and soil temperatures.

maximum air temperatures, and that the same soil temperature is observed throughout the whole soil profile.

Carbon Balance

One of the principal changes from version 1.5 of the model is the inclusion of a section for predicting photosynthesis and plant growth patterned after the BACROS model of de Wit et al. (*40*) and presented in simplified form by Goudriaan and van Laar (*11*). The model ROOTSIMU computes two photosynthetic rates: PHOTC, the maximum canopy photosynthetic rate under a completely clear sky, and PHOTD, the maximum possible photosynthetic rate under a completely overcast sky. Adjustments for shading within the canopy (based upon LAI) are made according to the method described by Goudriaan and van Laar (*11*). Based on data reported by Shibles and Weber (*35*), it is assumed that 100 percent of the incoming radiation is intercepted by the soybean canopy if the LAI is larger than three. Respiration, assimilation, and growth are treated as in the earlier version 1.5 of this model.

Version 1.5 of this model (*21*) considered partitioning of carbohydrates only between the root system (ROOTW) and a shoot system (SHOOTW) consisting of a single compartment. The shoot system compartment has been expanded to include separate compartments for leaf (LEAFW) and for stem tissue (STEMW), which permits a more accurate representation of canopy architecture, figure 1. It is assumed that stems only respire and that their photosynthetic capacity is small compared with the leaves, because of the relatively small surface area of the stems. It is assumed that the leaves, on the other hand, carry on both photosynthesis and respiration. Although it is known that the specific leaf area of soybean leaves varies with time and position (*25*), a constant specific leaf area is assumed in this model (*12,33*).

Additional constraints have been imposed on root growth in the model. For instance, a maximum root density is imposed: the total volume of roots in any soil compartment can never exceed a set fraction of the total pore-space. This allows for incorporation of a plow layer and other factors which increase soil strength and cause a reduction in root growth (*10*). Taylor and Klepper (*37*) reported that the rooting volume depends on both species and environment. The volume of roots (ROOTVL) is computed from root mass (ROOTWT), diameter (LNGFAC), and density (PRTL). Soil porosity (POROS) also is computed for each layer, based on bulk density (BULKDS), which is a function of depth (DEPTH) and particle density (PARTDS).

It is further assumed that the propensity for new root growth (BIRTH) and extension of existing roots (EXTENS) is inversely proportional to depth, which takes into account the longitudinal resistance to carbohydrate and water transport in the phloem tissue. Vertical extension of roots into a new layer can only occur when root length in the other layer exceeds a minimum threshold, MINRTL. No root growth is permitted in the lowest soil layer, which is assumed to represent a buffer between the water table and the soil layers in which the roots are growing actively, figure 1. Because simulated root growth is highly responsive to soil moisture conditions, a soil layer which is saturated with water might show an excessive amount of root growth, compared with the other drier soil layers. In the previous version (1.5) of the model, an unreasonably large mass of root tissue was predicted in the undrained bottom layer.

Water Balance

Validation data were obtained from the experiments of Huck et al. (*22,23*) in which soybean shoot and root growth was measured in the Auburn rhizotron under two different water regimes. The nonirrigated treatment (NI) was simulated by adding only the observed rainfall (RAIN) to the surface soil layer. In addition to observed rainfall, 250 cm^3 m^{-3} of irrigation water (IRQUAN) was automatically (PULSSW) added to the simulated irrigated treatment (IR) every 30 minutes (PULSIR) whenever the computed soil water potential (ψ_{soil}) at a depth of 0.4 m dropped below -15 kPa (IRMIN). In the rhizotron experiments, the trickle irrigation system was switched on for 3 to 5 minutes at hourly intervals whenever the tensiometer readings at a depth of 0.4 m fell below -10 to -15 kpa (*23*). An example of the ψ_{soil} measured by tensiometers at a depth of 0.4 m during the 1983 growing season is presented in figure 6.

The Darcian flow equations used to compute unsaturated water flow (NFLW) between layers has been retained in this version of the model, but infiltration is based on the assumptions of Green and Ampt (*12*). Water flows from the surface into deeper layers at a rate controlled by saturated conductivity (SATCON), but only when the matric potential of the conducting layer is near 0. Since each increment of added water begins percolation in the surface layer, the FLPFLP (flip-flop) function used in version 1.5 of the model (*12*) was eliminated. Each iterative calculation to balance water uptake by the roots, water flow in the soil and the plant, and transpiration now begins at the surface. When soil water content of any layer reaches saturation, flow through that layer is assumed to occur at the maximum (saturated conductivity) rate. Water is allowed to drain from the bottom layer to prevent accumulation in the soil profile (DRAING).

Relative conductivity was redefined as proposed by van Genuchten (*38*), and calculated as a function of soil matric potential. The constants 'a' (ALPHA) and 'n' (NU) were determined by nonlinear least-square analysis fit of the soil water-retention data (*38*). Possible vapor phase transport and the effects of entrapped air were ignored.

MODEL INITIATION

Weather Data

Weather data used as drivers for the model included: daily total solar radiation (RADN; Watt hours day^{-1} or Joule day^{-1}); daily minimum and maximum air temperatures (MINTEM, MAXTEM; degree Celsius or Fahrenheit); daily minimum and maximum soil temperatures (MINSTM, MAXSTM; degree Celsius or Fahrenheit); daily rainfall (CMRAIN; cm day^{-1} or inches day^{-1}) and daily open pan evaporation (PEVAP cm day^{-1} or inches day^{-1}). Because the units in which weather data are recorded vary from weather station to weather station, the numbers must be converted into SI units for the model to function. Weather generators can be used if one or more input variables are missing. For instance, when no soil

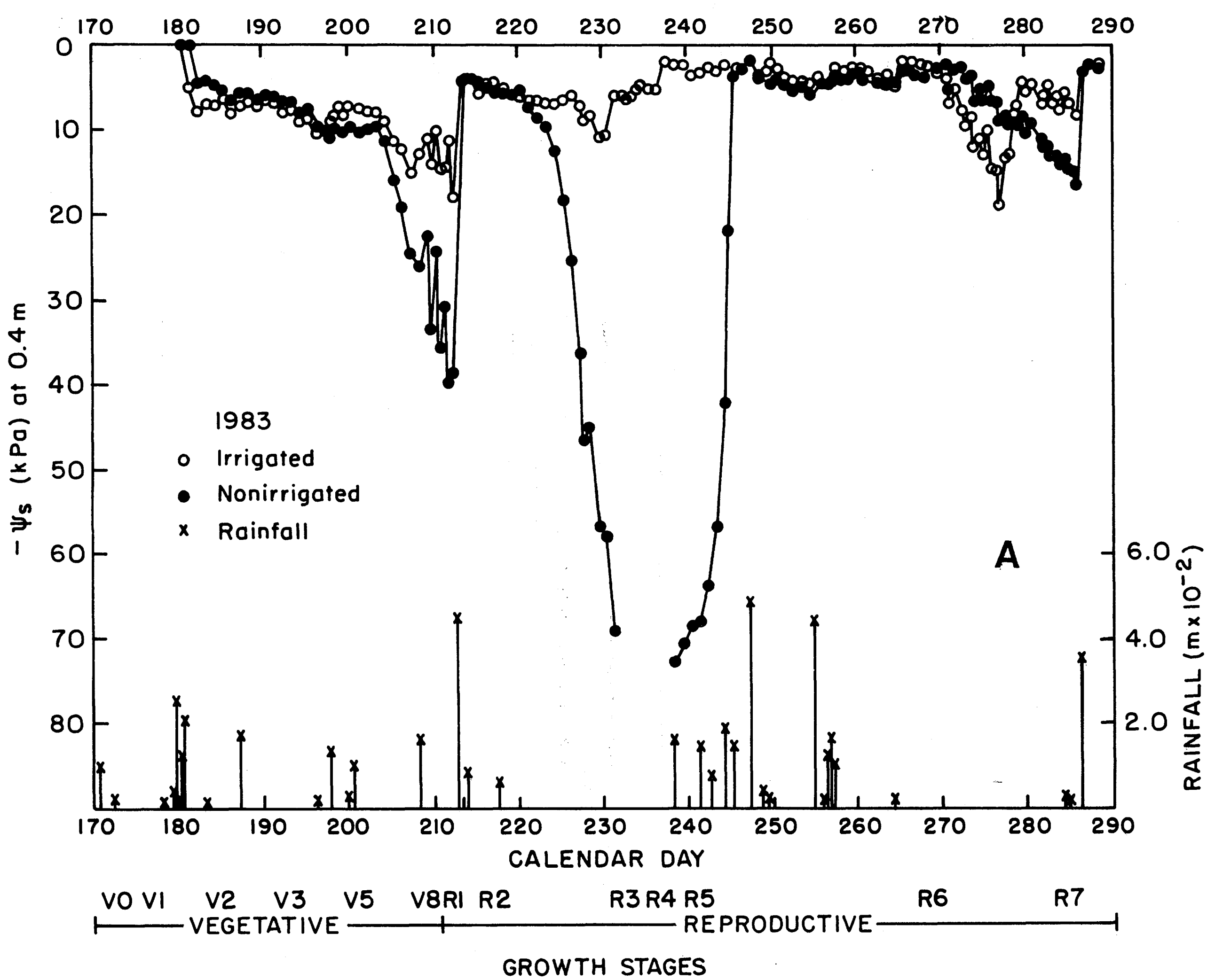

FIG. 6. Soil water conditions for the 1983 growing season. Above: Measured soil water potential at a depth of 0.4 m during the 1983 growing season (tensiometer readings below -50 kPa are subject to error). Below: Rainfall during the 1983 growing season and growth stages (*6*).

temperature data are available, it might be assumed that the soil temperature has a lag phase of 3 hours relative to air temperature.

The weather data used in demonstrating version 4.0 of the model were recorded during 1983 by the weather station at the Alabama Agricultural Experiment Station (*1*) located in Auburn. An example of the raw weather data for 1983 in the model is given in table 1. For calendar days 150 to 174, the values shown represent, from left to right, in units as reported by the weather station, daily total radiation (Watt hours), daily maximum air temperature and daily minimum air temperature (Fahrenheit) measured at a height of 5 feet (1.5 m) above the soil surface, daily total rainfall (inches), daily total open pan evaporation (inches), and daily maximum soil temperature and daily minimum soil temperature (Fahrenheit) measured at a depth of 4 inches (0.1 m). The year and calendar day are given at the far right on each line. In the model, the units of the input variables are converted into SI-units.

Plant Material

ROOTSIMU is a general root-growth model and can be used to simulate any type of plant, providing initiation variables and growth parameters are available. However, the input plant parameters used for this demonstration were chosen to match those of soybeans used for the validation data set collected at the Auburn rhizotron (*18,19,22,23*). The starting day of the year (PARAM START = 150), the number of simulation hours (FINISH HOURS = 2400 hours), and the site of the crop (PARAM LAT = 32.5 degree) were defined to match the actual crop grown. The initial shoot mass (PARAM ISHOOT = 0.010 kg m^{-2}) was set to a value representing the mass of the first trifoliolate leaf as it was observed on day 150. A partitioning factor for weight distribution between the leaves and the stem (PARAM STWTR = 0.25) and a specific leaf area parameter (PARAM LEAFTH = 30m^2kg^{-1}) were defined (33). For the roots, an initial root mass (PARAM

Table 1. Input Data File for Weather Data

From left to right, daily total solar radiation (RADN), daily maximum air temperature (MAXTEM), daily minimum air temperature (MINTEM), daily total rainfall (CMRAIN), daily total open pan evaporation (PEVAP), daily maximum soil temperature (MAXSTM), daily minimum soil temperature (MINSTM), year (YEAR), and calendar day (DAY)

RADN	MAXTEM	MINTEM	CMRAIN	PEVAP	MAXSTM	MINSTM	YEAR	DAY
W.hour	F	F	Inches	Inches	F	F		
5518	87.0	62.0	0.15	0.29	92	70	083	150
7397	88.0	62.0	0.00	.46	89	69	083	151
7377	83.0	59.0	0.00	.33	93	70	083	152
5666	78.0	53.0	0.00	.24	89	69	083	153
7700	83.0	60.0	0.00	.27	95	70	083	154
6943	88.0	64.0	.09	.30	96	74	083	155
5463	84.0	62.0	0.00	.20	92	75	083	156
4399	84.0	62.0	0.00	.16	91	75	083	157
5080	82.0	65.0	.48	.21	90	70	083	158
1511	72.0	58.0	.57	.09	76	68	083	159
7127	80.0	59.0	0.00	.26	86	68	083	160
6084	82.0	61.0	0.00	.23	86	68	083	161
7294	82.0	59.0	0.00	.31	89	68	083	162
7622	83.0	61.0	0.00	.33	92	70	083	163
7741	83.0	63.0	0.00	.38	94	71	083	164
7910	84.0	61.0	0.00	.37	97	73	083	165
6878	86.0	56.0	0.00	.26	97	73	083	166
6670	88.0	61.0	0.00	.26	97	74	083	167
5753	90.0	67.0	0.00	.17	98	76	083	168
4551	85.0	65.0	.23	.21	92	75	083	169
4108	83.0	65.0	.42	.24	87	73	083	170
2826	82.0	65.0	.47	.14	82	71	083	171
4944	82.0	67.0	0.00	.20	85	72	083	172
3218	79.0	67.0	.01	.14	81	73	083	173
4728	87.0	69.0	.02	.17	89	74	083	174

IROOT = 0.002 kg m^{-2}), factors for root growth distribution over the top soil layers (TABLE RRL(1-10) = 0.54, 0.38, 0.08, etc.), and root length to root mass ratio (PARAM LNGFAC = 13000 m kg^{-1}) were determined from the experimental plants on day 150.

The photosynthetic parameters are defined for C_3-plants in general, but can be adjusted if necessary: maximum photosynthetic rate, PARAM MXPHOT = 0.82 * 10^{-6} kg m^{-2} s^{-1}, (*39,11*) a light efficiency factor of the photosynthesis process, PARAM EFF = 0.01388 * 10^{-6} kg J^{-1} s^{-1}, (*3,26,11*); a maintenance respiration factor, PARAM RSPFAC = 1.0*10^{-7}kgkg^{-1}s^{-1} (*31,32*); a conversion efficiency factor, PARAM CONVRT = 0.30 kg kg^{-1} (*31,32*), and a growth factor, PARAM GROFAC = 1.0 * 10^{-5} kg kg^{-1} s^{-1}, (*40*).

The model also includes an aging and senescence factor for shoot tissue (PARAM AGFAC) which was set at 3.0 * 10^{-7} kg kg^{-1} s^{-1} and a death factor for root tissue (PARAM DTHFAC) which was set at 1.0 * 10^{-8} kg kg^{-1} s^{-1}. Both of these gave a good fit to the experimental data, although shoot and root death rates were not actually measured.

FRAC is a factor which partitions dry matter between the shoot and the roots, based on canopy water potential. The function FRACTB, which is used to compute an instantaneous value for FRAC, was redefined. Similarly, the function LAIFAC, which is the basis for computing photosynthetic rate from LAI and partitions water loss between the canopy and the soil, was redefined. Both functions can be adjusted when data are available. The water stress table (FUNCTION TRNTBL) was adapted from data for soybean plants (*5*), but the data in the table can be substituted with other values for different crops.

Root growth was divided into root branching, which was the formation of new roots and the extension of older roots in the same soil layer, and root extension which was the exten-

Table 2. Input Data File for Plant and Soil Parameters (Corresponding to READ Statement in FORTRAN Program)

Time variables [1]

FINTIM	OUTDEL	PRDEL	DELT	BGNDAY
4320000	01.0	3599.9999D00	1800.0	150.

Initial mass variables [1]

IPER	ISHOOT	IROOT	LGNFAC	NJ	RTDWPC
0.03	0.010	0.002	13000.0	10	10.

Soil variables [1]

ITHETA(I), I=1,NJJ

0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.230	0.300

RRL(I), I=1,NJ

0.54	0.38	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00

TCOM(I), I=1,NJJ

0.10	0.15	0.15	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20

LOPOT	HIPOT
-110.0	-100.0

DTRDEM	SATCON	ZLAM	PARTDS	THTAIR	STHETA	ALPHA	NU
0.01	5.0E-05	.64762	2.59	0.050	0.36	0.24890	1.21555

Growth variables [1]

REFT	REFTS	RSPFAC	MXPHOT	DKPHOT	EFF
25.0	25.0	1.0E-07	0.8200E-6	0.00E-6	0.01388E-6

CONVRT	DELAY	FRG	AGFAC	LEAFTH	STWTR
.3	21600	0.666	3.0E-7	30.00	0.25

GROFAC	DTHFAC	PB	BRMIN	EXTMIN	MINRTL
1.0E-05	1.0E-08	21.8258	-1.0	-2.0	5.0

BR	EXTNRT	AA	BB	B	DEPTHG
1.0E-04	3.0E-03	8.0E-03	2.0	1.0E-02	10.

URRS	UARS	MAXPOT	OUTF
1.00E+11	1.00E+11	-2.0	3.024E05

POTCR	LSNHS	DRCI	DROI	DRADI
-2.00	-0.500	3.5E+07	6.6E06	1.0E-10

CF	ERROR	LAT
0.100	0.010	32.5

[1]Definition and unit for each variable are given in Appendix D.

sion of root from one layer into the next layer. A relative branching factor (PARAM BR) was set at $1.0 * 10^{-4}$ m s^{-1} and the minimum ψ_{soil} at which root branching terminates (PARAM BRMIN) was defined as -10 kPa. A relative extension factor (PARAM EXTNRT) was set at $3.0 * 10^{-3}$ m s^{-1} and a minimum ψ_{soil} at which root extension from one layer into the next layer terminates (PARAM EXTMIN) was defined as -20 kPa. A factor to reduce root growth at increasing depth (PARAM DEPTHG) was set to 10 m m^{-1}.

Although measured root water uptake is more closely related to total root surface area (7), in this model, root resistance and water uptake rates are based on root length, which assumes a linear relationship between root length and root surface area (7). For root water uptake, an axial resistance (PARAM UARS = $1.0 * 10^{11}$ s m m^{-1}), a radial resistance (PARAM URRS = $1.0 * 10^{11}$ s m), and a factor relating soil conductivity, root length, and root conductivity, PARAM B = 0.01 m^{-1} (9) are required. The input parameters needed to define the initial plant conditions are shown in table 2, which is set up in the format to be read by the FORTRAN program in Appendix B and can be adjusted by the user. For instance, the first line in table 2 shows, respectively, the finished condition in seconds for the simulation run (FINTIM), the output intervals for plotting (OUTDEL) or printing (PRDEL), the time step of each simulation interval (DELT), and finally the starting day of the simulation run (BGNDAY).

Soil Conditions

Soil conditions are an important part of the model and greatly influence the results of the simulation. The experimental plants were grown in the A-horizon from a Dothan loamy sand (fine loamy, siliceous, thermic Plinthic Paleudult). A soil-water retention curve for this soil material was experimentally measured in the laboratory and used as a basis for defining the function SUTB. Saturated water content (PARAM STHETA = 0.36 m^3 m^{-3}), air dry water content (PARAM THTAIR = 0.050 m^3 m^{-3}), bulk density as a function of depth (FUNCTION BULKF), and particle density (PARAM PARTDS = 2.59 Mg m^{-3}) were also measured in the laboratory and used as input parameters in the model (4). To calculate water flow, a saturated conductivity (PARAM SATCON = $5.0 * 10^{-5}$ m day^{-1}) and the constants to define the van Genuchten (38) equation for calculating relative conductivity must be defined (PARAM ALPHA = 0.24890; PARAM NU = 1.21555).

In this revision of the model, the homogeneous soil profile was arbitrarily divided into 10 layers (PARAM NJ = 10) of 0.20 m (TABLE TCOM(1-20) = 0.10, 2*0.15, 17*0.20 m) except for the three top layers, which were 0.10, 0.15, and 0.15 m, respectively. The thickness of each layer can easily be adjusted if necessary.

The model provides an option for simulating irrigation treatments. A minimum ψ_{soil} threshold matching the tensiometer readings (PARAM IRFAC = 10 kPa) and the amount applied per irrigation pulse (PARAM IRQUAN = (0.0, 250.0 cm^3 m^{-2}) were defined.

Most of the initial soil conditions are shown in table 2, which represents an input file read on device #8 for the FORTRAN version (Appendix B) of the model. When the CSMP version of the model is used, both the IR and NI treatments can be run simultaneously and the results can be overlayed on plots.

MODEL RESTRICTIONS

One of the main limitations of this revision of the model is that it has no provisions for partitioning dry matter into reproductive structures such as flowers, pods, or seeds. Because Braxton (maturity group VII) soybean plants continue vigorous vegetative growth throughout the full-bloom (R2) and beginning pod-set (R3) stages (*6*), this portion of the growing season was included in the simulation examples presented below. When plants began full pod development (R4) and early-seed-filling stages (R5), most of the available dry matter was stored in pods and seeds. Thus, this version of the model, which accounts for vegetative growth only, cannot adequately describe carbon partitioning during seed formation and maturation. Therefore, only the first 100 days of the growing season, during which most of the vegetative soybean growth occurs, were simulated.

Because the model was developed mainly to simulate the effect of water stress on plant growth, it was assumed that the supply of nutrients would be optimal and that growth would not be inhibited by insects, diseases, or weeds. The model also did not account for soil environmental constraints (*21*), such as poor aeration, temperature extremes, salinity, or chemical toxicity, although they could be included if data were available. Some of these simplifications and assumptions of the model will be replaced by newly coded algorithms as the model is extended.

MODEL PREDICTIONS

Only predictions for the 1983 growing season are presented herein. Detailed trial simulation runs for the 1981 growing season, including comparisons between observed and simulated data, are described by Hoogenboom et al. (*17*).

Environmental Conditions

Figure 4 shows the intensity of solar radiation expressed as a continuous function over a 10-day period of the growing sea-

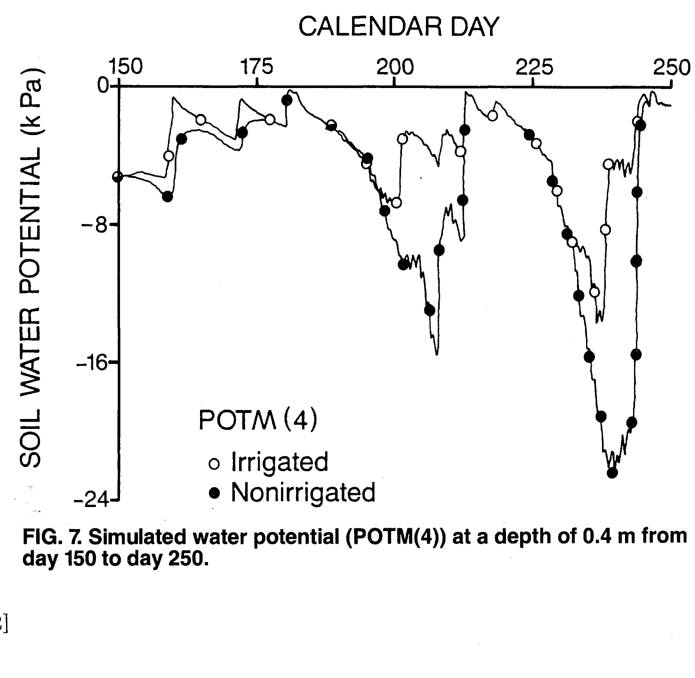

FIG. 7. Simulated water potential (POTM(4)) at a depth of 0.4 m from day 150 to day 250.

son as interpolated by the computer from measured daily totals. Soil and ambient-air temperature over the same 10-day period are shown in figure 5 (TEMP, STEMP), including the daily maximum (MAXTEM) and minimum (MINTEM) air temperature. Rainfall events as measured at the Auburn rhizotron are presented in figure 6. This figure also presents the experimentally measured ψ_{soil} for the 1983 growing season, while the simulated ψ_{soil} is shown in figure 7. The data for experimental and simulated NI treatments show low ψ_{soil} during the period without rainfall from day 205 to 215 and from day 225 to 250. Detailed model predictions from day 230 to 240 are presented in the next simulation examples, because during this period strong differences between IR and NI plants were observed.

Plant Growth

Because little rain was observed between days 230 and 240, figure 6b, canopy water potential (ψ_{canopy}) of the simulated NI plants reached lower values than ψ_{canopy} of simulated IR plants as the drought period continued, figure 8. Although simulated ψ_{canopy} and therefore water stress levels were different with the two treatments, no differences were observed between simulated photosynthetic rates, figure 9. The lower ψ_{canopy} of the simulated NI plants induced an increasing portion of the available dry matter to be used by the roots, as shown by the partitioning factor FRAC, figure 10. Although predicted shoot growth of both treatments was similar during this period, figure 11A, predicted root growth, especially in the NI plants, increased markedly, figure 12A. Predicted shoot death rates, figure 11B, increased during this period, while predicted root death rates had similar maximum rates every day, figure 12B.

Long term growth of shoot and root mass as predicted by

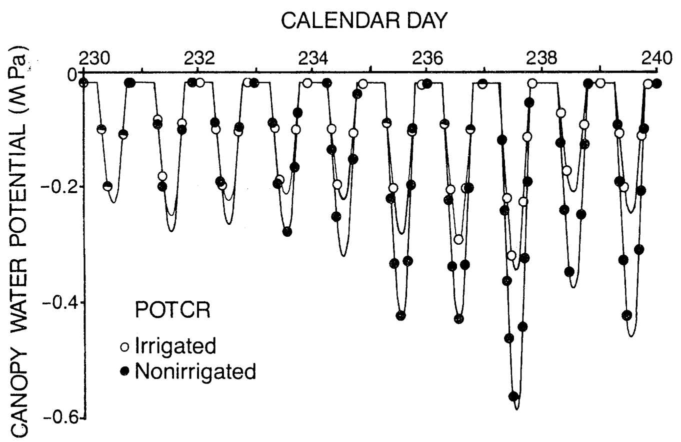

FIG. 8. Simulated canopy water potential (POTCR) from day 230 to day 240.

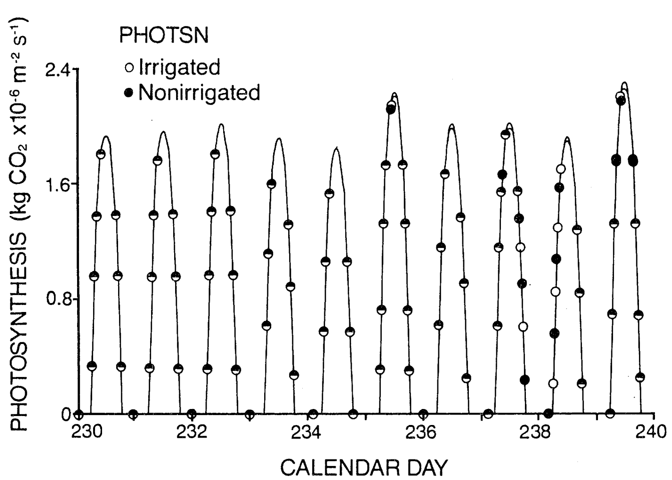

FIG. 9. Simulated canopy apparent photosynthesis (PHOTSN) from day 230 to day 240.

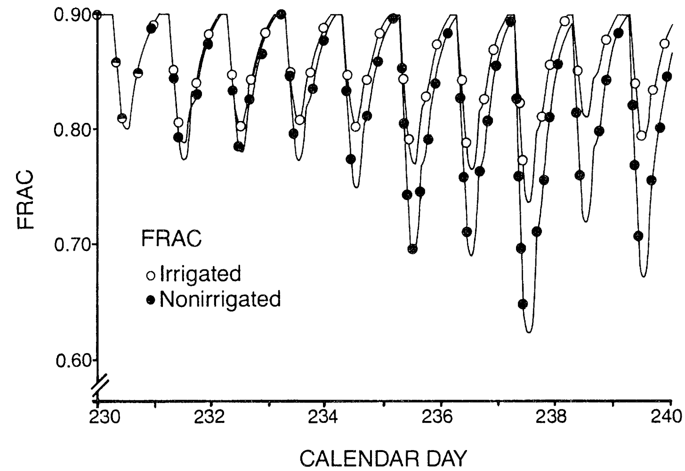

FIG. 10. Simulated partitioning factor for dry matter (FRAC) from day 230 to day 240.

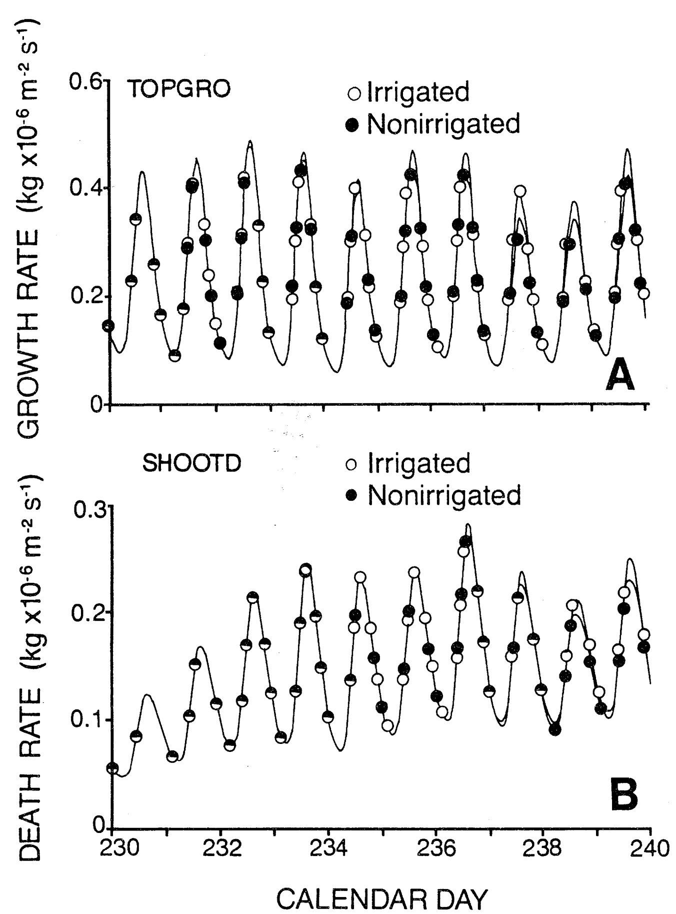

FIG. 11. Simulated growth and death rates of the shoot system from day 230 to day 240. A: Growth rates (TOPGRO). B: Death rates (SHOOTD)

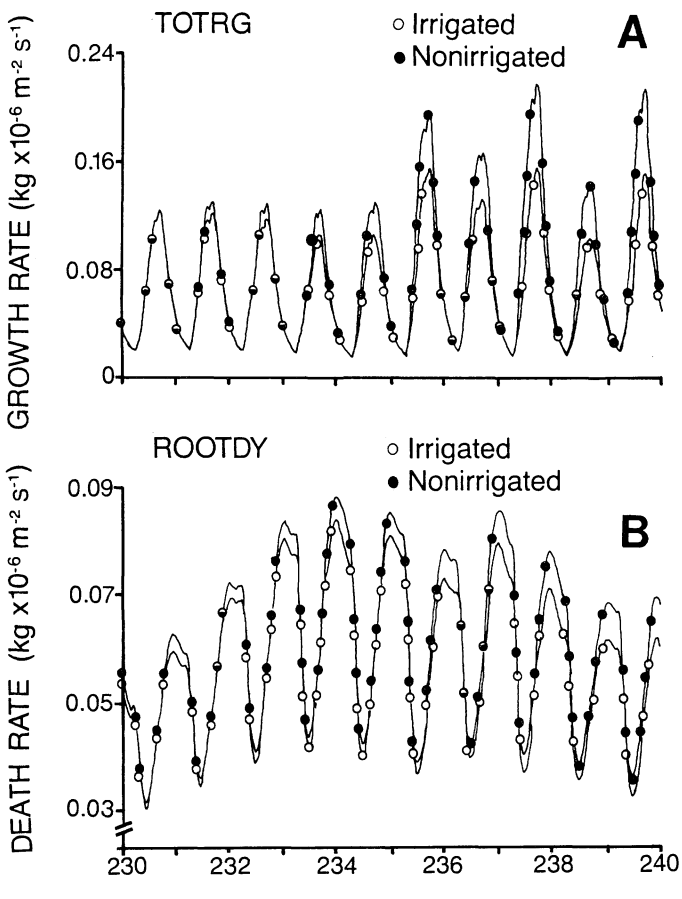

FIG. 12. Simulated growth and death rates of the root system from day 230 to day 240. A: Growth rates (TOTRG). B: Death rates (ROOTDY).

the model is presented in figure 13. Although there was no difference in simulated total dry weight of the two treatments, simulated IR plants had a larger shoot and therefore more leaf area, figure 14. On the other hand, simulated NI plants had a heavier root system with larger total root length, figure 15. The difference between the predicted root lengths of the two treatments was mainly found in the deeper soil layers, figure 16D, similar to experimental observations (*18,19*). No root growth was predicted in the surface layer for either treatment, figure 16A. Most of the predicted root growth was found between a depth of 0.25 and 1.00 m, figure 16B and C. The simulated IR plants had a larger root system between a depth of 0.60 and 1.00 m, while simulated NI plants had a larger root system between 1.00 and 1.40 m, figure 16C and D.

During the drought period between days 230 and 240, figure 6, a decrease in simulated net root growth occurred above 0.40 m, figure 17A, in the NI treatment. Simulated IR plants formed roots mainly between 0.25 and 0.80 m, while simulated NI plants formed roots mainly between 0.80 and 1.40 m, figure 17. The model predicted no water extraction from the top layer, because it was extremely dry due to evaporation. It therefore contained only the tap root and no small feeder roots, figure 17A. Simulated IR plants mainly extracted water between 0.25 m and 0.80 m, figure 17A and B, while NI plants mainly extracted water between 0.80 and 1.20 m, figure 17C and D. Predicted water extraction pat-

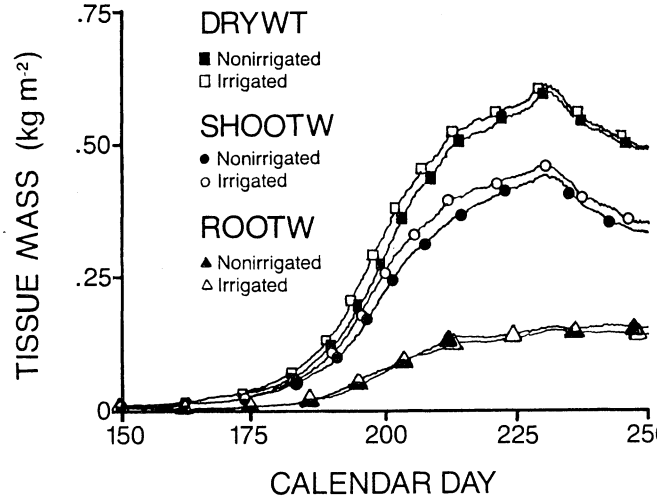

FIG. 13. Simulated dry matter accumulation in the whole plant (DRYWT), the shoot system (SHOOTW), and the root system (ROOTW) from day 150 to day 250.

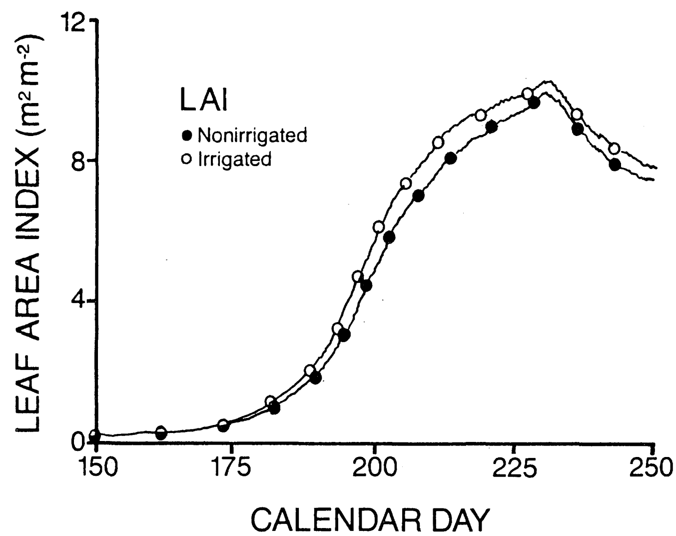

FIG. 14. Simulated increase in leaf area index (LAI) from day 150 to day 250.

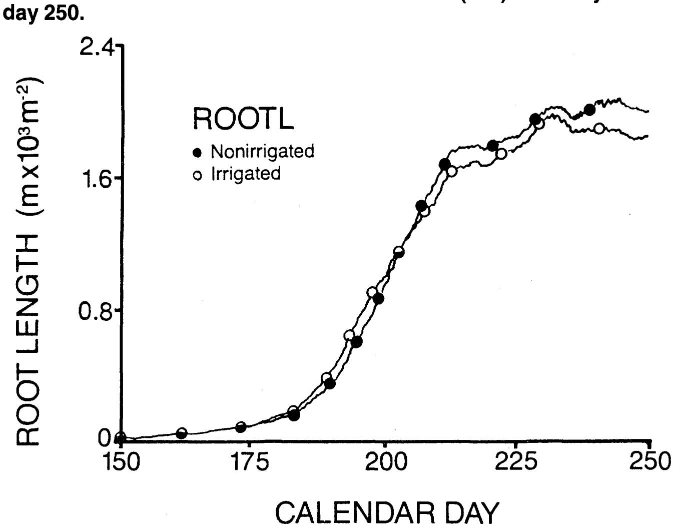

FIG. 15. Simulated increase in total root length (ROOTL) from day 150 to day 250.

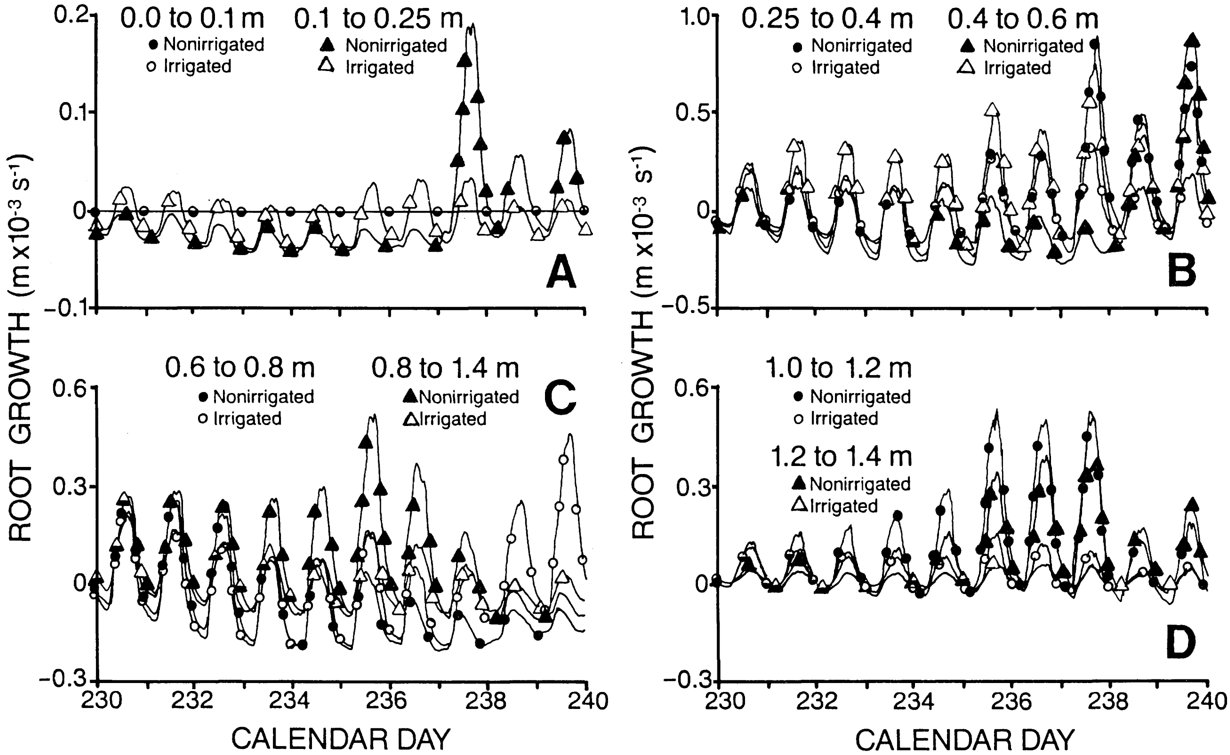

FIG. 16. Simulated root growth from day 150 to day 250. A: Between 0.00-0.10 m and between 0.10-0.25 m. B: Between 0.25-0.40 m and between 0.40-0.60 m. C: Between 0.60-0.80 m and between 0.80-1.00 m. D: Between 1.00-1.20 m and between 1.20-1.40 m.

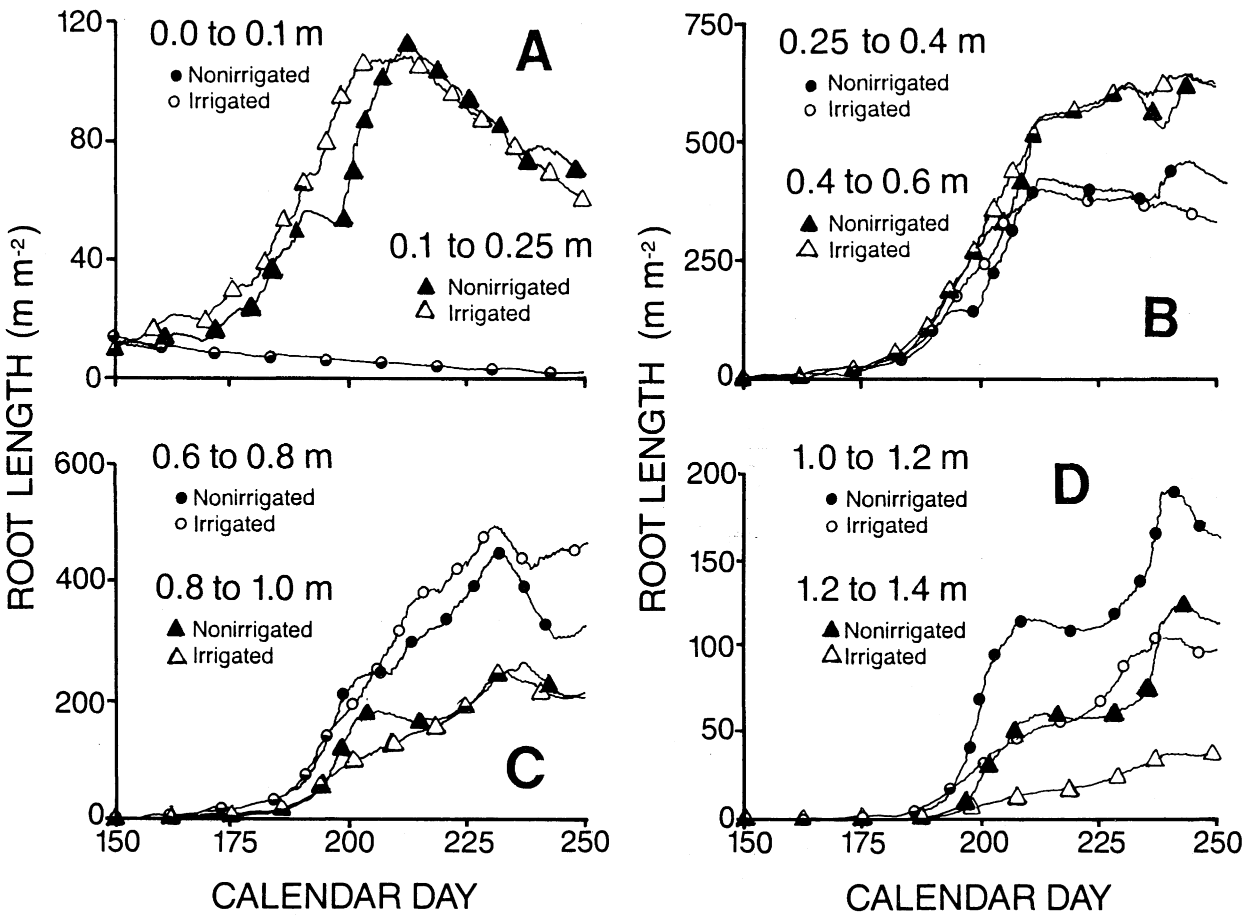

FIG. 17. Simulated net change in root length between day 230 and 240. A : Between 0.00-0.10 m and between 0.10-0.25 m. B: Between 0.25-0.40 m and between 0.40-0.60 m. C: Between 0.60-0.80 m and between 0.80-1.00 m. D: Between 1.00-1.20 m and between 1.20-1.40 m.

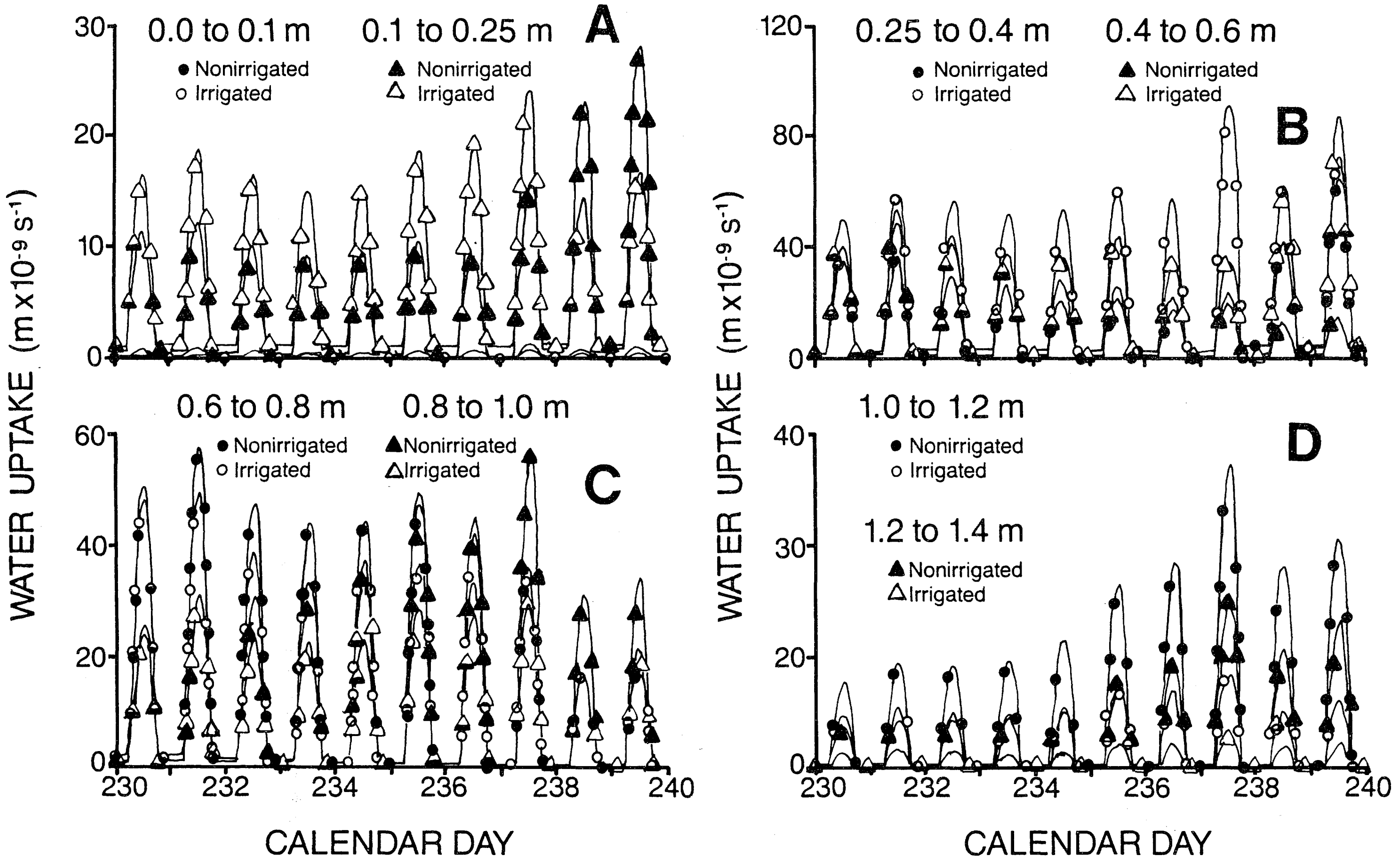

FIG. 18. Simulated soil water uptake between day 230 and day 240. A: Between 0.00-0.10 m and between 0.10-0.25 m. B: Between 0.25-0.40 m and between 0.40-0.60 m. C: Between 0.60-0.80 m and between 0.80-1.00 m. D: Between 1.00-1.20 m and between 1.20-1.40 m.

terns, figure 17, were similar to predicted root growth patterns by the simulation model, figure 18.

These examples show some of the capabilities of the model ROOTSIMU, version 4.0. Other variables, which represent either an environmental or plant parameter, are involved in the simulation process. The list of variables included in the model is given in Appendix D.

SIMULATION INSTRUCTIONS

The examples illustrated herein were generated by the CSMP version of the model. The UPDATE subroutine generated by the CSMP translator was kept and stored on disk on a mainframe computer so that the model could be run independently. The FORTRAN version of the model has been adapted and tested, so that results from this version of the model are the same as those obtained by running the CSMP version.

Mainframe or Mini-Computer

If a CSMP-package is available on a larger mainframe or mini-computer, the program can be run in a background mode, using the proper job control language and weather file as input data set, table 1. Plant and soil parameters are included in the CSMP version of the model. Because CSMP has a built-in plotting routine, output data sets need not be explicitly defined, and results will be plotted as specified on the XYPLOT statements. A similar strategy is applicable if an ACSL package is available (28).

If no simulation languages are available, the FORTRAN version of the model can also be run on any larger mainframe computer with a FORTRAN compiler. This FORTRAN version is less dynamic and subroutines must be included for many of the calculations which are performed automatically by CSMP or ACSL. The FORTRAN version of the model generally can be run in a background mode, while specifying UNIT 8 as input for the plant and soil parameters, table 2, and UNIT 12 as input for the weather data, table 1. Other device addresses can be specified as output files. After completion of the simulation, the output files are saved and then used for plotting with X-Y plotting routines adapted to the computer system available. An example of an output file is presented in table 3. Shown are rates of photosynthesis (PHOTSN), respiration (RESP), growth (GROWTH), transpiration (TRANSP), evaporation (EVAP), and water uptake from all soil layers (SUMR) on an hourly (HOURS) basis for the first 24 hours of simulation, starting on day 150.

Micro-Computer

The following instructions to run the FORTRAN version of the model on a micro-computer apply only for an IBM[3]-PC or compatible computer. The FORTRAN source code of Appendix B is compiled, linked, and stored in a binary field named

Table 3. Output Data Files on Disk

From left to right, hours of simulation (HOURS), photosynthetic rate (PHOTSN), growth rate (GROWTH), respiration rate (RESP), total water uptake by the roots (SUMR), evaporation rate (EVAP), and transpiration rate (TRANSP).

HOURS[1]	PHOTSN	GROWTH	RESP	SUMR	EVAP	TRANSP
h	kg $m^{-2}s^{-1}$	kg $m^{-2}s^{-1}$	kg $m^{-2}s^{-1}$	m s^{-1}	m s^{-1}	m s^{-1}
0.000E+00	0.754E-18	0.279E-08	0.934E-09	0.228E-09	0.805E-09	0.480E-10
.100E+01	.754E-18	.241E-08	.162E-08	.235E-09	.824E-09	.492E-10
.200E+01	.754E-18	.214E-08	.146E-08	.242E-09	.844E-09	.504E-10
.300E+01	.754E-18	.195E-08	.135E-08	.248E-09	.863E-09	.516E-10
.400E+01	.754E-18	.184E-08	.129E-08	.254E-09	.883E-09	.528E-10
.500E+01	.754E-18	.178E-08	.126E-08	.255E-09	.903E-09	.540E-10
.600E+01	.173E-07	.197E-08	.128E-08	.218E-08	.368E-07	.220E-08
.700E+01	.214E-07	.243E-08	.145E-08	.486E-08	.826E-07	.495E-08
.800E+01	.231E-07	.304E-08	.171E-08	.748E-08	.128E-06	.767E-08
.900E+01	.238E-07	.377E-08	.206E-08	.967E-08	.167E-06	.999E-08
.100E+02	.242E-07	.457E-08	.246E-08	.113E-07	.197E-06	.118E-07
.110E+02	.243E-07	.546E-08	.291E-08	.124E-07	.215E-06	.129E-07
.120E+02	.243E-07	.635E-08	.335E-08	.126E-07	.220E-06	.133E-07
.130E+02	.242E-07	.718E-08	.373E-08	.123E-07	.215E-06	.130E-07
.140E+02	.240E-07	.789E-08	.400E-08	.115E-07	.197E-06	.119E-07
.150E+02	.237E-07	.859E-08	.424E-08	.975E-08	.167E-06	.101E-07
.160E+02	.229E-07	.909E-08	.442E-08	.753E-08	.128E-06	.776E-08
.170E+02	.214E-07	.919E-08	.449E-08	.491E-08	.826E-07	.502E-08
.180E+02	.175E-07	.895E-08	.439E-08	.223E-08	.369E-07	.225E-08
.190E+02	.751E-18	.801E-08	.413E-08	.104E-09	.118E-08	.717E-10
.200E+02	.754E-18	.687E-08	.367E-08	.108E-09	.120E-08	.730E-10
.210E+02	.754E-18	.581E-08	.322E-08	.113E-09	.122E-08	.743E-10
.220E+02	.754E-18	.490E-08	.281E-08	.118E-09	.124E-08	.756E-10
.230E+02	.754E-18	.416E-08	.246E-08	.125E-09	.125E-08	.768E-10
.240E+02	.391E-18	.355E-08	.216E-08	.129E-09	.127E-08	.781E-10

[1]Definition and unit for each variable are given in Appendix D.

ROOTSIMU.EXE. To run this FORTRAN-compiled version of the model simply type:

ROOTSIMU

The program will respond with:

File name missing or blank
Please enter name : *UNIT8 ?*

Then type:

INPUTSG.FIL (inputs as in table 2)

to read the plant and soil parameters, presented in table 2.

UNIT12 ?

Then type:

DAT1983.FIL (inputs as in table 1)

to read the weather data, presented in table 1.

UNIT6 ?

Then type:

CON for console (display or keyboard) or
LPT1 or **PRN** for printer.

The program will now start reading the data and weather files and will print the first line of the weather data set

150.0 0.20E+08 30.56 16.67 0.38 0.74 33.33 22.11 5 30

followed by:

INITIATE

and the input weather data as presented for the first 25 days in table 4. After the program has read the last data line, it will come back and ask for an output file name

UNIT1 ?

Then type:

B:OUTPUT.FIL assuming a 2-drive machine; use
C:OUTPUT.FIL if hard disk is available.

The program will inform the user that it has finished the input and initiation process:

INITIATION NOW COMPLETE. ENTER DYNAMIC LOOP

and will write the results of the simulation at the fixed time

Table 4. Output Data Sent to Screen or Printer During Initiation of the Model

From left to right, calendar day (SIMDAY), daily total solar radiation (RADN), daily maximum air temperature (MAXTEM), daily minimum air temperature (MINTEM), daily total rainfall (CMRAIN), daily total open pan evaporation (PEVAP), daily maximum soil temperature (MAXSTM), daily minimum soil temperature (MINSTM), month (MONTH), and day of the month (DATE)

SIMDAY[1]	RADN	MAXTEM	MINTEM	CMRAIN	PEVAP	MAXSTM	MINSTM	MONTH	DATE
day	J m^{-2}	°C	°C	m day^{-1}	m day^{-1}	°C	°C		
150.0	0.20E+08	30.56	16.67	0.38	0.74	33.33	21.11	5	30
151.0	.27E+08	31.11	16.67	0.00	1.17	31.67	20.56	5	31
152.0	.27E+08	28.33	15.00	0.00	.84	33.89	21.11	6	1
153.0	.20E+08	25.56	11.67	0.00	.61	31.67	20.56	6	2
154.0	.28E+08	28.33	15.56	0.00	.69	35.00	21.11	6	3
155.0	.25E+08	31.11	17.78	.23	.76	35.56	23.33	6	4
156.0	.20E+08	28.89	16.67	0.00	.51	33.33	23.89	6	5
157.0	.16E+08	28.89	16.67	0.00	.41	32.78	23.89	6	6
158.0	.18E+08	27.78	18.33	1.22	.53	32.22	21.11	6	7
159.0	.54E+07	22.22	14.44	1.45	.23	24.44	20.00	6	8
160.0	.26E+08	26.67	15.00	0.00	.66	30.00	20.00	6	9
161.0	.22E+08	27.78	16.11	0.00	.58	30.00	20.00	6	10
162.0	.26E+08	27.78	15.00	0.00	.79	31.67	20.00	6	11
163.0	.27E+08	28.33	16.11	0.00	.84	33.33	21.11	6	12
164.0	.28E+08	28.33	17.22	0.00	.97	34.44	21.67	6	13
165.0	.28E+08	28.89	16.11	0.00	.94	36.11	22.78	6	14
166.0	.25E+08	30.00	13.33	0.00	.66	36.11	22.78	6	15
167.0	.24E+08	31.11	16.11	0.00	.66	36.11	23.33	6	16
168.0	.21E+08	32.22	19.44	0.00	.43	36.67	24.44	6	17
169.0	.16E+08	29.44	18.33	.58	.53	33.33	23.89	6	18
170.0	.15E+08	28.33	18.33	1.07	.61	30.56	22.78	6	19
171.0	.10E+08	27.78	18.33	1.19	.36	27.78	21.67	6	20
172.0	.18E+08	27.78	19.44	0.00	.51	29.44	22.22	6	21
173.0	.12E+08	26.11	19.44	.03	.36	27.22	22.78	6	22
174.0	.17E+08	30.56	20.56	.05	.43	31.67	23.33	6	23
175.0	.10E+08	25.56	18.33	.03	.33	27.78	22.22	6	24

[1]Definition and unit for each variable are given in Appendix D.

step interval read from unit 8 into this output file. For every hour of simulation it will also print the information presented in table 5 on the screen, to keep the user up to date with the progress of the current simulation run. The output file, table 3, can be read after the simulation is finished, and can be split into different data sets according to the output specification. These data sets can then be plotted by the X-Y plotting routines, available on the micro-computer.

Without an 8087 coprocessor, it takes about 14 seconds to simulate 1 hour of plant growth on an IBM-PC[3]. To speed up the simulation process, longer time steps can be used or less output can be generated. Another option is to use different math coprocessors or another micro-computer.

DISCUSSION

An update of the model ROOTSIMU version 4.0 described by Huck and Hillel (*21*) is presented. The major changes made in the model are inclusion of input statements, which read daily observed climatic data, and algorithms which calculate instantaneous values from given daily totals. The shoot was divided into a stem part and a leaf part and a new canopy-

Table 5. Output Data Sent to Screen or Printer During Current Simulation Run

From left to right, calendar day (JULIAN), shoot dry matter (SHOOTW), root dry matter (ROOTW), leaf area index (LAI), root length (ROOTL), photosynthetic rate (PHOTSN), canopy water potential (POTCR), and transpiration rate (TRANSP)

JULIAN : day SHOOTW : kg m^{-2} ROOTW : kg m^{-2} LAI : m^2 m^{-2}

ROOTL : m m^{-2} PHOTSN : kg $m^{-2}s^{-1}$ POTCR : m TRANSP : m s^{-1} [1]

```
JULIAN=150.00 SHOOTW=   0.01000 ROOTW=   0.00200 LAI=   0.225
ROOTL=     26.009 PHOTSN=  0.75E-18 POTCR=      -2.00 TRANSP=  0.48E-10

JULIAN=150.04 SHOOTW=   0.01001 ROOTW=   0.00200 LAI    0.225
ROOTL=     25.993 PHOTSN=  0.75E-18 POTCR=      -2.00 TRANSP=  0.49E-10

JULIAN=150.08 SHOOTW=   0.01002 ROOTW=   0.00200 LAI=   0.225
ROOTL=     25.976 PHOTSN=  0.75E-18 POTCR=      -2.00 TRANSP=  0.50E-10

JULIAN=150.12 SHOOTW=   0.01002 ROOTW=   0.00200 LAI=   0.225
ROOTL=     25.959 PHOTSN=  0.75E-18 POTCR=      -2.00 TRANSP=  0.52E-10

JULIAN=150.17 SHOOTW=   0.01003 ROOTW=   0.00200 LAI=   0.226
ROOTL=     25.941 PHOTSN=  0.75E-18 POTCR=      -2.00 TRANSP=  0.53E-10

JULIAN=150.21 SHOOTW=   0.01004 ROOTW=   0.00199 LAI=   0.226
ROOTL=     25.923 PHOTSN=  0.75E-18 POTCR=      -2.00 TRANSP=  0.54E-10

JULIAN=150.25 SHOOTW=   0.01004 ROOTW=   0.00199 LAI=   0.226
ROOTL=     25.906 PHOTSN=  0.17E-07 POTCR=     -12.70 TRANSP=  0.22E-08

JULIAN=150.29 SHOOTW=   0.01005 ROOTW=   0.00199 LAI=   0.226
ROOTL=     25.901 PHOTSN=  0.21E-07 POTCR=     -27.69 TRANSP=  0.49E-08

JULIAN=150.33 SHOOTW=   0.01006 ROOTW=   0.00199 LAI=   0.226
ROOTL=     25.912 PHOTSN=  0.23E-07 POTCR=     -42.57 TRANSP=  0.76E-08

JULIAN=150.37 SHOOTW=   0.01007 ROOTW=   0.00200 LAI=   0.226
ROOTL=     25.943 PHOTSN=  0.24E-07 POTCR=     -57.11 TRANSP=  0.98E-08

JULIAN=150.42 SHOOTW=   0.01008 ROOTW=   0.00200 LAI=   0.227
ROOTL=     25.989 PHOTSN=  0.24E-07 POTCR=     -71.17 TRANSP=  0.11E-07

JULIAN=150.46 SHOOTW=   0.01009 ROOTW=   0.00200 LAI=   0.227
ROOTL=     26.053 PHOTSN=  0.24E-07 POTCR=     -83.54 TRANSP=  0.12E-07

JULIAN=150.50 SHOOTW=   0.01010 ROOTW=   0.00201 LAI=   0.227
ROOTL=     26.137 PHOTSN=  0.24E-07 POTCR=     -92.39 TRANSP=  0.13E-07
```

[1] Units are given for information only and are not generated during the actual simulation run.

photosynthesis section was added. The root-growth and water-uptake sections were further refined and a section which reduces root growth under severe soil impedance conditions was added. Finally, an option was added to the model to simulate plant and root growth under irrigated and nonirrigated conditions, corresponding to experimental conditions at the Auburn rhizotron.

Detailed validation studies, using ROOTSIMU version 4.0 (CSMP-model) and 1981 experimental data, will be published by Hoogenboom et al. (*17*). For examples presented in this publication, 1983 weather data were used as input functions. The model was run in background mode on a mainframe computer. Although a large amount of CPU time was required, several simultaneous runs, which were needed to calibrate the model, could be executed at the same time. Trial runs on a micro-computer took several hours of actual simulation time. Depending on the resources available, the best performance of the model will be obtained by using the CSMP or ACSL version of the model on either a mainframe or minicomputer.

In these trial simulation runs, ψ_{canopy} was a critical value in determining total growth. After a rain, upper layers of soil rewet quickly, while water percolated slowly into deeper soil layers until a new equilibrium water potential was established. Plant water potential was high when many roots were present in wet soil, but as soil water reserves diminished, plant water stress increased. An increasing fraction of soluble carbohydrates was used in the formation of new root tissue as water was depleted from the soil. During the calibration runs of the model, it was observed that under extreme drought conditions plants lost turgor and finally died, usually from carbohydrate starvation because $C0_2$ exchange was blocked when stomata could not open due to water stress.

CONCLUSIONS

Based on calibration runs with the model ROOTSIMU version 4.0, it can be concluded that:

The approach used to handle climatic data provided good algorithms to input real weather data into the model.

The infiltration procedure, together with the Darcian flow equation, was successful in that the predicted below-ground water regime compared reasonably well to experimentally recorded values.

As with the Huck and Hillel (*21*) version, this model gave plausible indicators of plant response to climatic variables and selected soil variables.

The run time was not excessive on any large system. The model can be run on a personal computer, but considerable time is required.

The simulation languages CSMP and ACSL provided the best languages for running the model.

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APPENDIX A:
CSMP-LISTING OF SIMULATION MODEL

```
 ****************************************************************************
*                                                                          *
*                                                                          *
*          * **CONTINUOUS SYSTEM MODELING PROGRAM** *                      *
*                                                                          *
*                                                                          *
****************************************************************************
*                                                                          *
*                                                                          *
TITLE    WATER UPTAKE AND ROOT GROWTH IN A HOMOGENEOUS SOIL PROFILE        *
*        NEW PHOTOSYNTHESIS RESPONSE AND ROOT GROWTH FUNCTIONS             *
*        WEATHER DATA : 1981  -  AUBURN RHIZOTRON                          *
*        ==================================================================*
*                        * * VERSION 4.0 * *                               *
*                                                                          *
*          GERRIT HOOGENBOOM & M.G. HUCK; AUBURN UNIVERSITY,ALABAMA        *
*                           APRIL      1984                                *
*                                                                          *
****************************************************************************
*                                                                          *
*        AREA IS UNITY (M**2).  UNITS SI (MKS).                            *
*  ORGANIC MATTER PRODUCTION NORMALIZED TO 1 KG/M**2/YEAR                  *
*   WHICH IS 10 GM/M**2/DAY OR 0.01 MG/M**2/SEC, ON AVERAGE                *
*                                                                          *
****************************************************************************
*                      **  SETTING UP ARRAY VARIABLES **                   *
/     DIMENSION            PTOTL(20)
* NOTE THAT PTOTL NOW IS EQUAL TO HPOT,AS OSMOTIC CONTRIBUTION NEGLECTED
/     DIMENSION  LINE(101),  RK(20), DEPTH(20)
/     DATA  IX/'*'/,IB/' '/,LINE(1)/'1'/
STORAGE          RSRT(20), DIST(20), THETA(20), RRS(20), ARS(20)
STORAGE          FLW(20), COND(20) , AVCOND(20) , POTRT(20)
STORAGE  POTH(20), POTM(20), RSSL(20), Y(20), SCALE(20)
STORAGE      TCOM(20), RRL(20), SMIN(20), SMAX(20), ITHETA(20)
STORAGE         BIRTH(20), EXTENS(20), RTGRO(20), RTDTH(20)
STORAGE      DAYS(13),POROS(20),BULKDS(20)
FIXED T, ISEED,  DAYS, MONTH, I, J, IY, K, JDAY
FIXED   NJ,NJJ,NNJ,LINE,IX,IB,JJ,KK,IFUN,RUNS
*
*
*****  INTERPOLATION OF TEMPERATURE ALONG SINE PROFILE ( DE WIT ET AL.)
*
MACRO TEMP = WAVE(JULIAN,HOUR,MNTB,MXTB,RISE)
        TIM  = INSW(HOUR-14.,HOUR+10,HOUR-14.)
        MAXT = AFGEN(MXTB,(JULIAN-14/24.))
        MINT = AFGEN(MNTB,(JULIAN-RISE/24.))
        VALAV= 0.5*(MAXT+MINT)
        VALAMP=0.5*(MAXT-MINT)
        TEMPSR = VALAV-VALAMP*COS(PI*(HOUR-RISE)/(14.-RISE))
 *     TEMPERATURE DURING RISING OF THE SUN
        TEMPSS = VALAV+VALAMP*COS(PI*TIM/(10.+RISE))
```

```
*       TEMPERATURE DURING SETTING OF SUN
        TEMP = INSW(AND(HOUR-RISE,14.-HOUR)-0.5,TEMPSS,TEMPSR)
ENDMAC
*
****     DAILY TOTALS  (DE WIT ET AL.)
*
MACRO DTOT = DLYTOT(DTOTI,RATE)
       DTOT1 = INTGRL(DTOTI,RATE)
       DTOT = DTOT1-ZHOLD(IMPULS((AMAX1(DELT,60.)),86400.)*KEEP,DTOT1)
*      THE ACCUMULATOR IS EMPTIED AFTER MIDNIGHT,
*      SO CONTENTS ARE AVAILABLE FOR PRINTING
ENDMAC
*
*
MACRO MONTH, J = MTIME(JDAY)
   MONTH = (JDAY/29) + 1
   J = JDAY - DAYS(MONTH)
   IF (J.GE.1) GO TO 775
   MONTH = MONTH - 1
   J = JDAY - DAYS(MONTH)
775 CONTINUE
TABLE DAYS(1-13)=0,31,59,90,120,151,181,212,243,273,304,334,365
*  NOTE THAT THE NUMBER OF DAYS AT THE END OF EACH MONTH SHOWN ABOVE
*    IS ONLY CORRECT FOR NON-LEAP YEARS.   ADD 1 FEB-DEC FOR LEAP YEARS.
ENDMAC
SYSTEM GEN
SYSTEM NPOINT=6000
*DECK
TABLE  SMAX(1-6) = .35  , 1.0E10  , .004  , 2.0,+0.3E-7, 5.0E2
TABLE  SMIN(1-6) = .05  , -0.5  , 0.0  ,  -.1,-0.3E-7, 0.0
*  SCALE FACTORS FOR VERTICAL GRADIENT PLOTS
*
*
*
** * * * * * * * * * * *  INITIAL SEGMENT  * * * * * * * * * * * * * * *
INITIAL
*
      ZYX = DEBUG(01,0.0)
*
****      LOAD FUNCTIONS FOR REAL WEATHER DATA                       **
*
PROCEDURE MONTH,DAY,MAXTEM,MINTEM,CMRAIN,RADN,SIMDAY  = AAA(TIME)
*
*     XX = DEBUG(01,0.0)
*     READ(11,511) ISHOOT,IROOT,IDAY,ICHO
*     READ(11,512) (ITHETA(I),I=1,11)
*     READ(11,512) (RRL(I),I=1,10)
*     WRITE(06,511) ISHOOT,IROOT,IDAY,ICHO
*     WRITE(06,512) (ITHETA(I),I=1,11)
*     WRITE(06,512) (RRL(I),I=1,10)
  511 FORMAT(08G10.4)
  512 FORMAT(11G07.2)
      JULIAN = START + TIME / 86400.
      SIMDAY = JULIAN
```

```
1853 FORMAT(/,' INITIATE  ',/,4X,'SIMDAY',8X,'RADN',7X,'MAXTEM')
*      WRITE(6,1853)
       IF (START.GT.400) GO TO 500
FUNCTION MAXTMP
       CALL FGLOAD(MAXTMP,0.,19.,1)
       DO 01 K=1,365
       READ(4,91,END=301) RADN, MAXTEM, MINTEM, CMRAIN, PEVAP ,...
       MAXSTM,MINSTM,SIMDAY
*   READ IN  HISTORICAL WEATHER RECORDS OF INTEREST
   91 FORMAT(F3.0,1X,F5.1,F6.1,F6.2,F7.3,F3.0,F3.0,T76, F3.0)
       JULIAN = SIMDAY
       JDAY   = JULIAN
       MONTH, J = MTIME(JDAY)
       IF (SIMDAY.GT.400) GO TO 101
*      WRITE(6,92) SIMDAY, RADN, MAXTEM, MINTEM, CMRAIN, PEVAP,MONTH,...
*       MAXSTM,MINSTM,J , JDAY
   92 FORMAT(11G10.4)
  101  MAXTEM = ( MAXTEM - 32. ) * 5. / 9.
       CALL FGLOAD(MAXTMP,JULIAN,MAXTEM,1)
*   LOADING INPUT FILES INTO APPROPRIATE FUNCTIONS FOR INTERPOLATION
   01 CONTINUE
  301 CALL FGLOAD(MAXTMP,400.,MAXTEM,1)
*      GO TO 500
       REWIND 4
FUNCTION MINTMP
       CALL FGLOAD(MINTMP,0.,15.,1)
       DO 11 K=1,365
       READ(4,91,END=302) RADN, MAXTEM, MINTEM, CMRAIN, PEVAP ,...
       MAXSTM,MINSTM,SIMDAY
*   READ  HISTORICAL WEATHER RECORDS AGAIN (FGLOAD CAN LOAD ONLY ONE
*                                                FUNCTION AT A TIME).
       JDAY = SIMDAY
       JULIAN = JDAY
       MINTEM = ( MINTEM - 32. ) * 5. / 9.
       IF (SIMDAY.GT.200) GO TO 1011
*      WRITE(6,92) SIMDAY,                MINTEM,   JDAY, JULIAN
 1011 CALL FGLOAD(MINTMP,JULIAN,MINTEM,1)
*   LOADING OF MINTEM VALUES INTO FUNCTION MINTMP
   11 CONTINUE
  302 CALL FGLOAD(MINTMP,400.,MINTEM,1)
*      GO TO 500
   88 REWIND 4
FUNCTION RADFCN
       CALL FGLOAD(RADFCN,0.,100.,1)
       DO 12 K=1,365
       READ(4,91,END=303) RADN, MAXTEM, MINTEM, CMRAIN, PEVAP ,...
       MAXSTM,MINSTM,SIMDAY
*   READ  HISTORICAL WEATHER RECORDS YET ANOTHER TIME
       JDAY = SIMDAY
       JULIAN = JDAY
       RADN = RADN * 4.2 * 10000
       IF (SIMDAY.GT.365) GO TO 1012
*      WRITE(6,92) SIMDAY, RADN,    JULIAN,    JDAY
 1012 CALL FGLOAD(RADFCN,JULIAN,RADN,1)
```

```
*  LOADING OF RADN VALUES INTO FUNCTION RADFCN
   12 CONTINUE
  303 CALL FGLOAD(RADFCN,400.,RADN   ,1)
*      GO TO 500
   89 REWIND 4
FUNCTION RNFALL
      CALL FGLOAD(RNFALL,0.,0.1,1)
      DO 13 K=1,365
      READ(4,91,END=304) RADN, MAXTEM, MINTEM, CMRAIN, PEVAP ,...
      MAXSTM,MINSTM,SIMDAY
*  READ  HISTORICAL WEATHER RECORDS YET ANOTHER TIME
      CMRAIN = CMRAIN * 2.54
*     CMRAIN = 0.0
      JDAY = SIMDAY
      JULIAN = JDAY
      IF (SIMDAY.GT.200) GO TO 1013
*     WRITE(6,92) SIMDAY, CMRAIN,            JDAY
 1013 CALL FGLOAD(RNFALL,JULIAN,CMRAIN,1)
*  LOADING OF RADN VALUES INTO FUNCTION RADFCN
   13 CONTINUE
  304 CALL FGLOAD(RNFALL,400.,CMRAIN,1)
  500 CONTINUE
   90 REWIND 4
FUNCTION PEV
      CALL FGLOAD(PEV,0.,0.1,1)
      DO 14 K=1,365
      READ(4,91,END=305) RADN, MAXTEM, MINTEM, CMRAIN, PEVAP ,...
      MAXSTM,MINSTM,SIMDAY
*  READ  HISTORICAL WEATHER RECORDS YET ANOTHER TIME
      PEVAP = PEVAP * 2.54
      JDAY = SIMDAY
      JULIAN = JDAY
      IF (SIMDAY.GT.200) GO TO 1014
*     WRITE(6,92) SIMDAY, PEVAP,            JDAY
 1014 CALL FGLOAD(PEV,JULIAN,PEVAP,1)
*  LOADING OF PEVAP  VALUES INTO FUNCTION PEV
   14 CONTINUE
  305 CALL FGLOAD(PEV,400.,PEVAP,1)
  501 CONTINUE
  191 REWIND 4
FUNCTION MXSTMP
      CALL FGLOAD(MXSTMP,0.,19.,1)
      DO 1115 K=1,365
      READ(4,91,END=306) RADN, MAXTEM, MINTEM, CMRAIN, PEVAP ,...
      MAXSTM,MINSTM,SIMDAY
*  READ IN  HISTORICAL WEATHER RECORDS OF INTEREST
      JULIAN = SIMDAY
      JDAY   = JULIAN
      MONTH, J = MTIME(JDAY)
      MAXSTM = ( MAXSTM - 32. ) * 5. / 9.
      IF (SIMDAY.GT.200) GO TO 1015
*     WRITE(6,92) SIMDAY, RADN, MAXTEM, MINTEM, CMRAIN, PEVAP,MONTH,...
*      MAXSTM,MINSTM,J , JDAY
 1015 CALL FGLOAD(MXSTMP,JULIAN,MAXSTM,1)
```

```
*  LOADING INPUT FILES INTO APPROPRIATE FUNCTIONS FOR INTERPOLATION
 1115 CONTINUE
  306 CALL FGLOAD(MXSTMP,400.,MAXSTM,1)
*     GO TO 500
  192 REWIND 4
FUNCTION MNSTMP
      CALL FGLOAD(MNSTMP,0.,15.,1)
      DO 16 K=1,365
      READ(4,91,END=307) RADN, MAXTEM, MINTEM, CMRAIN, PEVAP ,...
      MAXSTM,MINSTM,SIMDAY
*  FINAL READING OF HISTORICAL WEATHER RECORDS AGAIN
*
      JDAY = SIMDAY
      JULIAN = JDAY
      MINSTM = ( MINSTM - 32. ) * 5. / 9.
      IF (SIMDAY.GT.200) GO TO 1017
*     WRITE(6,92) SIMDAY,               MINTEM,   JDAY, JULIAN
 1017 CALL FGLOAD(MNSTMP,JULIAN,MINSTM,1)
*  LOADING OF MINSTM VALUES INTO FUNCTION MNSTMP
   16 CONTINUE
  307 CALL FGLOAD(MNSTMP,400.,MINSTM,1)
*     GO TO 500
  193 REWIND 4
*
      JJ = J
      T = MONTH
      TT=T
*  DOUBLE LETTERS ARE REAL NUMBER REPRESENTATION FOR OUTPUT VARIABLES.
*
*     ZY= DEBUG(01,0.0)
ENDPRO
*
PARAM PI = 3.14159
PARAM ECON = 2.71828
      RAD = PI/180.
*  STANDARD MATHEMATICAL CONSTANTS
*
*****     LOCATION TO BE SIMULATED  - AUBURN ALA., USA.
PARAM LAT = 32.5
      CSLT = COS(RAD*LAT)
*     COSINE LATITUDE
      SNLT =SIN(RAD*LAT)
*     SINE LATITUDE
*
*
```

```
** * * * * * * * * * * * RUN CONTROL * * * * * * * * * * * * * * * * * * * *
*
TIMER   FINTIM= 4320000000., OUTDEL =03600.,PRDEL=3600.,...
   DELT=03600.,DELMIN=1.00,DELMAX=3600.
      JULIAN = START + TIME/86400.
*  BASIC TIMER UNITS ARE SECONDS.  SEE TIME DEFINITIONS IN DYNAMIC SECT.
       OUTF = 3.024E05
*  OUTPUT FUNCTION FOR VERTICAL GRADIENT PLOTS MADE DURING EXECUTION --
*  --INITIAL FREQUENCY FOR VERTICAL GRADIENT PLOTS IS INCREMENTED LATER.
*
*FINISH HOURS=2160.,POTCR= -300., SOLCHO = +1.0E-07, SHOOTW=0.0001, ...
FINISH HOURS=2400.,POTCR= -460., SOLCHO = +1.0E-07, SHOOTW=0.0001, ...
   TOPGRO = -1.0E-10, TOTRG = -1.0E-18 ,JULIAN=365.
*  THE SIMULATION WILL TERMINATE WHEN THE PLANT WATER POTENTIAL DROPS
*    BELOW -460 METERS WATER POTENTIAL (OR -4.5 MPA)  (BOYER, 1970),
* OR WHENEVER SOLUBLE CARBOHYDRATE IS EXPENDED (NO FOOD IN STORAGE).
      MTH = MONTH - 0.5 + ((DAY/30))
*  REAL-NUMBER REPRESENTATION OF MONTH, FOR INDEXING TABULAR FUNCTIONS.
*
*METHOD RECT
METHOD RKS
RELERR SOLCHO = 1.0E-02
ABSERR SOLCHO = 1.0E-02
RELERR POTCRD = 1.0E-01
ABSERR POTCRD = 1.0E-01
ABSERR LSNHS = 0.1
RELERR LSNHS = 0.1
RELERR SHOOTW = 1.0E-04
ABSERR SHOOTW = 1.0E-04
RELERR CUMRAD = 1.0E-03
ABSERR CUMRAD = 1.0E-03
*  SPECIFICATION OF CONVERGENCE CRITERIA FOR VARIABLE TIME-STEP INTGRLS
*
*
      RUNS = 0
      FLPFLP = -1.0
PARAMETER    ERROR  =  0.01
PARAMETER    CF  =  0.10
*  CORRECTION FACTOR AND ERROR PARAMETERS FOR ITERATIVE LOOP
*
*        **   INITIATION OF PLANT-GROWTH PARAMETERS
*
PARAM IPER = 0.03
      ICHO = (ISHOOT + IROOT) * IPER / ( 1. - IPER )
*  INITIAL CARBOHYDRATES (KG/M**2), AS DECIMAL FRACTION OF TOTAL WGT.
PARAM ISHOOT = 10.0E-03
PARAM IROOT = 02.00E-03
*   INITIAL SHOOT AND ROOT WEIGHTS, RESPECTIVELY (KG/M**2)
      DRYWT = ISHOOT + IROOT
      STEMW = STWTR * ISHOOT
      LEAFW = ISHOOT - STEMW
      LAI = LEAFW * LEAFTH
      IRTL = IROOT * LNGFAC
```

```
* METERS OF ROOT/SQUARE METER GROUND AREA AT INITIATION
PARAM RTDWPC = 10.
*  PERCENTAGE DRY MATTER OF ROOTS
PARAM LNGFAC = 13000.0
*  LENGTH FACTOR, AS METERS OF ROOT PER KG ROOT WEIGHT
*  (A FACTOR OF 1000 CORRESPONDS TO ABOUT 1 MM ROOT DIAMETER)
*  LEAF AREA INDEX -- AREA OF LEAF SURFACE/UNIT LAND AREA
TABLE  RRL(1-10) = 0.54, 0.38, 0.08, 0.00, 0.0,  ...
   0.0  , 0.0, 0.0, 0.0, 0.0
*TABLE  RRL(1-10) = 2.7E-01, 2.5E-01, 2.4E-01, 2.1E-01, 0.03,  ...
*     .00, 0.0, 0.0, 0.0, 0.0
*  RELATIVE ROOT LENGTH (AS FRACTION OF TOTAL)
      C1=2
      C2=1
      O1=2
      O2=1
*
*        **   INITIATION OF WATER-BALANCE PARAMETERS
*
TABLE  ITHETA(1-11) = 0.200, 0.200, 0.200, 0.200, 0.200, ...
      0.200, 0.200, 0.200, 0.200, 0.230,0.300
*  INITIAL SOIL WATER CONTENT (VOLUME FRACTION)
*    (INITIATED TO VALUES FOUND AFTER 12 DAYS OF DRAINING FROM
*     SATURATION AT 20% WATER IN ALL LAYERS)
*
PARAM STHETA = 0.36
      SATCON =  5.00E-03 / 100
*PARAM SATCON = 10.00E-03 / 100
*  SATURATED CONDUCTIVITY, AS M/SEC
       ETA = 2.0 + 3.0 * ZLAM
PARAM ZLAM = 0.64762
*  Z(LAMBDA), AFTER LALIBERTE, BROOKS, & COREY
PARAM ALPHA = 0.24890
PARAM NU = 1.21555
      MU = 1 - ( 1 / NU )
* A,N,M FOR HYDRAULIC CONDUCTIVITY CALCULATIONS AFTER VAN GENUCHTEN,1978
PARAM PARTDS = 2.59
*  PARTICLE DENSITY
FUNCTION BULKF = ((0.0,1.52),(1.0,1.52),(2.0,1.52))
* BULKDENSITY AS A FUNCTION OF DEPTH
TABLE  TCOM(1-20) = .10, 2 * .15 ,17 * .20
*  THICKNESS OF EACH VERTICAL LAYER (COMPARTMENT),  METERS
*
NOSORT
**PROCEDURE DEPTH,DIST,PRTL,RSRT,IVOLW = INTLZ(TCOM,RRL)
*     ZYX = DEBUG(01,0.0)
PARAM NJ = 10
      NJJ = NJ+1
*  ONE MORE THAN THE NUMBER OF LAYERS IN THE SOIL PROFILE (NJ)
      NNJ = NJ - 1
*  ONE LESS THAN THE NUMBER OF LAYERS IN THE SOIL PROFILE (NJ)
      DO 15 I = 1,NJJ
  15  FLW(I) = 0.0
*  FLOW OF WATER PAST BOTTOM OF EACH LAYER, INITIATED TO 0.0
```

```
*  THE NUMBER OF LAYERS(J) IN THE SOIL PROFILE
      DEPTH(1) = .5*(TCOM(1))
      DIST(1) = DEPTH(1)
      IVOLW(1) =  ITHETA(1)*TCOM(1)*1.0
      DO 20  I = 2,NJJ
         DIST(I) = .5*(TCOM(I-1)+TCOM(I))
         DEPTH(I) = DEPTH(I-1) + DIST(I)
         IVOLW(I) =  ITHETA(I)*TCOM(I)*1.0
*  INITIAL VOLUME OF WATER IN EACH SOIL LAYER
   20 CONTINUE
 853 FORMAT(/,' INITIATE  ',/,9X,'I',3X,'IPRTL',5X,'RSRT',8X,'IVOLW')
       WRITE(6,853)
* 853 FORMAT(/, ' INITIATION    ', /, 8X, 'I', 5X, 'IPRTL', 5X, ...
*      'RSAT', 6X, 'IVOLW', 5X, 'TCOM', 4X, 'ITHETA', 5X, 'IRTL', ...
*      6X, 'RRL', 5X, 'DEPTH', /)
      DO 30  I = 1,NJ
      IPRTL(I) = IRTL * RRL(I)
*  PARTIAL ROOT LENGTH, AT INITIATION
      IRTWT(I) = IPRTL(I) / LNGFAC
*  ROOT WEIGHT, AT INITIATION
      IRTVL(I) = IRTWT(I) * 100. / (RTDWPC*1000)
*  ROOT VOLUME, AT INITIATION
      RRS(I) = URRS / (IPRTL(I) +NOT(IPRTL(I))*1.0E-10)
*  RADIAL RESISTANCE TO WATER FLOW IN THE ROOT
      ARS(I) = UARS * DEPTH(I) / (IPRTL(I) + NOT(IPRTL(I))*1.0E-10)
*  AXIAL RESISTANCE -- ALONG THE XYLEM TRANSPORT SYSTEM
      RSRT(I) = RRS(I) + ARS(I)
* RESISTANCE OF THE ROOTS
      WRITE(6,454) I,IPRTL(I),RSRT(I),IVOLW(I),TCOM(I),ITHETA(I), ...
        IRTL, RRL(I), DEPTH(I)
  454 FORMAT(3G10.3, 3F10.5, G10.3, 2F10.5, 3G10.3)
   30 CONTINUE
**ENDPRO
*
      POTCR = -20.000
* POTENTIAL OF THE CROWN (SHOOT), INITIATED BELOW DRIEST SOIL LAYER
*  (-20 METERS = -0.2 MPA)
*
FUNCTION  SUTB = (0.00,60.),(0.0674,40.81),(0.0940,21.21),...
(0.1119,15.27),(0.1263,7.325),(0.1363,4.11),(0.1531,2.01),...
(0.1705,0.99),(0.2063,0.425),(0.2461,0.264),...
(0.36,0.0),(0.42,0.0),(0.50,0.0)
*   IN - SITU RHIZOTRON DATA 1982
NOSORT
      DO 10  I = 2,101
   10 LINE(I) = IB
*  INITIATES PRINT-LINE FOR VERTICAL PLOTS TO BLANK CHARACTER-STRING
*
*
      ZZZ = DEBUG(01,0.0)
*
```

```
** * * * * * * * * * *  DYNAMIC SEGMENT  * * * * * * * * * * * * * * *
DYNAMIC
*
*
*     YYY =DEBUG(100,1359000.)
*     ZZ = DEBUG(01,86400.)
*
*
**                             **  TIME CALCULATIONS  **
PARAM START = 150.
*  BEGINNING DATE FOR THIS SIMULATION RUN
      JULIAN = START + TIME/86400.
      DAY = JULIAN
*  JULIAN DATE OF SIMULATION
      JDAY =  JULIAN
*  INTEGER REPRESENTATION OF JULIAN DAY, FOR INPUT TO MTIME
PROCEDURE MONTH, J = AAA(JDAY)
      MONTH, J = MTIME(JDAY)
ENDPRO
*
      T = MONTH
      TT = T
*  INTEGER AND REAL-NUMBER REPRESENTATIONS, RESPECTIVELY.
      MTH = MONTH - 0.5 + ((AGE/30))
*  REAL-NUMBER REPRESENTATION OF MONTH, FOR INDEXING AND OUTPUT
*
      JJ = J
*  CALENDAR DAY OF THE MONTH
      AGE = HOURS / 24.00
* DAYS OF SIMULATION (CUMULATIVE, SINCE BEGINNING OF RUN).
*
      HOURS = TIME/3600.0
*  CUMULATIVE HOURS OF SIMULATION TIME
      HOUR = AMOD(HOURS,24.0)
*  CLOCK TIME, IN HOURS
      RUN = RUNS
*  CREATES A REAL-NUMBER COUNTING VARIABLE FOR PRINTER OUTPUT
*
*        DIRECTION OF THE SUN
      DEC = -23.4*COS(2.*PI*(JULIAN+10.)/365.)
*     DECLINATION OF THE SUN
      SNDC = SIN(RAD*DEC)
*     SINE DECLINATION
      CSDC = COS(RAD*DEC)
*     COSINE DECLINATION
      SNHSS=SNLT*SNDC+CSLT*CSDC*COS(PI*(HOUR+12.)/12.)
*     SINE OF THE HEIGHT OF THE SUN
      LSNHS=INTGRL(-0.5,(SNHSS-LSNHS)/DELT)
*     SUN HEIGHT AT LAST TIME STEP
      RISE = ZHOLD(AND(SNHSS,-LSNHS)-0.5,HOUR-SNHSS*DELT/      ...
             ((NOT(SNHSS-LSNHS)+SNHSS-LSNHS)*3600.)-RISEI)+RISEI
*     TIME OF SUN RISE TODAY, IN HOURS, ESTIMATED FOR TOMORROW
INCON RISEI = 4.8
*
```

```
*
*                 **  ESTIMATION OF TEMPERATURE EFFECTS  **
*
      TMPFCS = 10.0 ** ((TEMP-REFT) * 0.030103)
      TMPFCR = 10.0 ** ((STEMP-REFTS) * 0.030103)
*  BIOLOGICAL Q-10 -- DOUBLING REACTION RATE AT EACH 10 DEGREE TEMP CHNG
      TEMP = WAVE(JULIAN,HOUR,MINTMP,MAXTMP,RISE)
*  AIR TEMPERATURE, AS DEGREES C.
      REFT = 25.
      AVAT = (MAXTEM + MINTEM) * 0.500
*   AVERAGE AIR TEMPERATURE, FROM DAILY MEASUREMENT DATA
      MAXTEM = AFGEN(MAXTMP,JULIAN-(14./24.))
      MINTEM = AFGEN(MINTMP,JULIAN-(RISE/24.))
*   LINEAR INTERPOLATION FROM INPUT DATA-FILE
      RANGE = (MAXTEM - MINTEM) * 0.500
*  AIR TEMPERATURE, AS DEGREES C.
*
      STEMP = WAVE((JULIAN-0.16),(HOUR-4.),MNSTMP,MXSTMP,RISE)
      REFTS = 25.
      AVST = (MAXSTM + MINSTM) * 0.500
*   AVERAGE SOIL TEMPERATURE, FROM DAILY MEASUREMENT DATA
      MAXSTM = AFGEN(MXSTMP,JULIAN-(14.+4.)/24.)
      MINSTM = AFGEN(MNSTMP,JULIAN-(RISE+4.)/24.)
*   LINEAR INTERPOLATION FROM INPUT DATA-FILE
      RANGES = (MAXSTM - MINSTM) * 0.500
*   AMPLITUDE OF DAILY TEMPERATURE OSCILLATIONS
PARAM DELAY = 21600.
* DELAY FUNCTION, BASED UPON SOIL HEAT CAPACITY (HALF-TIME FOR
* EQUILIBRATION, IN RECIPROCAL SECONDS).
*
*          **       RESERVE LEVELS AND TISSUE GROWTH             **
*
      RESL = SOLCHO / (SOLCHO + ROOTW + SHOOTW)
*  RESERVE LEVEL, % FREE CARBOHYDRATE IN TISSUES
*
      SOLCHO = INTGRL(ICHO, (PHOTSN * PHTCAR - GROWTH - RESP) )
      PHTCAR = 30. / 44.
*  SOLUBLE CARBOHYDRATES (FREELY MOBILE, AS METABOLIC RESERVES)
*     (KG/SQUARE METER)
*
      GROWTH = TOPGRO + TOTRG
*  TOTAL GROWTH OF BOTH SHOOT AND ROOT SYSTEM
*
*
**                **  ESTIMATION OF RADIATION INTENSITY  **
*
      CUMRAD = INTGRL(0.,RADN/86400.)
      DAYRAD = (1-IMPULS(0.,86400.))*INTGRL(0.,RADN/86400.)
*  CUMULATIVE TOTAL RADIATION RECEIVED--COMPARE WITH INPUT VALUES.
      RADN = AMAX1(0.0, SIN(2*PI * (DAY - 0.250))) * MAXRAD * 3.0
*  RADIATION INTENSITY (INSTANTANEOUS VALUE)
*    FACTOR OF 3.0 PUTS ABSOLUTE VALUE ON SCALE WITH RIGHT UNITS
      MAXRAD = AFGEN(RADFCN,JULIAN)/86400.
```

```
*   RADIATION INTENSITY, INTERPOLATED FROM INPUT FILE
      SNHS = AMAX1(0.,SNHSS)
      HSUN = ATAN(SNHS/SQRT(1.-SNHS*SNHS))/RAD
      DIFOV = AFGEN(DFOVTB,HSUN)
FUNCTION DFOVTB = (0.,0.),(5.,6.),(15.,26.),(25.,45.),(35.,64.),...
         (45.,80.),(55.,94.),(65.,105.),(75.,112.),(90.,116.)
*     DIFFUSE OVERCAST VISIBLE
      DIFON = 0.7 * DIFOV
*     DIFFUSE OVERCAST INFRARED
      DIFCL = AFGEN(DFCLTB,HSUN)
FUNCTION DFCLTB = (0.,0.),(5.,29.),(15.,42.),(25.,49.),(35.,56.),...
         (45.,64.),(55.,68.),(65.,71.),(75.,75.),(90.,77.)
*     DIFFUSE CLEAR
      SUNDCL = AFGEN(SUNTB,HSUN)
FUNCTION SUNTB = (0.,0.),(5.,0.),(15.,88.),(25.,175.),(35.,262.),...
         (45.,336.),(55.,402.),(65.,452.),(75.,483.),(90.,504.)
*     DIRECT CLEAR
      CRC = (SUNDCL+DIFCL)*2.
*     CURRENT RADIATION CLEAR, ALL WAVELENGTHS
      CRO = DIFOV + DIFON
*     CURRENT RADIATION, OVERCAST
      DRC = DLYTOT(DRCI,CRC)
      DRO = DLYTOT(DROI,CRO)
INCON DROI = 6.6E6
INCON DRCI = 3.5E7
      DRCP = ZHOLD(IMPULS(0.,86400.),DRC)
      DROP = ZHOLD(IMPULS(0.,86400.),DRO)
      DTRR=AFGEN(RADFCN,(JULIAN-0.0))
      DTR = ZHOLD(IMPULS(0.,86400.)*KEEP,DTRR)
      FCL = (DTR - DROP)/(NOT(DRCP-DROP)+DRCP-DROP)
      FOV = 1. - FCL
      LFOV = LIMIT(0.,1.,FOV)
      LFCL = 1. - LFOV
      RADIAT = LFCL * CRC + LFOV * CRO
      DRAD = DLYTOT(DRADI,RADIAT)
INCON DRADI = 1.E-10
*
*
*                   **     PHOTOSYNTHETIC ACTIVITY     **
*
*PARAM MXPHOT = 0.6944E-6
PARAM MXPHOT = 0.8200E-6
* MAXIMUM PHOTOSYNTHETIC RATE  -  25 MG CO2 DM-2 (LEAF) H-1
PARAM DKPHOT = 0.
* NET ASSIMILATION IN THE DARK - DARK RESPIRATION OF THE LEAVES
      RADCPH = 0.5 * CRC
      RADOPH = 0.5 * CRO
* PHOTOSYNTHETIC ACTIVE RADIATION
PARAM EFF = 0.01388E-6
*EFFICIENCY AT THE LIGHT COMPENSATION POINT - 0.5 KG CO2 J-1 HA-1 H-1 M2
      SLLA = AMIN1(LAI,2*SNHS)
* SUNLIT LEAF AREA
      DLLA = LAI - SLLA
```

```
* TOTAL LEAF AREA IN THE SHADE
      XOVC = RADOPH * EFF / ( MXPHOT * LAI )
      POVC = XOVC / ( XOVC + 1. )
      PHOTD = LAI * MXPHOT * POVC
* MAXIMUM CANOPY PHOTOSYNTHESIS UNDER AN OVERCAST SKY
      XS = ALOG ( 1+(0.45 * EFF*RADCPH/(AMAX1(SLLA,0.0001)*MXPHOT)))
      PS = XS / ( 1 + XS )
      PHOTS = SLLA * MXPHOT * PS
* MAXIMUM CANOPY PHOTOSYNTHESIS UNDER A CLEAR SKY FOR SUNLIT LEAFAREA
      XSH = ALOG( 1+(0.55 * EFF * RADCPH/(AMAX1(DLLA,0.0001)*MXPHOT)))
      PSH = XSH / ( 1 + XSH )
      PHOTSH = DLLA * MXPHOT * PSH
* MAXIMUM CANOPY PHOTOSYNTHESIS UNDER A CLEAR SKY FOR SHADED LEAFAREA
PROCEDURE PHOTC,PHOTSN,PHOTSM=PROCPH(PHOTS,PHOTSH,PHOTD,WATRST,TMPFCS)
      PHOTC = PHOTS + PHOTSH
      IF ( LAI .GT. 03) GO TO 31
      IF (  RADIAT .EQ. 0 ) GO TO 31
      FINT = ( 1. - EXP(-0.8*LAI))
      C1 = FINT * PHOTC
      C2 = LAI * MXPHOT
      O1 = FINT * PHOTD
      O2 = C2
      IF ( C1 .GT. C2 ) GO TO 32
      C0 = C1
      C1 = C2
      C2 = C0
   32 CONTINUE
      PHOTC = C2 * ( 1. - EXP ( - C1 / (NOT(C2)+C2) ))
      IF ( O1 .GT. O2 ) GO TO 33
      O0 = O1
      O1 = O2
      O2 = O0
   33 CONTINUE
      PHOTD = O2 * ( 1. - EXP ( - O1 / (NOT(O2)+O2) ))
   31 CONTINUE
      PHOTSN = WATRST * ( PHOTC * LFCL + PHOTD * LFOV)
      PHOTSM = ( 1.- IMPULS(1800.,86400.))*AMAX1(PHOTSN,PHOTSM)
*  PHOTOSYNTHETIC RATE (NET CARBON FIXATION, KG/SQUARE METER/SECOND
ENDPRO
*
*
*        **            ROOT AND SHOOT RESPIRATION          **
*
      RESP = RESPSH + RESPRT
*  TOTAL RESPIRATION, INCLUDING BOTH SHOOT AND ROOT SYSTEM
      RESPSH = SHMRES + SHGRES
*  RATE OF SHOOT RESPIRATION (KG/SQ METER/SEC)
*    (SUM OF GROWTH RESPIRATION AND MAINTENANCE RESPIRATION)
      SHMRES = SHOOTW * TMPFCS * RSPFAC
      CSTMRS = INTGRL( 0.0,SHMRES)
*  SHOOT MAINTENANCE RESPIRATION
PARAM RSPFAC = 1.0E-07
*  RESPIRATION FACTOR, CONVERTING UNITS AND PROPORTIONING
      SHGRES = TOPGRO * CONVRT
```

```
*   SHOOT GROWTH RESPIRATION
PARAM CONVRT = 0.30
*  CONVERSION EFFICIENCY (WEIGHT OF TISSUE PRODUCED PER GRAM INPUT
*   (INCLUDES RESPIRATION FOR TRANSPORT AND CHEMICAL CONVERSIONS)
*
      RESPRT = RTMRES + RTGRES
*  RESPIRATION OF ROOT SYSTEM
      RTMRES = ROOTW * RSPFAC * TMPFCR
      CRTMRS = INTGRL(0.0,RTMRES)
*  ROOT MAINTENANCE RESPIRATION
      RTGRES = TOTRG*CONVRT
*  ROOT GROWTH RESPIRATION, INCLUDING CHEMICAL CONVERSION AND TRANSPORT
*
*           **   GROWTH AND DEATH OF SHOOT TISSUE       **
*
      SHOOTW = INTGRL(ISHOOT, (TOPGRO - SHOOTD))
*  WEIGHT OF LIVING SHOOT TISSUE (KG/SQ METER)
*
      TOPGRO = TMPFCS * GROFAC * SOLCHO * FRAC
*     TOPGRO = TMPFCS * GROFAC * SOLCHO * FRG
*   RATE AS (KG/SQ METER/SEC) OF SHOOT (STEMS, LEAVES, AND FRUIT)
*     FRAC = AFGEN(FRACTB,POTCR)
      FRAC = AFGEN(FRACTB,POTCRE)
*   FRACTIONAL GROWTH, AS PERCENT OF CARBON GOING INTO THE SHOOT
      POTCRE = AMIN1(POTCR, POTCRD)
*  EFFECTIVE CANOPY WATER POTENTIAL
      POTCRD = INTGRL(10.,(POTCR - POTCRD)/DELAY)
*  DELAYED CANOPY WATER POTENTIAL
*PARAM DELAY = (21600., 1800.)
PARAM DELAY =  21600.
*  DELAY TIME FOR COMPUTING OF POTCRD, IN SECONDS
PARAM FRG = 0.666
*PARAM FRG = (0.0, 1.0, 0.666)
*  FRACTION OF CARBOHYDRATES GOING TOWARD SUPPORT OF SHOOT GROWTH
FUNCTION FRACTB = -500.,.05, -200.,.20, -050.,.65, -05.,.90, ...
      100.,.90
*  UNITS = %, AS A FUNCTION OF CANOPY WATER POTENTIAL, POTCR
*
*
      SHOOTD = LEAFW * TMPFCS * DTHBGN * AGING
*     SHOOTD = SHOOTW * TMPFCS * DTHBGN * AGING
*  SHOOT DEATH RATE (PRINCIPALLY LEAF-DROP DUE TO AGE AND WATER STRESS)
      DTHBGN = AFGEN(DTBL, LAI)
*  LEAVES BEGIN DYING AS LAI INCREASES ABOVE 2, DUE TO SELF-SHADING
FUNCTION DTBL = 0.0,0.0, 2.0,0.03, 5.0,0.33, 07.0,0.97,10.,1.00,25.,1.0
      AGING = AGFAC * (AGE/30.)
*PARAM AGFAC = 3.0E-7
PARAM AGFAC = 3.0E-07
*
      DRYWT = SHOOTW + ROOTW
      STEMW = STWTR * SHOOTW
      LEAFW = SHOOTW - STEMW
PARAM STWTR = 0.25
      LAI = LEAFW * LEAFTH
```

```
*  LEAF AREA INDEX, DIMENSIONLESS (AREA OF LEAF SURFACE/UNIT LAND AREA)
*PARAM LEAFTH =(2.5,5.0)
*PARAM LEAFTH = 4.0
PARAM LEAFTH = 30.
*  ROGERS ET AL., 1982
*  LEAF THICKNESS -- SQ. METERS LEAF AREA/SQ. METER SOIL, FOR EACH
*     KG. SHOOT WGT ON THE SAME LAND AREA
*
*              **        GROWTH AND DEATH OF AGGREGATED ROOT SYSTEM   **
*
      ROOTW = INTGRL(IROOT,(TOTRG-ROOTDY))
*  WEIGHT OF LIVE ROOT TISSUE(ALL SOIL LAYERS)
      ROOTL = ROOTW * LNGFAC
*  LENGTH OF LIVE ROOT TISSUE(ALL SOIL LAYERS)
      TOTRG = (1.0 - FRAC) * SOLCHO * GROFAC * TMPFCR
*     TOTRG = (1.0 - FRG) * SOLCHO * GROFAC * TMPFCR
*  TOTAL ROOT GROWTH, SUM OF ROOT WEIGHT IN ALL SOIL LAYERS
PARAM GROFAC = 1.0E-05
*  RELATIVE CONSUMPTION RATE FOR RESERVES -- AFTER DE WIT:
*   (GROWTH FACTOR, CONVERTING SOLUBLE CARBOHYDRATE TO TISSUE BIOMASS)
*
      ROOTDY = ROOTW / RESL* DTHFAC * TMPFCR
*  RATE OF DYING FOR TOTAL ROOT SYSTEM -- MODULATED IN SUMMATION  OF
*    DEATH RATES FOR ROOTS IN EACH SOIL LAYER IN A LATER SECTION.
* INVERSELY PROPORTIONAL TO CARBOHYDRATE RESERVES--DYING OFF WHEN HUNGRY
*  (RATE EXPRESSED AS KG ROOTS/SQUARE METER/SECOND -- WHOLE PLANT)
PARAM DTHFAC = 1.0E-08
*PARAM DTHFAC = (1.0E-07, 1.0E-09, 1.0E-05)
*  FACTOR TO SCALE ROOT DEATH RATE
*
*
*               **  TRANSPIRATION **
*
      TRANSP = 1.0 * WATRST * PET * LAIFAC
*  TRANSPIRATION LOSSES, AS METER/SECOND
      WATRST = AFGEN(TRNTBL,POTCR)
*  WATER STRESS IN PLANT TISSUE
*
FUNCTION TRNTBL = -500.,.05, -245.,.05,-163.,0.50,-112.,0.95,0.,1.0
*  TRANSPIRATION TABLE FOR SOYBEAN ( BOYER, 1970)
*FUNCTION TRNTBL = -500.,.05, -200.,.05, -010.,0.95, 0.,1.0, 100.,1.0
*  TRANSPIRATION TABLE FOR SUCCULENT CROPS SUCH AS MAIZE
*FUNCTION TRNTBL = -500.,0., -400.,0.02, -300.,0.06,      ...
*      -150.,0.75, -50.,0.96, 0.,1.00, +200.,1.00
*  TRANSPIRATION TABLE FOR DROUGHT-TOLERANT CROPS-EG. COTTON OR SORGHUM
*
      LAIFAC = AFGEN(LAITBL,LAI)
*  LEAF AREA INDEX FACTOR, PARTITIONS WATER LOSS BETWEEN PLANT & SOIL
FUNCTION LAITBL =
0.,0.,2.0,0.5,4.0,0.8,6.0,0.9,10.0,0.95,25.,0.95
*
```

```
**                   **  ESTIMATION OF SOIL WATER BALANCE  **
*
      WATER = ZHOLD(IMPULS(0.,86400.)*KEEP,RNF)
      RAIN = WATER / 86400.
      DAYRAI = DLYTOT(DRADI,RAIN)
* CUMULATIVE SUM OF WATER ADDED BY RAINFALL--COMPARE WITH WEATHER DATA
      RNF = AFGEN(RNFALL,JULIAN) * 0.01
*   RAINFALL (M) OCCURRING ON THIS DATE, IN UNITS OF CM/DAY
*
      PET =AMAX1(PEVV * 0.01 / 86400., RADIAT * PEVVV /...
           (AMAX1(0.01,DTR *  1.0 )))
*  POTENTIAL EVAPOTRANSPIRATION, BASED ON TEMPERATURE (& RADIATION)
*   (NOT LESS THAN 1% OF AVERAGE TRANSP. DEMAND--NEGATIVES ELIMINATED)
*
       CUMPET = DLYTOT(DRADI,PET)
*  CUMULATIVE POTENTIAL EVAPOTRANSPIRATION -- COMPARE OUTPUT WITH AVPET
*
      PEVV = AFGEN(PEV,JULIAN) * 0.01
*  MEASURED POTENTIAL EVAPOTRANSPIRATION IN FIELD (METER PER DAY)
      PEVVV = ZHOLD(IMPULS(0.,86400.)*KEEP,PEVV)
      SLEVAP = PET * (1.0 - LAIFAC) * 1.0
* SOIL EVAPORATION (METER/SEC), PET REDUCED BY LEAF SHADING
*
*                   **  SOIL WATER MOVEMENT CALCULATIONS **
*
      VOLW   = INTGRL  (IVOLW   , NFLW ,12)
*  VOLUME OF WATER STORED IN EACH SOIL LAYER
*
*       **  COMPUTE SOIL WATER CONTENT, POTENTIALS, AND CONDUCTIVITY
*
NOSORT
*PROCEDURE THETA, POTM, POTH, MPOT, RK, COND, C, D, E, F, G, H  ...
*       = PROC1(TIME, PB)
*     IRRIGATION SYSTEM
PARAM IRFAC = 10.
      IRMIN = 10.2118 * IRFAC / 100.
      PULSIR = IMPULS(0.0,1800.)
PARAM IRQUAN = (0.0,250.0)
*PARAM IRQUAN = 250.0
      PULSSW = INSW((IRMIN+POTM(3)),(IRQUAN*1.0E-6),0.)
      VOLW(1) = VOLW(1) + RAIN * DELT + PULSSW * PULSIR
*     VOLW(NJJ) = TCOM(NJJ) * 0.30
      DO 100 I = 1,NJJ
      BULKDS(I) = AFGEN(BULKF,DEPTH(I))
      POROS(I) = 1 - (BULKDS(I) / PARTDS)
*  POROSITY OF EACH SOIL LAYER
      THETA(I) = VOLW(I)/TCOM(I)
      DRAING = (AMAX1(0.0,THETA(NJJ)-STHETA))*TCOM(NJJ)/DELT
      THETA(I) = AMIN1(THETA(I),STHETA)
      VOLW(I) = THETA(I) * TCOM(I)
      POTM(I) = -AFGEN(SUTB,THETA(I))
      POTH(I) = POTM(I) - DEPTH(I)
  100 CONTINUE
*     WRITE (6, 854)(POTM(J),J=1,NJ)
```

```
*
*                    **  COMPUTE SOIL HYDRAULIC CONDUCTIVITY  **
*
      DO 85 I = 1, NJJ
      MPOT = -POTM(I) * 100.0
      IF (MPOT.LE. 0.0) GO TO 84
PARAM PB = 21.8258
*   BUBBLING PRESSURE (AIR ENTRY VALUE FOR TOPSOIL)
      AH = ALPHA * MPOT
      RK(I)=(1-(AH)**(NU-1)*(1+(AH)**NU)**(-MU))**2/                ...
       ((1+(AH)**NU)**(MU/2))
*   RELATIVE CONDUCTIVITY (AS A FRACTION OF SATURATED CONDUCTIVITY)
      GO TO 87
   84 RK(I) = 1.0
*  RELATIVE CONDUCTIVITY CAN NEVER BE MORE THAN 1.0;
*   THUS, SATURATED CONDUCTIVITY APPLIES IF MATRIC POTENTIAL IS POSITIVE
   87 CONTINUE
*     WRITE(6,854) I, MPOT, RK(I), AH, JDAY
  854 FORMAT(12G10.3)
      RK(I) = AMIN1(1.00, RK(I))
*  CONDUCTIVITY IS LIMITED TO A MAXIMUM OF THE SATURATED CONDUCTIVITY
      COND(I) = RK(I) * SATCON
*     COND(I) = RK(I) * SATCON / 8.6400E06
*  SOIL HYDRAULIC CONDUCTIVITY, METERS/SECOND
   85 CONTINUE
*     WRITE (6, 854)(RK(J), J=1,NJ)
*     WRITE (6, 854)(COND(J),J=1,NJ)
*
*ENDPRO
*
*    ** COMPUTE VERTICAL SOIL WATER FLOW (DARCIAN)     **
*
*PROCEDURE AVCOND, FLW, NFLW , CC, DD, EE = PROC2(POTH,FF)
      DO 110 I = 2,NJJ
      AVCOND(I) = .5 * (COND(I-1) + COND(I))
      FLW(I) = AVCOND(I) * (POTH(I-1)-POTH(I)) / DIST(I)
  110 CONTINUE
      FLW(NJJ+1) = DRAING
      NFLW(NJJ+1) = DRAING
PARAM THTAIR = 0.050
      POTMAR = - AFGEN(SUTB,THTAIR)
      IF (POTM(1) .GT. POTMAR) FLW(1)=-SLEVAP
      IF (POTM(1) .LE. POTMAR) FLW(1)=FLW(2)
* WATER FLOW OUT THE TOP IS LIMITED BY SUPPLY IF TOP LAYER IS DRY
      DO 120 I = 1,NJJ
         NFLW(I) = FLW(I) - FLW(I+1) - RTEX(I)
  120 CONTINUE
*ENDPRO
*
*   **  PARTITIONING AGGREGATE ROOT GROWTH BETWEEN SOIL LAYERS    **
*
*PROCEDURE BIRTH,EXTENS,RTGRO,SUMRG,RTDTH,SUMRD,NETGRO, ...
* W, AAA,BBB,CCC,DDD,EEE,FFF,GGG,SUMRTG,SUMRTD = PROC3(POTM,HHH)
*
```

```
*               **               ROOT GROWTH IN EACH LAYER                **
*
*PARAM BRMIN = -1.00
*PARAM EXTMIN = -2.00
PARAM BRMIN = -1.00
PARAM EXTMIN = -2.00
* THRESHOLD POTENTIAL, THE DRIEST SOIL IN WHICH ROOT GROWTH CAN OCCUR
*
      W =  AMAX1(0.0,  (POTM(2) - EXTMIN))
      DO  1010  I=1,NNJ
      X =  AMAX1(0.0,  (POTM(I) - BRMIN))
      XX =  AMAX1(0.0,  (POTM(I) - EXTMIN))
PARAM DEPTHG = 10.
      BIRTH(I)=(BR*(1.0-EXP(-AA*X**BB)))/(((DEPTH(I)*DEPTHG))**1.)
PARAM BR = 1.0E-04
*PARAM BR = 1.0E-08
*  BRANCHING RATE, FOR NEW ROOT GROWTH IN THE SAME SOIL LAYER
      EXTENS(I)=(EXTNRT*(1.0-EXP(-AA*XX**BB)))/(((DEPTH(I)*DEPTHG))**1.)
      IF ( PRTL(I) .LT. MINRTL * TCOM(I)) EXTENS(I) = 0.
PARAM MINRTL = 5.
PARAM EXTNRT = 3.0E-03
*  EXTENSION RATE, FOR NEW ROOT GROWTH FROM ONE LAYER INTO THE NEXT,
*    IN UNITS OF METERS/SECOND
PARAM AA =  8.0E-3
PARAM BB = 2.0
* COEFFICIENTS FOR SIGMOID ROOT GENERATION CURVES
*
 1010 CONTINUE
      RTGRO(1) = PRTL(1) * BIRTH(1) * (1.0 - FRAC) * TMPFCR
      SUMRG = RTGRO(1)
*  SUMMATION OF INSTANTANEOUS ROOT GROWTH RATES, OVER ALL SOIL LAYERS
*   (EXPRESSED AS METERS ROOTS/SQUARE METER SURFACE/SECOND)
      DO 647 I = 2,NNJ
      RTGRO(I) = (PRTL(I-1)*EXTENS(I-1) + PRTL(I)*BIRTH(I)) * ...
      (1.0 - FRAC) * TMPFCR
*     RTGRO(I) = (PRTL(I-1)*EXTENS(I) + PRTL(I)*BIRTH(I))
*  GROWTH EXPRESSED AS METERS/SEC IN EACH SQUARE METER OF EACH LAYER
*     RTGRO(NNJ) = 0.0
      SUMRG = RTGRO(I) + SUMRG
  647 CONTINUE
      RTGRO(NJ) = 0.0
*  TOTAL INCREASE, WHOLE PLANT, IN METERS/SQ. METER/SECOND
*
      SUMRTG = 0.0
      DO 648 I = 1,NNJ
      IF (SUMRG.EQ.0.00) GO TO 648
      RTGRO(I) = RTGRO(I) * TOTRG/SUMRG * LNGFAC
*  (BRINGS ACTUAL ROOT GROWTH IN EACH LAYER INTO LINE WITH TOTAL
*    PHOTOSYNTHATE AVAILABLE AT ANY GIVEN TIME).
      SUMRTG = SUMRTG + RTGRO(I)
  648 CONTINUE
*
      IF (YY .GT. 0.0) GO TO 751
      IF (TIME.GT.300)  GO TO 127
```

```
  751 CONTINUE
*     WRITE(6, 852)
  852 FORMAT( /, 15X, 'ROOT LENGTH, M/SQ.M, BY LAYER', T102, 'TIME')
*     WRITE (6,854) (PRTL(J),J=1,NJ), TIME
*     WRITE(6, 851)
  851 FORMAT(//, 35X, ' ROOT GROWTH RATE', 50 X, 'MATRIC POTENTIAL')
*     WRITE (6,854) (RTGRO(J),J=1,NJ), (POTM(J), J=1,2)
  127 CONTINUE
*
*                 **          ROOT DEATH IN EACH LAYER          **
*
      SUMRD = 0.0
      DO 649 I = 1, NNJ
      RTDTH(I) =PRTL(I) * DTHFAC * TMPFCR
*  ROOT DEATH, AS METERS/SECOND LOST FROM EACH LAYER
      SUMRD = SUMRD + RTDTH(I)
  649 CONTINUE
      RTDTH(NJ) = 0.
*
      SUMRTD = 0.0
      DO 651 I = 1, NNJ
      IF (SUMRD.EQ.0.) GO TO 651
      RTDTH(I) = RTDTH(I) * ROOTDY/SUMRD * LNGFAC
*  SCALES ACTUAL DEATH RATE TO TOTAL AGGREGATE REQUIRED FOR C-BALANCE
      SUMRTD = SUMRTD + RTDTH(I)
*  TOTAL FOR PLANT, AS METERS/SQ. METER/SECOND
  651 CONTINUE
*
      IF (YY .GT. 0.1) GO TO 752
      IF (TIME.GT.300) GO TO 652
  752 CONTINUE
*     WRITE (6,859)
  859 FORMAT(/, 35X, 'ROOT DEATH RATE')
*     WRITE (6,854) (RTDTH(J),J=1,NJ)
  652 CONTINUE
*
*           **          SUMMARY OF GROWTH AND DEATH IN EACH LAYER      **
*
      DO 653 I = 1,NNJ
      NETGRO(I) = RTGRO(I) - RTDTH(I)
      IF ( ROOTVL(I) .GT. POROS(I) * TCOM(I)) NETGRO(I) = 0
      NETWTG(I) = NETGRO(I) / LNGFAC
      NETVLG(I) = NETWTG(I) * 100 / ( RTDWPC * 1000.)
  653 CONTINUE
      NETGRO(NJ) = 0.
      NETWTG(NJ) = 0.
      NETVLG(NJ) = 0.
*  NET CHANGE IN ROOT LENGTH, AS METERS/SECOND CHANGE IN EACH LAYER.
      IF (YY .GT. 1.0) GO TO 753
      IF (TIME.GT.300) GO TO 654
  753 CONTINUE
*     WRITE (6,856)
  856 FORMAT(     35X, 'NET GROWTH')
*     WRITE (6,854) (NETGRO(J),J=1,NJ)
```

```
*     WRITE(6,857)
 857  FORMAT(/, 50X, 'ITERATION TO FIND POTCR', /)
  654 CONTINUE
*
      PRTL   = INTGRL(IPRTL,NETGRO,10)
      ROOTWT = INTGRL(IRTWT,NETWTG,10)
      ROOTVL = INTGRL(IRTVL,NETVLG,10)
*  PARTIAL ROOT LENGTH, IN EACH SOIL LAYER -- SUM OF GROWTH LESS DEATH
*ENDPRO
*
*               ** ROOT SYSTEM RESISTANCE AND WATER UPTAKE **
*
NOSORT
**PROCEDURE RSSL, PTOTL, RSRT, AAAA, BBBB, CCCC = PROC4(COND,SUMRG,DDDD)
      DO 102 I = 1,NNJ
      RSSL(I) = 1./(B*COND(I)*(PRTL(I)+NOT(PRTL(I))*1.0E-10))
*PARAM B = (1.0E-04,1.0E-03,1.0E-02,1.0E-01,1.0)
PARAM B = 1.0E-02
*PARAM B = 1.0E-04
*  CONSTANT, RELATING ROOT CONDUCTIVITY TO ROOT LENGTH, AFTER GARDNER.
      PTOTL(I) = POTH(I)
*  NOTE THAT PTOTL IS THE SAME AS HYDRAULIC POTENTIAL IN THIS VERSION
PARAM URRS = 1.00E11
*  UNITS FOR RADIAL RESISTANCE
PARAM UARS = 1.00E11
*  UNITS FOR AXIAL RESISTANCE (IN THE XYLEM)
      RRS(I) = URRS / (PRTL(I) + NOT(PRTL(I))*1.0E-10)
*  RADIAL RESISTANCE TO WATER FLOW IN THE ROOT
      ARS(I) = UARS * DEPTH(I) / (PRTL(I) + NOT(PRTL(I))*1.0E-10)
*  AXIAL RESISTANCE -- ALONG THE XYLEM TRANSPORT SYSTEM
      RSRT(I) = RRS(I) + ARS(I)
*  COMBINED AXIAL AND CONDUCTIVE RESISTANCE OF ROOTS IN THIS LAYER
  102 CONTINUE
**ENDPRO
*
*
*      **   CALCULATION OF POTCR AND PARTITIONING OF ROOT WATER UPTAKE
*
      CUMREM = INTGRL(0.0,SUMR)
*  CUMULATIVE WATER REMOVAL (BY ROOT SYSTEM) FROM ALL SOIL LAYERS
*
**PROCEDURE  SUMR,DIFF,DIF,RTEX,POTCR,POTRT,AAAAA,BBBBB = ...
*          PROC5(POTH, TRANSP, RUN, RSRT, CCCCC, DDDDD)
*
      COUNT = 0.0
*     FLPFLP = -FLPFLP
  115 CONTINUE
      COUNT = COUNT  +  1.0
      IF  (  COUNT .LT.  100.0  )  GO TO 116
*     WRITE (6,666)  TRANSP, SUMR, DIF, POTCR, COUNT, TIME
  666 FORMAT  ( ' T S D P C  ', 7E15.5  )
      GO TO 165
*   IN CASE THE LOOP DOES NOT CONVERGE IN 100 TRIES, GO AHEAD ANYWAY
  116 CONTINUE
```

```
*
      SUMR =  0.0
      DO 150 J = 1,NNJ
      I = J
      IF ( FLPFLP .EQ. 1.0 )  I = NJ - J + 1
      RTEX(I) = AMAX1(0.0 ,(POTH(I) - POTCR) / (RSSL(I) + RSRT(I) ) )
*  ROOT EXTRACTION, M/SECOND
      IF (RUNS.GT.02) GO TO 117
      IF (COUNT.GT.5)  GO TO 117
*     WRITE(6,854) J, I, POTH(I), POTCR, RSSL(I), RSRT(I), RTEX(I), ...
*        SUMR, TRANSP, DIFF, DIF, COUNT
  117 CONTINUE
      SUMR = SUMR + RTEX(I)
*  SUM OF WATER REMOVALS BY ROOTS IN ALL LAYERS
  150 CONTINUE
      RTEX(NJ) =0.
      RTEX(NJJ) =0.
      DIFF = TRANSP - SUMR
*     IF (SUMR .LT. TRANSP) RTEX(NJ) = AMAX1(RTEX(NJ),DIFF)
*
*  FOR EACH LAYER, WATER EXTRACTION IS ASSUMED ON THE BASIS OF CURRENT
*   VALUE FOR CANOPY POTENTIAL.  ITERATION WILL CONTINUE UNTIL EQUAL.
      DIF = (SUMR - TRANSP) / TRANSP
      IF (COUNT.GT.100.0) GO TO 165
      IF(RUNS.GT.2) GO TO 118
*     WRITE(6,754)
  754 FORMAT(4X, 'DIF', 7X, 'SUMR', 5X, 'DIFF', 4X, 'POTCR')
*  INSERTS HEADERS BETWEEN SUCCESSIVE PASSES IN ITERATION LOOP
*     WRITE(6,854) DIF, SUMR, DIFF, POTCR
*     WRITE(6, 860)
*     WRITE(6,858)
  858 FORMAT(9X,'J',9X,'I',3X,'POTH',5X,'POTCR',7X,'RSSL',6X,'RSRT')
  860 FORMAT(T65,'RTEX',6X,'SUMR',5X,'TRANSP',6X,'DIFF',6X,'DIF')
  118 CONTINUE
*
      IF ( ABS(DIF) .LE. ERROR ) GO TO 165
*  ADJUSTMENT OF CANOPY WATER POTENTIAL UP OR DOWN AS NEEDED TO BALANCE.
  160 POTCR = AMIN1((POTCR - DIF*POTCR*CF),MAXPOT)
PARAM MAXPOT = -2.0
*  MAXIMUM ALLOWABLE CANOPY POTENTIAL, (-2 METERS, OR -0.2 BARS)
      GO TO 115
*
  165 CONTINUE
      DO 170 I = 1,NNJ
      POTRT(I) = POTCR + RTEX(I) * RSRT(I)
  170 CONTINUE
**ENDPRO
*
*       **   SUMMARY OF WATER MOVEMENT AND EVAPORATIVE LOSSES
*
      CRTEX  =  INTGRL  ( 0.0 , RTEX ,11)
*  CUMULATIVE ROOT EXTRACTION
*
      EVAP = AMIN1(-FLW(1), SLEVAP)
```

```
*  EVAPORATION FROM SOIL SURFACE - LIMITED BY AVAILABILITY OF WATER
*   (COMING FROM DEEPER SOIL LAYERS) OR BY THERMAL INSOLATION AT SURFACE
      CEVAP = INTGRL(0.0, EVAP)
*  CUMULATIVE EVAPORATION FROM SOIL SURFACE
      DRAIN = INTGRL  (0.,DRAING)
*  INTERNAL DRAINAGE, AS WATER PASSES THE BOTTOM OF THE LOWEST LAYER
      FLWNJN = - AMIN1(0.0,FLW(NJJ))
      CAPRIS = INTGRL (0.,FLWNJN)
*  CAPILLARY RISE, PAST THE BOTTOM LAYER
      CTRAN = INTGRL (0.,TRANSP)
*  CUMULATIVE TRANSPIRATION, AS M/SQUARE METER
*
*
*
      IF (KEEP.NE.1) GO TO 314
*     WRITE(11,313) HOURS,RADIAT,TEMP,SHOOTW,ROOTW,PHOTSN,WATRST
  313 FORMAT(5F8.3,G10.2,F8.3)
  314 CONTINUE
      RUNS = RUNS + 1
*
** * * * * * * * * * * *  TERMINAL SEGMENT * * * * * * * * * * * * *
TERMINAL
*
PRINT DAY,HOUR, PHOTSN, POTCR, SOLCHO, SHOOTW, ROOTW,...
    ROOTW, CTRAN, CEVAP, DELT
*
     ZYY = DEBUG(01,TIME)
OUTPUT DAY,RADIAT,RAIN
LABEL  RADIATION AND RAINFALL
LABEL
PAGE XYPLOT, MERGE,HEIGHT=3.,WIDTH=05.0
OUTPUT DAY,TEMP,STEMP
LABEL  AIR AND SOIL TEMPERATURE
LABEL
PAGE XYPLOT, MERGE,HEIGHT=3.,WIDTH=05.0,GROUP=2
OUTPUT DAY,SHOOTW,ROOTW,DRYWT
LABEL  DRY WEIGHT OF SHOOT AND ROOT (KG/M2)
LABEL
LABEL
PAGE XYPLOT, MERGE,HEIGHT=3.,WIDTH=04.0,GROUP
OUTPUT DAY,LAI,ROOTL
LABEL LEAF AREA INDEX AND ROOT GROWTH
LABEL
LABEL
PAGE XYPLOT, MERGE,HEIGHT=3.,WIDTH=04.0
OUTPUT DAY,FRAC(0.0,1.0)
LABEL BIOMASS PARTITIONING
LABEL
LABEL
PAGE XYPLOT, MERGE,HEIGHT=3.,WIDTH=04.0
OUTPUT DAY,PHOTSN
LABEL PHOTOSYNTHESIS (KG/M2/SEC)
LABEL
PAGE XYPLOT, MERGE,HEIGHT=  3.,WIDTH=04.0
```

```
OUTPUT DAY,POTCR
LABEL CANOPY WATER POTENTIAL
LABEL
PAGE XYPLOT, MERGE,HEIGHT=  3.,WIDTH=04.0
OUTPUT DAY,TOPGRO, TOTRG, SHOOTD, ROOTDY
LABEL TISSUE GROWTH AND DEATH (KG/M2/S)
LABEL
PAGE XYPLOT, MERGE,HEIGHT=3.,WIDTH=05.0,GROUP=4
OUTPUT DAY,SHMRES, SHGRES, RTMRES, RTGRES
LABEL COMPONENTS OF RESPIRATION   ( KG/M2 )
LABEL
LABEL MAINTENANCE AND GROWTH OF SHOOT AND ROOT
LABEL
PAGE XYPLOT, MERGE,HEIGHT=3.,WIDTH=04.0,GROUP=4
OUTPUT DAY,NETGRO(1-8)
LABEL NET INCREASE IN ROOT LENGTH (M/M2/S)
LABEL
PAGE XYPLOT, MERGE,HEIGHT=3.,WIDTH=04.0,GROUP
OUTPUT DAY,TRANSP,EVAP
LABEL TRANSPIRATION AND EVAPORATION (M/S)
LABEL
PAGE XYPLOT, MERGE,HEIGHT=3.,WIDTH=04.0,GROUP
OUTPUT DAY,CTRAN,CEVAP
LABEL  CUMULATIVE WATER UPTAKE AND EVAPOTRANSPIRATION (M)
LABEL
PAGE XYPLOT, MERGE,HEIGHT=3.,WIDTH=04.0,GROUP
OUTPUT DAY,NFLW(1-8)
LABEL  NET FLOW OF WATER (M3/M2/S)
LABEL
PAGE XYPLOT, MERGE,HEIGHT=3.,WIDTH=04.,GROUP
OUTPUT DAY,RTEX(1-8)
LABEL  ROOT EXTRACTION (M3/M3/SEC)
LABEL
PAGE XYPLOT, MERGE,HEIGHT=3.,WIDTH=04.,GROUP
OUTPUT DAY,POTM(1-8)
LABEL  SOIL MATRIC POTENTIAL
LABEL
PAGE XYPLOT,MERGE,HEIGHT=3.,WIDTH=04,GROUP
OUTPUT DAY,THETA(1-8)
LABEL  SOIL WATER CONTENT
LABEL
PAGE XYPLOT,MERGE,HEIGHT=3.,WIDTH=04,GROUP
OUTPUT DAY,PRTL(1-8)
LABEL  PARTIAL ROOT LENGTH  (M/M2)
LABEL
PAGE XYPLOT,MERGE,HEIGHT=103.,WIDTH=04.,GROUP
*
END
STOP
ENDJOB
```

APPENDIX B:

FORTRAN LISTING OF SIMULATION MODEL

```
C
C
C  ***  WATER UPTAKE AND ROOT GROWTH IN A HOMOGENEOUS SOIL PROFILE
C
C     SUBROUTINE UPDATE (SUPPLIED BY CSMP TRANSLATOR)
C      (AS MODIFIED BY M. G. HUCK & G. HOOGENBOOM)
C        VERSION 4.0 ---  MAY     1985
C
C * * * * * * * * * * * *  SYSTEM SEGMENT  * * * * * * * * * * * * * * *
C
C    SYSTEM SEGMENT OF MODEL
      INTEGER RUNS, MONTH, JDAY, DATE
      REAL*4   IMPULS,NOTT,IRFAC,IRMIN,IRQUAN,PULSIR,PULSSW,PULS1,INSW
      REAL*8   VOLW  ( 20)
      REAL*8   PRTL  ( 20),IPRTL(20),IRTWT(20),IRTVL(20),ROOTWT(20)
      REAL*8   CRTEX ( 20),ROOTVL(20)
      REAL*4   NFLW  (  20),IVOLW (  20), POROS(20),BULKDS(20)
      REAL*4   NETGRO(  20),NETWTG(20),NETVLG(20)
      REAL*4   RTEX  (  20)
      REAL*4   TIME, ZZTIME, PRDEL,LSNHS,MINRTL,NU,MU
      EQUIVALENCE(ZZTIME,TIME  )
C     EQUIVALENCE(DFOVTX,DFCLTX,SUNTBX)
      REAL*8  SOLCHO, CUMRAD, DAYCUM, DRCI, DROI, DRADI,
     $ CSTMRS, CRTMRS, SHOOTW, POTCRD, ROOTW, CUMRAN, CUMPET,
     $ CUMREM, CEVAP, DRAIN, CAPRIS, CTRAN ,SNLS
      REAL*4 RSRT  (    20)
      REAL*4 DIST  (    20)
      REAL*4 THETA (    20)
      REAL*4 RRS   (    20)
      REAL*4 ARS   (    20)
      REAL*4 FLW   (    20)
      REAL*4 COND  (    20)
      REAL*4 AVCOND(    20)
      REAL*4 POTRT (    20)
      REAL*4 POTH  (    20)
      REAL*4 POTM  (    20)
      REAL*4 RSSL  (    20)
      REAL*4 Y     (    20)
      REAL*4 SCALE (    20)
      REAL*4 BIRTH (    20)
      REAL*4 EXTENS(    20)
      REAL*4 RTGRO (    20)
      REAL*4 RTDTH (    20)
      REAL*4 RRL(20)
      REAL*4 ITHETA(20)
      REAL*4 TCOM(20)
      REAL*4 MAXTEM
      REAL*4 MAXTMP
      REAL*4 MINTEM
```

```
      REAL*4 MINTMP
      REAL*4 MAXSTM
      REAL*4 MINSTM
      REAL*8 INTGRL, OLDVAL
      REAL*4  ICHO   ,JULIAN, LFOV, LFCL, LOPOT, LAT
     1,ISHOOT,IROOT ,IPER   ,LEAFTH,LNGFAC,MAXFOT,MAXPOT,MAXRAD,LAITBL
     1,IL     ,IRTL  ,LAI    ,LAIFAC,MPANEV,MPOT, MXPHOT,LEAFW
C
      REAL*4 SMAX(6),SMIN(6),SUNTBX(10),DFCLTX(10),DFOVTX(10),
     1DFOVTY(10),DFCLTY(10),SUNTBY(10),SUTBX(13),SUTBY(13),
     2FRACTX(5),FRACTY(5),DTBLX(6),DTBLY(6),TRANX(6),TRANY(6),
     3AVPETX(2),AVPETY(2),LAITX(6),LAITY(6),TIMEX(400),RADNY(400),
     4MAXTMY(400),MINTMY(400),RAINY(400),PEVAPY(400),MAXSTY(400),
     5MINSTY(400),BULKX(5),BULKY(5)
      DIMENSION     PTOTL(20)
      DIMENSION   RK(20), DEPTH(20)
C
C  TABLE DEFINITIONS:
      DATA SUNTBX/ 0., 5., 15., 25., 35., 45., 55., 65.,
     $    75., 90./
      DATA DFCLTX / 0., 5., 15., 25., 35., 45., 55., 65.,
     $    75., 90./
      DATA DFOVTX / 0., 5., 15., 25., 35., 45., 55., 65.,
     $    75., 90./
      DATA DFOVTY / 0., 6., 26., 45., 64., 80., 94., 105.,
     $   112., 116./
      DATA DFCLTY / 0., 29., 42., 49., 56., 64., 68.,  71.,
     $    75.,  77./
      DATA SUNTBY / 0., 0., 88., 175., 262., 336., 402., 452.,
     $   483., 504./
C
C  FUNCTION DEFINITIONS:
C FUNCTION SUTB = (.025, 20.) , (.05 , 5.) , (.075 ,  3.0),    ...
C      (.10 , 1.7) , (.15 ,  0.6) , (.20 , .25 ) ,       ...
C      (.25 , .15) , (.30 ,  .10) ,          ...
C      (.35 , .05) , (.40 , 0.01) , (.45, 0.0) ,      ...
C      (.50, -1.00)
      DATA SUTBX/0.00,.0674,.0940,.1119,.1263,.1363,0.1531,.1705,.2063,
     $ 0.2461,0.36,0.42,0.50/
      DATA SUTBY/60.,40.8,21.21,15.27,7.325,4.11,2.01,0.99,0.425,
     $ 0.264,0.0,0.0,0.0/
C FUNCTION FRACTB = -500.,.05, -200.,.25, -050.,.70, -10.,.95, ...
C     100.,.95
      DATA FRACTX/-500., -200., -50., -05., +100.  /
      DATA FRACTY/ .05,    .20, .65,  .90,    .90   /
C FUNCTION DTBL = 0.0,0.0, 2.0,0.03, 5.0,0.33, 07.0,0.97, 10.,100.
      DATA DTBLX/0.0, 2.0,  5.0,  7.0, 10.0 , 25./
      DATA DTBLY/0.0,  .03, 0.33, 0.97, 1.0 , 1.0/
C FUNCTION TRNTBL = -500.,.05, -200.,.05, -100.,0.95, 0.,1.0, 100.,1.0
      DATA TRANX/-500.,  -245.,  -163., -112., 0.001, +100. /
      DATA TRANY/ 0.05,  0.05,  0.50, 0.95, 1.00,  1.00  /
C FUNCTION LAITBL = 0.,0., 3.0,0.5, 6.0,0.9, 10.0,0.95
      DATA LAITX/ 0.0, 2.0, 4.0, 6.0, 10.0, 25.0 /
      DATA LAITY/ 0.0, 0.5, 0.8, 0.9, 0.95, 0.95 /
```

```
      DATA BULKX/0.0,0.5,1.0,1.5,2.0/
      DATA BULKY/1.52,1.52,1.52,1.52,1.52/
      DATA RADNY/400*1.0/
      DATA MAXTMY/400*40./, MINTMY/400*10./
      DATA RAINY/400*0./, PEVAPY/400*0./
      DATA MAXSTY/400*30./, MINSTY/400*10./
C
C  * * * * * * * * * * INITIAL SEGMENT  * * * * * * * * * * * * * * *
C   INITIAL SEGMENT OF MODEL
C
      RUNS=0
      KEEP = 1
      TIME = 0.0D00
      HOURS=TIME/3600.0
      DAY=HOURS/24.00
      PI=3.14159
      RAD=PI/180.
      READ (8,*) FINTIM, OUTDEL, PRDEL, DELT, BGNDAY
      READ (8,*) IPER, ISHOOT, IROOT, LNGFAC, NJ,RTDWPC
      NJJ = NJ + 1
      NNJ = NJ - 1
      READ (8,*) (ITHETA(I), I=1,NJJ)
      READ (8,*) (RRL(I),I=1,NJ)
      READ (8,*) (TCOM(I),I=1,NJJ)
      READ (8,*) LOPOT, HIPOT
C   FOR LINEAR INTERPOLATION OF POTCR, WHEN THIS IS USED.
      READ (8,*) DTRDEM, SATCON, ZLAM, PARTDS,THTAIR,STHETA,ALPHA,NU
      READ (8,*) REFT, REFTS, RSPFAC, MXPHOT, DKPHOT, EFF
      READ (8,*) CONVRT, DELAY, FRG, AGFAC, LEAFTH, STWTR
      READ (8,*) GROFAC, DTHFAC, PB, BRMIN, EXTMIN, MINRTL
      READ (8,*) BR, EXTNRT, AA, BB, B, DEPTHG
      READ (8,*) URRS, UARS, MAXPOT, OUTF
      READ (8,*) POTCR, LSNHS, DRCI, DROI, DRADI
      READ (8,*) CF, ERROR, LAT
C
      DO 79 I = 1,400
      TIMEX(I) = I
   79 CONTINUE
C
C
      CSLT=COS(RAD*LAT)
      SNLT=SIN(RAD*LAT)
      PHTCAR=30./44.
C MOLECULAR WEIGHT/VOLUME RATIO FOR CO2
C
      READ(12,91,END=193)RADN,MAXTEM,MINTEM,CMRAIN,PEVAP,MAXSTM,MINSTM,
     $   SIMDAY
   91 FORMAT(F4.0,F5.1,F6.1,F6.2,F7.3,F3.0,F3.0,
     $  41x, F3.0)
C     READ(12,91,END=193)SIMDAY, RADN,MAXTEM,MINTEM,CMRAIN,PEVAP,
C    $ MAXSTM, MINSTM
C  91 FORMAT(8F8.2,2I6)
      START  = SIMDAY
      REWIND 12
```

```
      WRITE(6,92)SIMDAY,RADN,MAXTEM,MINTEM,CMRAIN,PEVAP,MAXSTM,
     $   MINSTM
C
      WRITE(19,1853)
      WRITE(6,1853)
1853  FORMAT(/,' INITIATE  ',/,'SIMDAY',3X,'RADN',3X,' MAXTEM',
     $  ' MINTEM', ' CMRAIN',  ' PANVAP',  ' MAXSTM',
     $  ' MINSTM', ' MONTH',  ' DATE', / )
      IF(SIMDAY.GT.400)GO TO 193
C
C
      DO 01 KOUNT=1,365
C     READ(12,91,END=193)SIMDAY, RADN,MAXTEM,MINTEM,CMRAIN,PEVAP,
C    $  MAXSTM, MINSTM, MONTH, DATE
      READ(12,91,END=193,ERR=193) RADN,MAXTEM,MINTEM,CMRAIN,PEVAP,
     $  MAXSTM,MINSTM,SIMDAY
      JDAY = SIMDAY
      CALL MTIME(MONTH,DATE,JDAY)
C     MAXSTM = MINSTM + 0.75 * (MAXTEM - MINTEM)
C  (NOTE THAT THIS APPROXIMATION IS NEEDED ONLY FOR SOUTHERN HEMISPHERE)
      IF(SIMDAY.GT.400)GO TO 101
92    FORMAT(F6.1,E10.2,6F07.2,2I5)
101   CONTINUE
      K = SIMDAY
      TIMEX(K) = SIMDAY
      RADNY(K) = RADN * 3600.
C  CONVERTS FROM LY/SQ. CM. INTO JOULES/SQ. METER
      MAXTMY(K) = ( MAXTEM - 32. ) * 5./9.
      MINTMY(K) = ( MINTEM - 32. ) * 5./9.
C  CONVERTS FROM DEGREES FAHRENHEIT INTO DEGREES C.
      RAINY(K) = CMRAIN * 2.54
      PEVAPY(K) = PEVAP * 2.54
C  CONVERTS INCHES OF RAINFALL OR EVAPORATION INTO CENTIMETERS.
      MAXSTY(K) = ( MAXSTM - 32. ) * 5./9.
      MINSTY(K) = ( MINSTM - 32. ) * 5./9.
WRITE(6,92)SIMDAY,RADNY(K),MAXTMY(K),MINTMY(K),RAINY(K),PEVAPY(K),
     $   MAXSTY(K),MINSTY(K),MONTH,DATE
WRITE(19,92)SIMDAY,RADNY(K),MAXTMY(K),MINTMY(K),RAINY(K),PEVAPY(K)
     $ , MAXSTY(K),MINSTY(K),MONTH,DATE
   01 CONTINUE
C
  193 CONTINUE
      KK = START
      LL = SIMDAY
C
      KKK = KK + 10
      DO 307 K = 170,200
  307 CONTINUE
      JDAY=DAY+BGNDAY
C
      SHOOTW = ISHOOT
      POTCRD = 10.
      POTCRE = POTCRD
      ROOTW = IROOT
```

```
      DRYWT = SHOOTW + ROOTW
      STEMW = STWTR * SHOOTW
      LEAFW = SHOOTW - STEMW
      ICHO=(ISHOOT+IROOT)*IPER/(1.-IPER)
      SOLCHO = ICHO
      IRTL=ROOTW*LNGFAC
      LAI=LEAFW*LEAFTH
      ETA=2.0+3.0*ZLAM
C
      DEPTH(1)=.5*(TCOM(1))
      DIST(1)=DEPTH(1)
      IVOLW(1)=ITHETA(1)*TCOM(1)
C
      DO 20 I=2,NJJ
      DIST(I)=.5*(TCOM(I-1)+TCOM(I))
      DEPTH(I)=DEPTH(I-1)+DIST(I)
      IVOLW(I)=ITHETA(I)*TCOM(I)
      VOLW(I) = ITHETA(I) * TCOM(I)
      THETA(I) = VOLW(I)/TCOM(I)
      BULKDS(I) = AFGEN(BULKX,BULKY,DEPTH(I))
      POROS(I) = 1 - (BULKDS(I) / PARTDS)
20    CONTINUE
      POROS(1)= POROS(2)
C
      DO 30 I=1,NJ
      DRAING = (AMAX1(0.0,THETA(NJJ)-STHETA))*TCOM(NJJ)/DELT
      THETA(I) = AMIN1(ITHETA(I),STHETS)
      POTM(I)=-AFGEN(SUTBX,SUTBY,THETA(I))
C     POTM(I) = -0.01 * EXP(-37.31 * THETA(I) + 16.97)
C  (CHOOSE LOOKUP TABLE OR FUNCTION, DEPENDING ON DATA AVAILABLE)
      POTH(I)=POTM(I)-DEPTH(I)
      IPRTL(I)=IRTL*RRL(I)
      IRTWT(I) = IPRTL(I)/LNGFAC
      IRTVL(I) = IRTWT(I)*100./(RTDWPC*1000)
      RRS(I)=URRS/ (IPRTL(I) + NOTT(IPRTL(I))*1.0E-10)
      ARS(I)=UARS*DEPTH(I)/ (IPRTL(I) + NOTT(IPRTL(I))*1.0E-10)
      RSRT(I)=RRS(I)+ARS(I)
30    CONTINUE
      DO 15 I=1,NJJ
      RTEX(I) = 0.0
      NFLW(I) = 0.0
15    FLW(I)=0.0
      RISE = 4.8
      PLSNHS = 0.0
      TOPGRO = 0.0
      TOTRG = 0.0
      GROWTH = TOPGRO + TOTRG
      SHOOTD = 0.
      ROOTDY = 0.
      CUMRAD = 0.00
      DAYCUM = 0.00
      DRCP = 3.5E+07
      DROP = 6.6E+06
      DRCI = DRCP
```

```
      DROI = DROP
      DRADI = 1.0E-10
      DRADZ = DRADI
      DROZ = DROI
      DRCZ = DRCI
      RAINZ = 0.00
      DAYRAI = 0.00
      DRADI = 0.00
      PULS = 0.00
      PEVV = 0.00
      CSTMRS = 0.0
      CRTMRS = 0.0
      CUMRAN = 0.00
      CUMPET = 0.0D0
      DO 37 I = 1,NJ
      VOLW(I) = IVOLW(I)
      PRTL(I) = IPRTL(I)
      ROOTWT(I) = IRTWT(I)
      ROOTVL(I) = IRTVL(I)
      CRTEX(I) = 0.0
      RTEX(I) = 0.0
   37 NETGRO(I) = 0.0
      CUMREM = 0.0
      CEVAP = 0.0D0
      DRAIN = 0.0
      CAPRIS = 0.0
      CTRAN = 0.0
      SUMR = 0.0
      COUNT = 0.0
      DTOT = 0.0
      DTOTI = 0.0
      DTOTZ = 0.0
      RATE = 0.0
C
      TIME = 0.0D00
      HOUR = 0.0
      XXX  = 0.0000
      YY   = 0.0
C
      WRITE(1,876)
  876 FORMAT(1X, 'HOURS', 3X, 'POTH(1)', 2X, 'POTH(2)  ETC. --->')
      WRITE(2,877)
  877 FORMAT(2X, 'HOURS', 4X, 'NFLW(1)   NFLW(2)   ETC. --->')
      WRITE(3,878)
  878 FORMAT(2X, 'HOURS', 5X, 'HOUR', 4X, 'POTCRE', 4X, 'POTCR',
     $ 6X, 'SOLCHO', 5X, 'SHOOTW', 4X, 'ROOTW', 5X, 'CTRAN', 5X,
     $ 'CEVAP', 4X, 'JULIAN')
      WRITE(4,879)
  879 FORMAT(3X, 'HOURS', 3X, 'PHOTSN', 4X, 'GROWTH', 5X, 'RESP',
     $ 6X, 'ZZ1022', 4X,'SUMR', 6X,
     $ 'EVAP', 5X, 'TRANSD')
      WRITE(9,880)
  880 FORMAT(2X, 'HOURS', 5X, 'RADN', 6X, 'TEMP', 7X, 'PET',
     $ 7X, 'RSSL(3)', 3X, 'RSRT(3)', 3X, 'COND(3)', 5X, 'RESP', 5X,
```

```
     $ 'SUMRTG', 4X, 'SUMRTD')
      WRITE(10,881)
  881 FORMAT(2X, 'HOURS    RTEX(1)   RTEX(2)    ETC. ---> ')
      WRITE(11,882)
  882 FORMAT(2X, 'HOURS', 6X, 'LFOV', 6X, 'DTR', 6X, 'DTRR', 6X,
     $ 'LFCL', 6X, 'CRO', 7X, 'CRC', 7X, 'RANGE', 6X, 'AVAT', 5X,
     $ 'STEMP')
      WRITE(13,883)
  883 FORMAT(2X, 'HOURS', 6X, 'MONTH', 4X, 'DATE', 6X, 'HOUR', 6X,
     $ 'RAIN', 6X, 'ROOTDY', 4X, 'LAI', 7X, 'FLW(8)', 6X,' TEMP',
     $ 5X,'STEMP')
      WRITE(14,884)
  884 FORMAT(2X, 'HOURS', 6X, 'MONTH', 4X, 'DATE', 6X, 'HOUR', 6X,
     $ 'DRC ', 6X, 'DRCP  ', 4X, 'DRO', 7X, 'DROP ', 6X, 'LFCL',
     $ 5X, 'RADCAL')
      WRITE(15,885)
  885 FORMAT(2X, 'HOURS', 6X, 'MONTH', 4X, 'DATE', 6X, 'HOUR', 6X,
     $ 'WATRST', 4X, 'PHOTC ', 4X, 'PHOTD', 5X, 'PHOTSN', 6X, 'LAI ',
     $ 5X, 'LFCL  ')
      WRITE(6,1856)
 1856 FORMAT(/,' INITIATION NOW COMPLETE.  ENTER DYNAMIC LOOP',//)
C
C  * * * * * * * * * * DYNAMIC SEGMENT  * * * * * * * * * * * * * * *
C   DYNAMIC SEGMENT OF MODEL
C
C
C
 6001 CONTINUE
      JULIAN=BGNDAY+TIME/86400.
      JDAY=JULIAN
      CALL MTIME(MONTH,DATE,JDAY)
      T=MONTH
      TT=T
      MTH=MONTH-0.5+((DAY/30))
      RUN=RUNS
      HOURS=TIME/3600.0
      HOUR=AMOD(HOURS,24.0)
      DAY=HOURS/24.00
      YY = AMOD(HOURS,OUTDEL)
      XXX = AMOD(TIME,PRDEL)
      IF (TIME.GT.1.0D15) GO TO 6002
C     IF (YY  .GT.0.01 ) GO TO 6002
 6002 CONTINUE
C
C
      IF (TIME.GT.FINTIM) GO TO 99
      IF (HOURS.GT.1200.) GO TO 99
      IF (POTCR.LT.-476.) GO TO 99
      IF (SOLCHO.LT.+1.0E-07) GO TO 99
C
C
      DEC=-23.4*COS(2.*PI*(JULIAN+10.)/365.)
C CHANGE TO -23.4 WHEN WORKING WITH DATA FROM NORTHERN HEMISPHERE
C     DEC=+23.4*COS(2.*PI*(JULIAN+10.)/365.)
```

```
C (+10 IS TIME BETWEEN DEC 21 AND DEC 31--FOR SIDEREAL YEAR)
C
      SNDC=SIN(RAD*DEC)
      CSDC=COS(RAD*DEC)
      SNHSS=SNLT*SNDC+CSLT*CSDC*COS(PI*(HOUR+12.)/12.)
C  SINE OF SUN HEIGHT(INCLUDING NEGATIVE VALUES)
      SNLS = SNHSS - LSNHS
      RISE1= (AND(SNHSS,-LSNHS))-0.5
      RISE2= HOUR-SNHSS*DELT/((NOTT(SNLS)+SNLS)*3600.)
      RISE = ZHOLD(RISE,RISE1,RISE2)
C  TIME OF SUNRISE
      LSNHS  =SNHSS
C  SINE HEIGHT OF SUN ON PREVIOUS DAY
C
      DTRR=AFGEN(TIMEX, RADNY,(JULIAN-0.0))
C  DAILY TOTAL GLOBAL RADIATION(MEASURED, INTERPOLATED FROM DAY TO DAY.
      DTR=RADNY(JDAY)
C  DAILY TOTAL RADIATION (FROM INPUT FILE--JOULE/METER2/DAY)
      SNHS=AMAX1(0.,SNHSS)
C  SINE, HEIGHT OF SUN, NEGATIVE VALUES REMOVED
      HSUN=ATAN(SNHS/SQRT(1.-SNHS*SNHS))/RAD
C  HEIGHT OF THE SUN, EXPRESSED IN DEGREES, ABOVE HORIZON
      SUNDCL=AFGEN(SUNTBX,SUNTBY,  HSUN)
C  SUNLIGHT, DIRECT, UNDER A CLEAR SKY.
      DIFCL=AFGEN(DFCLTX,DFCLTY,HSUN)
C  DIFFUSE VISIBLE RADIATION UNDER A STANDARD CLEAR SKY
      CRC=(SUNDCL+DIFCL)*2.
C  CURRENT RADIATION INTENSITY UNDER A CLEAR SKY (DIRECT + DIFFUSE)
      DIFOV=AFGEN(DFOVTX, DFOVTY,HSUN)
C  DIFFUSE VISIBLE RADIATION UNDER A STANDARD OVERCAST
      DIFON=0.7*DIFOV
C  DIFFUSE NEAR-INFRARED UNDER A STANDARD OVERCAST SKY
      CRO=DIFOV+DIFON
C  CURRENT RADIATION UNDER AN OVERCAST SKY
      CALL DLYTOT(DROZ,DRO,DROI,CRO,TIME,DELT)
      CALL DLYTOT(DRCZ,DRC,DRCI,CRC,TIME,DELT)
      PULS = IMPULS(TIME,0.0,86400.)
      DRCP = ZHOLD(DRCP,PULS,DRC)
      DROP = ZHOLD(DROP,PULS,DRO)
      FCL=(DTR-DROP) /(AMAX1((DRCP-DROP),0.0001))
C  FRACTION OF THE TIME THAT SKY IS CLEAR
      FOV=1.-FCL
C  FRACION OF THE TIME THAT SKY IS OVERCAST
      LFOV=AMIN1(1.,FOV)
      LFOV=AMAX1(0.,LFOV)
      LFCL=1.-LFOV
C  FRACTIONS FCL AND FOV RESTRAINED BETWEEN 0 AND 1 (IN CASE OF ERROR)
      RADCAL=LFCL*CRC+LFOV*CRO
C  RADIATION, CALCULATED--INSTANTANEOUS RATE
      CUMRAD  =INTGRL     (CUMRAD,RADCAL,DELT)
C  CUMULATIVE TOTAL RADIATION RECEIVED--COMPARE WITH INPUT VALUES.
      CALL DLYTOT(DRADZ,DRAD,DRADI,RADCAL,TIME,DELT)
C
C
```

```
C        **  ESTIMATION OF TEMPERATURE EFFECTS  **
C
C
C
      MAXTEM = AFGEN(TIMEX,MAXTMY,(JULIAN-(14./24.)))
      MINTEM = AFGEN(TIMEX,MINTMY,(JULIAN-(RISE/24.)))
C  LINEAR INTERPOLATION FROM INPUT DATA-FILE
      RANGE = (MAXTEM - MINTEM) * 0.250
C  GENERATING FACTOR -- MINIMUM AT 3 AM; MAXIMUM AT 3 PM
      AVAT = (MAXTEM + MINTEM) * 0.500
C  AVERAGE AIR TEMPERATURE
      CALL WAVE(TEMP,JULIAN,HOUR,MINTEM,MAXTEM,RISE,PI)
C  COMPUTED AIR TEMPERATURE, DEGREES C.
C
      MAXSTM = AFGEN(TIMEX,MAXSTY,(JULIAN-(14.+4.)/24.))
      MINSTM = AFGEN(TIMEX,MINSTY,(JULIAN-(RISE+4.)/24.))
C  LINEAR INTERPOLATION FROM INPUT DATA-FILE
      RANGES = (MAXSTM - MINSTM) * 0.500
C  AMPLITUDE (RANGE) OF DAILY SOIL TEMPERATURE OSCILLATIONS
      AVST = (MAXSTM + MINSTM) * 0.500
C  AVERAGE SOIL TEMPERATURE, FROM DAILY MEASUREMENT DATA
C
      CALL WAVE(STEMP,(JULIAN-0.16),(HOUR-4.),MINSTM,MAXSTM,RISE,PI)
C  SOIL TEMPERATURE, AS DEGREES CELSIUS
C
C
      TMPFCS = 10.0 ** ((TEMP-REFT) * 0.030103)
      TMPFCR = 10.0 ** ((STEMP-REFTS) * 0.030103)
C  BIOLOGICAL Q-10 -- DOUBLING REACTION RATE AT EACH 10 DEGREE TEMP CHNG
C
C*
C**       **  ESTIMATION OF RADIATION INTENSITY  **
C*
C*
C*          **     PHOTOSYNTHETIC ACTIVITY    **
C*
      LAI=LEAFW *LEAFTH
      LAIFAC=AFGEN(LAITX, LAITY, LAI)
      WATRST=AFGEN(TRANX, TRANY, POTCR)
C
      RADCPH = 0.5 * CRC
      RADOPH = 0.5 * CRO
C   PHOTOSYNTHETIC ACTIVE RADIATION
      SLLA = AMIN1(LAI,2*SNHS)
C  SUNLIT LEAF AREA
      DLLA = LAI - SLLA
C  TOTAL LEAF AREA IN THE SHADE
      XOVC = RADOPH * EFF / ( MXPHOT * LAI )
      POVC = XOVC / ( XOVC + 1. )
      PHOTD = LAI * MXPHOT * POVC
C  MAXIMUM CANOPY PHOTOSYNTHESIS UNDER AN OVERCAST SKY
      XS = ALOG ( 1+(0.45 * EFF*RADCPH/(AMAX1(SLLA,0.0001)*MXPHOT)))
      PS = XS / ( 1 + XS )
      PHOTS = SLLA * MXPHOT * PS
```

```
C  MAXIMUM CANOPY PHOTOSYNTHESIS UNDER A CLEAR SKY FOR SUNLIT LEAFAREA
      XSH = ALOG( 1+(0.55 * EFF * RADCPH/(AMAX1(DLLA,0.0001)*MXPHOT)))
      PSH = XSH / ( 1 + XSH )
      PHOTSH = DLLA * MXPHOT * PSH
C  MAXIMUM CANOPY PHOTOSYNTHESIS UNDER A CLEAR SKY FOR SHADED LEAFAREA
C
      PHOTC = PHOTS + PHOTSH
      IF ( LAI .GT. 3 ) GO TO 31
      IF (  RADCAL .LT. 1.0     ) GO TO 31
      FINT = ( 1. - EXP(-0.8*LAI))
      C1 = FINT * PHOTC
      C2 = LAI * MXPHOT
      O1 = FINT * PHOTD
      O2 = C2
      IF ( C1 .GT. C2 ) GO TO 32
      C0 = C1
      C1 = C2
      C2 = C0
   32 CONTINUE
      PHOTC = C2 * ( 1. - EXP ( AMAX1(-50., ( -C1/C2))))
      IF ( O1 .GT. O2 ) GO TO 33
      O0 = O1
      O1 = O2
      O2 = O0
   33 CONTINUE
      PHOTD = O2 * ( 1. - EXP ( AMAX1(-50., ( -O1/O2))))
   31 CONTINUE
      PHOTSN = WATRST * ( PHOTC * LFCL + PHOTD * LFOV)
C  PHOTOSYNTHETIC RATE (NET CARBON FIXATION, KG/SQUARE METER/SECOND
C
C*
C*         **       RESERVE LEVELS AND TISSUE GROWTH    **
C*
      SHMRES=SHOOTW*TMPFCS*RSPFAC
      CSTMRS  =INTGRL     (CSTMRS  ,SHMRES,DELT)
      SHGRES=TOPGRO*CONVRT
      RESPSH=SHMRES+SHGRES
      RTMRES=ROOTW*RSPFAC*TMPFCR
      CRTMRS  =INTGRL     (CRTMRS  ,RTMRES,DELT)
      RTGRES=TOTRG*CONVRT
      RESPRT=RTMRES+RTGRES
      RESP=RESPSH+RESPRT
      ZZ1022  =(PHOTSN*PHTCAR-GROWTH-RESP)
      SOLCHO  =INTGRL     (SOLCHO  ,ZZ1022,DELT)
      FRAC=AFGEN(FRACTX,FRACTY,POTCRE)
      TOPGRO=TMPFCS*GROFAC*SOLCHO*FRAC
      TOTRG=(1.0-FRAC)*TMPFCR*GROFAC*SOLCHO
      GROWTH=TOPGRO+TOTRG
      RESL=SOLCHO/(SOLCHO+ROOTW+SHOOTW)
C*  RESERVE LEVEL, % FREE CARBOHYDRATE IN TISSUES
      IF (RESL.GT.0.75) GO TO 99
      SHOOTW  =INTGRL(SHOOTW,(TOPGRO-SHOOTD),DELT)
      ROOTW  =INTGRL(ROOTW,(TOTRG-ROOTDY),DELT)
      ROOTL = ROOTW * LNGFAC
```

```
      DRYWT = SHOOTW + ROOTW
      STEMW = STWTR * SHOOTW
      LEAFW = SHOOTW - STEMW
      DTHBGN=AFGEN(DTBLX, DTBLY, LAI)
      AGING=AGFAC*(DAY/30.)
      SHOOTD=SHOOTW*TMPFCS*DTHBGN*AGING
      ROOTDY=ROOTW/RESL*DTHFAC*TMPFCR
C
C           ** OVERALL WATER BALANCE **
C
      RNF=AFGEN(TIMEX, RAINY, JULIAN)*0.01
      WATER= RAINY(JDAY)*0.01
      RAIN=WATER/86400.
      CALL DLYTOT(RAINZ,DAYRAI,DRADI,RAIN,TIME,DELT)
      CUMRAN  =INTGRL     (CUMRAN  ,RAIN ,DELT)
C
      PEVV=AFGEN(TIMEX, PEVAPY,JULIAN)*0.01
      PEVVV=PEVAPY(JDAY)*0.01
      PET=AMAX1(PEVV*0.01/86400.,RADCAL*PEVVV/(AMAX1(0.01,DTR*1.0)))
      CUMPET  =INTGRL     (CUMPET  ,PET ,DELT)
      TRANSD = PET * LAIFAC
C  TRANSPIRATION DEMAND IN THE ABSENCE OF STOMATAL CLOSURE--USED IN
C   ESTIMATING POTCR BY THE INTERPOLATION METHOD (BUT NOT ITERATIVE)
      TRANSP=WATRST*PET*LAIFAC
      SLEVAP=PET*(1.0-LAIFAC)*1.0
      IRFAC = 10.
      IRMIN = 10.2118 * IRFAC / 100.
      PULSIR = IMPULS(TIME,0.0,1800.)
      IRQUAN = 000.0 * 1.0E-6
      PULS1 = IRMIN+POTM(3)
      PULSSW = INSW(PULS1,IRQUAN,0.0)
      VOLW(1) = VOLW(1) + RAIN * DELT + PULSSW * PULSIR
C
      DO 1001 I = 1,NJJ
      BULKDS(I) = AFGEN(BULKX,BULKY,DEPTH(I))
      POROS(I) = 1 - (BULKDS(I) / PARTDS)
      THETA(I) = VOLW(I)/TCOM(I)
      DRAING = (AMAX1(0.0,THETA(NJJ)-STHETA))*TCOM(NJJ)/DELT
      THETA(I) = AMIN1(THETA(I),STHETA)
      VOLW(I) = THETA(I) * TCOM(I)
      POTM(I)=-AFGEN(SUTBX,SUTBY,THETA(I))
C     POTM(I) = -0.01 * EXP(-37.31 * THETA(I) + 16.97)
C  (CHOOSE LOOKUP TABLE OR FUNCTION, DEPENDING ON DATA AVAILABLE)
      POTH(I)=POTM(I)-DEPTH(I)
1001  CONTINUE
C
      DO 85 I=1,NJJ
      MPOT=-POTM(I)*100.0
      IF(MPOT.LE.0.0)GO TO 84
      MU = 1 - ( 1/ NU )
      AH = ALPHA * MPOT
      RK(I)=(1-(AH)**(NU-1)*(1+(AH)**NU)**(-MU))**2/
     $ ((1+(AH)**NU)**(MU/2))
C   RELATIVE CONDUCTIVITY (AS A FRACTION OF SATURATED CONDUCTIVITY)
```

```
C      RK(I)=(PB/MPOT)**ETA
       GO TO 87
84     RK(I)=1.0
87     CONTINUE
854    FORMAT(12G10.3)
       RK(I)=AMIN1(1.00,RK(I))
       COND(I)=RK(I)*SATCON
C      COND(I) = 0.01 * EXP(-5.69-2.059*ALOG(-POTM(I)*100.0))
C   (CHOOSE BROOKS & COREY OR EXPONENTIAL, AS DATA INDICATES.)
85     CONTINUE
       DO 110 I=2,NJJ
       AVCOND(I)=.5*(COND(I-1)+COND(I))
       FLW(I)=AVCOND(I)*(POTH(I-1)-POTH(I))/DIST(I)
110    CONTINUE
       FLW(NJJ+1) = DRAING
       NFLW(NJJ+1) = DRAING
       POTMAR = - AFGEN(SUTBX,SUTBY,THTAIR)
       IF(POTM(1).GT. POTMAR)FLW(1)=-SLEVAP
       IF(POTM(1).LE. POTMAR)FLW(1)=FLW(2)
       DO 120 I=1,NJJ
       NFLW(I)=FLW(I)-FLW(I+1)-RTEX(I)
120    CONTINUE
       DO 62 I = 1,NJJ
       VOLW(I)  =INTGRL     (VOLW(I)  ,NFLW(I),DELT)
   62 CONTINUE
C*
C
C
C
       W=AMAX1(0.0,(POTM(2)-EXTMIN))
       DO 1010 I=1,NNJ
       X=AMAX1(0.0,(POTM(I)-BRMIN))
       XX=AMAX1(0.0,(POTM(I)-EXTMIN))
       BIRTH(I)=(BR*(1.0-EXP(-AA*X**BB)))/(((DEPTH(I)*DEPTHG))**1.)
       EXTENS(I)=(EXTNRT*(1.0-EXP(-AA*XX**BB)))/(((DEPTH(I)*DEPTHG))**1.)
       IF ( PRTL(I) .LT. MINRTL* TCOM(I)) EXTENS(I) = 0.
1010   CONTINUE
       RTGRO(1)=PRTL(1)*BIRTH(1) * (1.0 - FRAC) * TMPFCR
       SUMRG=RTGRO(1)
       DO 647 I=2,NNJ
       RTGRO(I)=(PRTL(I-1)*EXTENS(I-1)+PRTL(I)*BIRTH(I)) *
      $ (1.0 - FRAC) * TMPFCR
647    SUMRG=RTGRO(I)+SUMRG
       SUMRTG=0.0
       DO 648 I=1,NNJ
       IF(SUMRG.EQ.0.00)GO TO 648
       RTGRO(I)=RTGRO(I)*TOTRG/SUMRG*LNGFAC
       SUMRTG=SUMRTG+RTGRO(I)
648    CONTINUE
       IF(YY   .GT.1.0)GO TO 127
       IF(TIME.GT.300)GO TO 127
751    CONTINUE
127    CONTINUE
       SUMRD=0.0
```

```
      DO 649 I=1,NNJ
      RTDTH(I)=PRTL(I)*DTHFAC*TMPFCR
649   SUMRD=SUMRD+RTDTH(I)
      SUMRTD=0.0
      DO 651 I=1,NNJ
      IF(SUMRD.EQ.0.)GO TO 651
      RTDTH(I)=RTDTH(I)*ROOTDY/SUMRD*LNGFAC
      SUMRTD=SUMRTD+RTDTH(I)
651   CONTINUE
      DO 653 I=1,NNJ
      NETGRO(I)=RTGRO(I)-RTDTH(I)
      IF ( ROOTVL(I) .GT. POROS(I)*TCOM(I)) NETGRO(I)=0.
      NETWTG(I) = NETGRO(I) / LNGFAC
      NETVLG(I) = NETWTG(I) * 100. / (RTDWPC*1000.)
653   CONTINUE
      NETGRO(NJ) = 0.
      NETWTG(NJ) = 0.
      NETVLG(NJ) = 0.
      DO 63 I = 1,NNJ
      PRTL(I)    =INTGRL     (PRTL(I),NETGRO(I),DELT)
      ROOTWT(I)  =INTGRL     (ROOTWT(I),NETWTG(I),DELT)
      ROOTVL(I)  =INTGRL     (ROOTVL(I),NETVLG(I),DELT)
  63  CONTINUE
C
      DO 102 I=1,NNJ
      RSSL(I)=1./(B*COND(I)*(PRTL(I)+NOTT(PRTL(I))*1.0E-20))
      PTOTL(I)=POTH(I)
      RRS(I)=URRS/(PRTL(I)+NOTT(PRTL(I))*1.0E-10)
      ARS(I)=UARS*DEPTH(I)/(PRTL(I)+NOTT(PRTL(I))*1.0E-20)
      RSRT(I)=RRS(I)+ARS(I)
102   CONTINUE
C
      CUMREM  =INTGRL     (CUMREM  ,SUMR ,DELT)
      COUNT=0.0
115   CONTINUE
      COUNT=COUNT+1.0
      IF(COUNT.LT.100.0)GO TO 116
      GO TO 165
116   CONTINUE
C
      SUMR=0.0
      DO 150 J=1,NNJ
      I=J
      RTEX(I)=AMAX1(0.0,(POTH(I)-POTCR)/(RSSL(I)+RSRT(I)))
      IF(RUNS.GT.02)GO TO 117
      IF(COUNT.GT.3)GO TO 117
117   CONTINUE
      SUMR=SUMR+RTEX(I)
150   CONTINUE
C
      DIFF=TRANSP-SUMR
      DIF=(SUMR-TRANSP)/TRANSP
      IF(COUNT.GT.100.0)GO TO 165
      IF(RUNS.LT.099)GO TO 118
```

```
118   CONTINUE
C
      IF(ABS(DIF).LE.ERROR)GO TO 165
C     IF(DIF)160,165,160
160   POTCR=AMIN1((POTCR-DIF*POTCR*CF),MAXPOT)
      GO TO 115
165   CONTINUE
      DO 170 I=1,NNJ
      POTRT(I)=POTCR+RTEX(I)*RSRT(I)
170   CONTINUE
C
      DOUBLP = (POTCR-POTCRD)/DELAY
      POTCRD  =INTGRL(POTCRD,DOUBLP,DELT)
      SINGLP = POTCRD
      POTCRE=AMIN1(POTCR,SINGLP)
C   SINGLP IS A REAL*4 REPRESENTATION OF POTCRD, FOR THE AMIN1 FUNCTION
      DO 67 I = 1, NNJ
      CRTEX(I)  =INTGRL     (CRTEX(I)   ,RTEX(I),DELT)
  67  CONTINUE
C
      EVAP=AMIN1(-FLW(1),SLEVAP)
      CEVAP  =INTGRL     (CEVAP   ,EVAP ,DELT)
      DRAIN  =INTGRL(DRAIN,DRAING,DELT)
      FLW8N=-AMIN1(0.0,FLW(8))
      CAPRIS  =INTGRL     (CAPRIS   ,FLW8N ,DELT)
      CTRAN   =INTGRL     (CTRAN    ,TRANSP,DELT)
      DRAING=FLW(8)
C
C     IF(YY   .GT.0.1)GO TO 1200
C     OUTDEL = OUTDEL + OUTDEL
C
1000  CONTINUE
1200  CONTINUE
C
      TIME = TIME + DELT
      RUNS=RUNS+1
C
      IF (XXX.GT.1) GO TO 6001
      WRITE(1,276) HOURS, (POTH(I),I=1,09)
  276 FORMAT(10E10.3)
      WRITE(2,276) HOURS, (NFLW(I),I=1,9)
      WRITE(3,276) HOURS, HOUR, POTCRE, POTCR, SOLCHO, SHOOTW,
     $ ROOTW, CTRAN, CEVAP, JULIAN
      WRITE(4,276) HOURS, PHOTSN, GROWTH, RESP, ZZ1022,
     $ SUMR, EVAP, TRANSD
      WRITE(9,276) HOURS,RADCAL,TEMP, PET, RSSL(3), RSRT(3), COND(3),
     $ RESP, SUMRTG, SUMRTD
      WRITE(10,276) HOURS, (RTEX(I),I=1,9)
      WRITE(11,276) HOURS, LFOV, DTR, DTRR, LFCL, CRO, CRC, RANGE,
     $ AVAT, STEMP
  277 FORMAT(1E10.3,2I10,7E10.3)
      WRITE(13,277) HOURS, MONTH, DATE, HOUR, RAIN, ROOTDY, LAI,
     $ FLW(8), TEMP, STEMP
      WRITE(14,277) HOURS, MONTH, DATE, HOUR, DRC , DRCP    , DRO,
```

```
     $ DROP , LFCL, RADCAL
      WRITE(15,277) HOURS, MONTH, DATE, HOUR,WATRST,PHOTC,PHOTD,
     $ PHOTSN,LAI,LFCL
      WRITE(16,276) HOURS, (PRTL(I),I=1,9)
      WRITE(17,276) HOURS, (ARS(I),I=1,9)
      WRITE(18,276) HOURS, (RRS(I),I=1,9)
      WRITE(6, 392) JULIAN,SHOOTW,ROOTW,LAI,ROOTL,PHOTSN,POTCR,TRANSP
      WRITE(20, 392) JULIAN,SHOOTW,ROOTW,LAI,ROOTL,PHOTSN,POTCR,TRANSP
  392 FORMAT(/' JULIAN=', F6.2,' SHOOTW=',F10.5,' ROOTW=',
     $F10.5,' LAI=', F8.3,/' ROOTL=', F10.3,' PHOTSN=',E10.2,' POTCR=',
     $ F10.2,' TRANSP=',E10.2)
      GO TO 6001
C
C
C
C * * * * * * * * * * *  TERMINAL SEGMENT  * * * * * * * * * * * * * *
C
C
C  TERMINAL SEGMENT OF MODEL
   99 CONTINUE
      WRITE(6, 591) HOUR, MONTH, DATE
  591 FORMAT(//, '   FINISH CONDITION REACHED AT ', F4.1,
     $ ' HOURS ON', I4, ' /', I2)
      WRITE(6, 391) JULIAN,MAXRAD,RADN,LAI,WATRST,TIME,SOLCHO,POTCR
  391 FORMAT(//,'   JULIAN = ', F8.4, '  MAXRAD = ', F12.4, '  RADN =',
     $F12.4, '  LAI = ', F8.3, '  WATRST = ', F10.3, //, 5X,
     $ ' TIME= ',F10.2,' SOLCHO = ',F10.7,' POTCR = ',F10.2,
     $  ' CUMREM',4X,' HOURS',5X,'  XXX',6X,'   YY')
      STOP
      END
C
      FUNCTION INSW(FIRST,SECOND,THIRD)
      REAL INSW
      INSW = THIRD
      IF (FIRST.LT.0.) INSW=SECOND
      RETURN
      END
C
      FUNCTION IMPULS(FIRST,SECOND,THIRD)
      REAL IMPULS
      IMPULS = 0.00000
      DO 10 I=1,10000
      COUNT = SECOND + I*THIRD
      IF (FIRST.LT.COUNT)GO TO 11
      IF (FIRST.EQ.COUNT)GO TO 12
   10 CONTINUE
   12 CONTINUE
      IMPULS = 1.
   11 CONTINUE
      RETURN
      END
C
      FUNCTION NOTT(INIT)
      REAL*8 INIT
```

```
      REAL*4 NOTT
      NOTT = 0.
      IF (INIT .LE. 0) NOTT = 1.
      RETURN
      END
C
      FUNCTION AND(LOW,HIGH)
      REAL LOW,HIGH
      AND = 1.0
      IF (LOW .LT. 0 .OR. HIGH .LT. 0) AND = 0.0
      RETURN
      END
C
      FUNCTION LIMIT(BOTTOM,TOP,START)
      REAL LIMIT
      LIMIT = START
      IF (START.LT.BOTTOM) LIMIT = BOTTOM
      IF (START.GT.TOP) LIMIT = TOP
      RETURN
      END
C
      FUNCTION AMOD(INPUT,INPUTD)
      REAL INPUT,INPUTD
      AMOD = INPUT
      DO 10 I=1,1000
      IF (AMOD .GT. INPUTD) AMOD = AMOD - INPUTD
   10 CONTINUE
      RETURN
      END
C
      FUNCTION ZHOLD(FIRST,INTEND,THIRD)
      REAL INTEND
      ZHOLD = FIRST
      IF ( INTEND .GT. 0.000001) ZHOLD=THIRD
      RETURN
      END
C
      FUNCTION INTGRL(OLDVAL,DERIV,DELT)
      REAL*8 INTGRL,OLDVAL
      INTGRL = OLDVAL + DERIV*DELT
      RETURN
      END
C
      FUNCTION AFGEN(XVAL, YVAL, ARG)
      REAL NEWX, NEWY, OLDX, OLDY
      DIMENSION XVAL(1), YVAL(1)
      OLDX = XVAL(1)
      OLDY = YVAL(1)
      DO 101 I = 2,400
      NEWX = XVAL(I)
      IF (ARG.LT.XVAL(I)) GO TO 102
      OLDX = NEWX
  101 CONTINUE
  102 CONTINUE
```

```
      IF (OLDX.EQ.NEWX) OLDX = OLDX - 1.0E-10
      IF (OLDX.EQ.ARG) OLDX = OLDX - 1.0E-10
      NEWY = YVAL(I)
      OLDY = YVAL(I-1)
      AFGEN = OLDY + ((NEWY-OLDY)/(NEWX-OLDX) * (ARG-OLDX))
      RETURN
      END
C
      SUBROUTINE MTIME(MONTH,DATE,JDAY)
      INTEGER MONTH, DATE
      INTEGER DAYS(13)
      DATA DAYS /0,31,59,90,120,151,181,212,243,273,304,334,365/
C  CALENDAR--NUMBER OF DAYS AT END OF EACH MONTH
C   (NOTE THAT FOR LEAP-YEARS, 1 MUST BE ADDED FOR FEB-DEC)
C
      MONTH=(JDAY/29)+1
      J=JDAY-DAYS(MONTH)
      IF(J.GE.1)GO TO 775
      MONTH=MONTH-1
      J=JDAY-DAYS(MONTH)
  775 CONTINUE
      DATE = J
      RETURN
      END
C
      SUBROUTINE DLYTOT(DTOTZ,DTOT,DTOTI,RATE,TIME,DELT)
      REAL IMP,IMPULS
      REAL*8 INTGRL, DTOTI
      DTOTI = INTGRL(DTOTI,RATE,DELT)
      IMP =IMPULS(TIME,DELT,86400.)
      DUMMY = DTOTI
      DTOTZ = ZHOLD(DTOTZ,IMP,DUMMY)
      DTOT = DTOTI-DTOTZ
C
C     THE ACCUMULATOR IS EMPTIED AFTER MIDNIGHT,
C     SO CONTENTS ARE AVAILABLE FOR PRINTING.
      RETURN
      END
C
      SUBROUTINE WAVE(TEMP,JULIAN,HOUR,MINT,MAXT,RISE,PI)
      REAL MAXT,MINT,JULIAN,INSW
      TIM1 = HOUR - 14.
      TIM2 = HOUR + 10.
      TIM = INSW(TIM1,TIM2,TIM1)
C     WRITE(6,11) TIM1,TIM2,TIM,HOUR
   11 FORMAT(' TIM1 =',G10.2,'TIM2 =',G10.2,' TIM =',G10.2,'HOUR=',G9.2)
      VALAV = 0.5*(MAXT+MINT)
      VALAMP=0.5*(MAXT-MINT)
C     WRITE(6,12) MAXT,MINT,VALAV,VALAMP
   12 FORMAT(' MAXT =',G10.2,' MINT =',G10.2,' VALAV=',G10.2,' VALAMP=',
     $ G10.2)
      TEMPSR=VALAV-VALAMP*COS(PI*(HOUR-RISE)/(14.-RISE))
      TEMPSS=VALAV+VALAMP*COS(PI*TIM/(10.+RISE))
C     WRITE(6,13) TEMPSR,TEMPSS,VALAV,VALAMP
```

```
   13 FORMAT('TEMPSR=',G10.2,'TEMPSS=',G10.2,' VALAV=',G10.2,' VALAMP=',
     $ G10.2)
      AN1 = HOUR - RISE
      AN2 = 14. - HOUR
      AANNDD=-0.5 + AND(AN1,AN2)
      TEMP=INSW(AANNDD,TEMPSS,TEMPSR)
C     WRITE(6,14) TEMPSR,TEMPSS,TEMP,AANNDD
   14 FORMAT(' TEMPSR=',G10.2,' TEMPSS=',G10.2,' TEMP=',G10.2,' AND=',
     $ G10.2)
      RETURN
      END
```

APPENDIX C:

ACSL-LISTING OF SIMULATION MODEL (VERSION 1.5)

```
'          ****ADVANCED CONTINUOUS SIMULATION LANGUAGE****                 '
'                   *** VERSION 1.5 *** '
PROGRAM    WATER UPTAKE AND ROOT GROWTH IN A HOMOGENEOUS SOIL PROFILE
'CODED BY M.HUCK, D.HILLEL & G.HOOGENBOOM, AUBURN UNIVERSITY -OCT.,1982'
'  (NOW INCLUDES SEPARATE GROWTH AND MAINTENANCE RESPIRATION FACTORS)  '
'                                                                      '
'        AREA IS UNITY (M**2).  UNITS SI (MKS).                        '
'  ORGANIC MATTER PRODUCTION NORMALIZED TO 1 KG/M**2/YEAR              '
'   WHICH IS 10 GM/M**2/DAY OR 0.01 MG/M**2/SEC, ON AVERAGE            '
'                                                                      '
' FOLLOWING STATEMENT CHANGES INDEPENDENT VARIABLE TO TIME IN ACSL'
'CALL GSIZE(150.,11.0,1100)                                        '
VARIABLE TIME = 0.0
CINTERVAL CINT = 600.
NSTEPS NSTEP = 1
MINTERVAL MINT = 1.0
MAXTERVAL MAXT = 3600.
ALGORITHM IALG = 5
CONSTANT YY = 0.0
ARRAY   CRTEX(10),RSRT(20), DIST(20), THETA(10), RRS(20), ARS(20)
ARRAY      VOLW(10),FLW(20), COND(20) , AVCOND(20) , POTRT(20),IVOLW(10)
ARRAY    POTH(20), POTM(20), RSSL(20), Y(20), SCAAL(20) ,IRTEX(10)
ARRAY   NFLW(10),TCOM(10), RRL(10), SMIN(10), SMAX(10), ITHETA(10)
ARRAY    PRTL(10),BIRTH(20), EXTENS(20), RTGRO(20), RTDTH(20)
ARRAY             IPRTL(10),NETGRO(10),RTEX(10),PTOTL(20)
ARRAY      LINE(101),  RK(20), DEPTH(20)
INTEGER J,NJ,NJJ,I,LINE,IX,IB,IFUN,RUNS,IL,KEEP
CONSTANT IX=1H*,IB=1H ,KEEP=1,LINE(1)=1HI
CONSTANT  SMAX   = .35 , 4.50 , .004 , 2.0,+0.3E-7, 5.0E2,0.,0.,0.,0.
CONSTANT SMIN    = .05 , -0.5 , 0.0 ,  -.1,-0.3E-7, 0.0,0.0,0.,0.,0.
'  SCALE FACTORS FOR VERTICAL GRADIENT PLOTS                            '
CONSTANT OUTF = 3.024E05
'  OUTPUT FUNCTION FOR VERTICAL GRADIENT PLOTS MADE DURING EXECUTION --'
'  --INITIAL FREQUENCY FOR VERTICAL GRADIENT PLOTS IS INCREMENTED LATER'
'  SPECIFICATION OF CONVERGENCE CRITERIA FOR VARIABLE TIME-STEP INTGRLS'
'                                                                      '
CONSTANT DAY = 0.0
'                                                                      '
CONSTANT     ERROR  =  0.01
CONSTANT     CF  =  0.10
'  CORRECTION FACTOR AND ERROR PARAMETERS FOR ITERATIVE LOOP BELOW     '
'                                                                      '
'  A STANDARD MATHEMATICAL CONSTANT                                    '
CONSTANT PI = 3.14
CONSTANT BGNDAY = 180.
CONSTANT CLOCK = 0.
' JULIAN DATE AT BEGINNING OF SIMULATION RUN                           '
CONSTANT STEMP = 25.0
' TEMPERATURE OF THE SOIL, AS DEGREES C                                '
CONSTANT RANGE = 5.0
```

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' RANGE BETWEEN AVERAGE (REFT) TEMPERATURE AND MINIMUM OR MAXIMUM          '
CONSTANT REFT = 25.0
'THE MEAN TEMPERATURE, ABOUT WHICH SIMULATED TEMPERATURE OSCILLATES        '
CONSTANT MAXRAD = 700.
' INCOMING RADIATION                                                      '
CONSTANT MAXFOT = 3.00E-06
' MAXIMUM PHOTOSYNTHETIC RATE                                             '
'                                                                         '
'                                                                         '
'        **   INITIALIZATION OF PLANT-GROWTH PARAMETERS                   '
'                                                                         '
CONSTANT IPER = 0.03
CONSTANT ISHOOT = 0.1,  IROOT = 0.05
'   INITIAL SHOOT AND ROOT WEIGHTS, RESPECTIVELY (KG/M**2)                '
CONSTANT LNGFAC = 13000.0
'  LENGTH FACTOR, AS METERS OF ROOT PER KG ROOT WEIGHT                    '
'  (A FACTOR OF 1000 CORRESPONDS TO ABOUT 1 MM ROOT DIAMETER)             '
CONSTANT RRL     = 2.7E-01, 2.3E-01, 2.2E-01, 1.9E-01, 0.06,  ...
    .018, 1.0E-02, 1.0E-3, 1.0E-4, 1.0E-3
'  RELATIVE ROOT LENGTH (AS FRACTION OF TOTAL)                            '
CONSTANT RSPFAC = 1.0E-07
' RESPIRATION FACTOR, CONVERTING UNITS AND PROPORTIONING                  '
CONSTANT CONVRT = 0.30
' CONVERSION EFFICIENCY (MASS OF TISSUE PRODUCED PER GRAM INPUT)          '
CONSTANT FRG = 0.6666
' FRACTION OF CARBOHYDRATES GOING TOWARD SUPPORT OF SHOOT GROWTH          '
CONSTANT AGFAC = 3.0E-07
CONSTANT LEAFTH = 40.0
' LEAF THICKNESS--SQ. METERS LEAF AREA/SQ. METER SOIL, FOR EACH           '
'  KG. SHOOT MASS ON THE SAME LAND AREA                                   '
CONSTANT GROFAC = 1.0E-05
CONSTANT DTHFAC = 1.0E-10
' FACTOR TO SCALE ROOT DEATH RATE                                         '
TABLE FRACTB,1,5/-500.,-200.,-050.,-10.,100.,...
      0.05,0.25,0.70,0.95,0.95/
'  UNITS = =, AS A FUNCTION OF CANOPY WATER POTENTIAL                     '
TABLE DTHBGN,1,5/0.0,2.0,5.0,7.0,10.0,...
      0.0,0.03,0.33,0.97,1.00/
'                                                                         '
'        **   INITIALIZATION OF WATER-BALANCE PARAMETERS                  '
'                                                                         '
CONSTANT ITHETA     = 0.0938, 0.1192, 0.1249, 0.1353, 0.1444, ...
      0.1508, 0.1613, 0.1817, 0.2326, 0.3500
'  INITIAL SOIL WATER CONTENT (VOLUME FRACTION)                           '
'    (INITIALIZED TO VALUES FOUND AFTER 12 DAYS OF DRAINING FROM          '
'     SATURATION AT 20= WATER IN ALL LAYERS)                              '
CONSTANT DTRDEM = 0.01
'  DAILY TRANSPIRATION DEMAND, M/DAY                                      '
CONSTANT DLAY = 21600.
CONSTANT SATCON = 5.3348
'  SATURATED CONDUCTIVITY, AS CM/DAY                                      '
CONSTANT ZLAM = 0.64762
'  Z(LAMBDA), AFTER LALIBERTE, BROOKS & COREY                             '
CONSTANT TCOM     = .10, 2 * .15 , 7 * .20
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'  THICKNESS OF EACH VERTICAL LAYER (COMPARTMENT),  METERS                  '
CONSTANT PB = 21.8258
' BUBBLING PRESSURE ( AIR ENTRY VALUE FOR TOP SOIL)                          '
CONSTANT BRMIN = -0.30
CONSTANT EXTMIN = -1.00
' THRESHOLD POTENTIAL, THE DRIEST SOIL IN WHICH ROOT GROWTH CAN OCCUR        '
CONSTANT BR = 1.0E-10
CONSTANT EXTNRT = 3.0E-04
' EXTENSION RATE, FOR NEW ROOT GROWTH FROM ONE LAYER INTO THE NEXT,          '
'  IN UNITS OF METER/SECOND                                                  '
CONSTANT AA = 7.945089E-05,  BB = 2.429255
' COEFFICIENTS FOR SIGMOID ROOT GENERATION CURVES                            '
CONSTANT B = 1.0E-02
' CONSTANT, RELATING ROOT CONDUCTIVITY TO ROOT LENGTH, AFTER (GARDNER)       '
CONSTANT URRS = 1.00E11
'  UNITS FOR RADIAL RESISTANCE                                               '
CONSTANT UARS = 1.00E09
' UNITS FOR AXIAL RESISTANCE                                                 '
CONSTANT MAXPOT = -2.0
'  MAXIMUM ALLOWABLE CANOPY POTENTIAL,( -2 METER, OR -0.2 BAR)               '
TABLE SUCTB,1,12/0.025,0.05,0.075,0.10,0.15,0.20,0.25,0.30,0.35,...
      0.40,0.45,0.50,...
      20.,5.,3.,1.7,0.6,0.25,0.15,0.10,0.05,0.01,0.0,-1.00/
'TABLE WATRST,1,5/-500.,-200.,-100.,0.,100.,...'
    '0.05,0.05,0.95,1.0,1.0/'
' TRANSPIRATION TABLE FOR SENSITIVE CROPS SUCH AS MAIZE OR SOYBEANS          '
 TABLE WATRST,1,7/-500.,-400.,-300.,-150.,-50.,0.,200.,...
   0.,0.02,0.06,0.75,0.96,1.00,1.00/
' TRANSPIRATION FOR DROUGHT-TOLERANT CROPS-EG. COTTON OR SORGHUM             '
TABLE AVPET,1,2/0.0,366.,0.01,0.01/
'  MEASURED PAN EVAPORATION LOSSES - HERE ALL THE SAME TO CHECK MODEL'
TABLE LAIFAC,1,4/0.,3.0,6.0,10.,...
      0.,0.5,0.9,0.95/
'  LEAF AREA INDEX FACTOR, PARTITIONS WATER LOSSS BETWEEN PLANT & SOIL       '
'                                                                            '
'* * * * * * * * * * INITIAL SEGMENT * * * * * * * * * * * * * * * * * *    '
'                                                                            '
INITIAL
RUNS = 0
FLPFLP = -1.0
      JDAY = BGNDAY
ICHO = ( ISHOOT + IROOT ) * IPER / ( 1. - IPER )
'  INITIAL CARBOHYDRATES (KG/M**2), AS DECIMAL FRACTION OF TOTAL MASS.'
      IRTL = IROOT * LNGFAC
' METER OF ROOT/SQUARE  METER GROUND AREA AT INITIALIZATION                  '
      LAI = ISHOOT * LEAFTH
'LEAF AREA INDEX  -- AREA OF LEAF SURFACE/UNIT LAND AREA                     '
      ETA = 2.0 + 3.0 * ZLAM
'                                                                            '
CONSTANT NJ = 10
'  THE NUMBER OF LAYERS(J) IN THE SOIL PROFILE                               '
      DEPTH(1) = .5*(TCOM(1))
      DIST(1) = DEPTH(1)
      DO 20  I = 2,NJ
```

```
         DIST(I) = .5*(TCOM(I-1)+TCOM(I))
         DEPTH(I) = DEPTH(I-1) + DIST(I)
  20..CONTINUE
853..FORMAT(/,' INITIALIZE',/,9X,'I',3X,'IPRTL',5X,'RSRT',8X,'IVOLW')
      LINES(2)
      WRITE(6,853)
      DO 30  I = 1,NJ
      IRTEX(I) = 0.0
      IPRTL(I) = IRTL * RRL(I)
'  PARTIAL ROOT LENGTH, AT INITIALIZATION                                   '
      IVOLW(I) =  ITHETA(I)*TCOM(I)
'  INITIAL VOLUME OF WATER IN EACH SOIL LAYER                               '
      RRS(I) = URRS / IPRTL(I)
'  RADIAL RESISTANCE TO WATER FLOW IN THE ROOT                              '
      ARS(I) = UARS * DEPTH(I) / IPRTL(I)
'  AXIAL RESISTANCE -- ALONG THE XYLEM TRANSPORT SYSTEM                     '
      RSRT(I) = RRS(I) + ARS(I)
' RESISTANCE OF THE ROOTS                                                   '
      LINES(1)
      WRITE(6,454) I,IPRTL(I),RSRT(I),IVOLW(I),TCOM(I),ITHETA(I), ...
        IRTL, RRL(I), DEPTH(I)
 454..FORMAT(3G10.3, 3F10.5, G10.3, 2F10.5, 3G10.3)
  30..CONTINUE
'                                                                           '
      POTCR = -20.000
      POTCRD= -20.00
' POTENTIAL OF THE CROWN (SHOOT), INITIALIZED BELOW DRIEST SOIL LAYER       '
'  (-20 METERS = -2 BARS)                                                   '
'                                                                           '
      DO 10  I = 2,101
  10..LINE(I) = IB
'  INITIALIZES PRINT-LINE FOR VERTICAL PLOTS TO BLANK CHARACTER-STRING      '
'                                                                           '
      NJJ = NJ+1
'  ONE MORE THAN THE NUMBER OF LAYERS IN THE SOIL PROFILE (NJ)              '
      DO 15 I = 1,NJJ
  15..FLW(I) = 0.0
'  FLOW OF WATER PAST BOTTOM OF EACH LAYER, INITIALIZED TO 0.0              '
'                                                                           '
'                                                                           '
END$  ' INITIAL                                                             '
'  * * * * * * * * * *  DYNAMIC SEGMENT  * * * * * * * * * * * * * * *      '
DYNAMIC
'                                                                           '
'                                                                           '
'                 ***   DEFINITION OF TIME-BASES      ***                   '
'                                                                           '
'                                                                           '
      HOURC = TIME/3600.0
'  CUMULATIVE HOURS OF SIMULATION TIME                                      '
      CLOCK = AMOD(HOURC,24.0)
'  CLOCK TIME, IN HOURS                                                     '
      DAY = HOURC / 24.00
      JDAY = DAY + BGNDAY
```

```
'  JULIAN DATE, AS DECIMAL FRACTION, DURING THE SIMULATION             '
      RUN = RUNS
'  CREATES A REAL-NUMBER COUNTING VARIABLE FOR PRINTER OUTPUT          '
DERIVATIVE
'                                                                      '
'                  **  ESTIMATION OF TEMPERATURE EFFECTS  **           '
'                                                                      '
      TMPFCS = 10.0 ** ((TEMP-REFT) * 0.030103)
      TMPFCR = 10.0 ** ((STEMP-REFT) * 0.030103)
' BIOLOGICAL Q-10 -- DOUBLING REACTION RATE AT EACH 10 DEGREE TEMP CHNG'
      TEMP = REFT + ((SIN(2 * PI * (DAY - 0.375))) * RANGE)
'   TEMPERATURE FACTOR, MULTIPLIER FOR TEMPERATURE EFFECT              '
'                                                                      '
'           **      RESERVE LEVELS AND TISSUE GROWTH           **      '
'                                                                      '
      RESL = SOLCHO / (SOLCHO + ROOTW + SHOOTW)
'  RESERVE LEVEL, = FREE CARBOHYDRATE IN TISSUES                       '
'                                                                      '
      SOLCHO = INTEG((PHOTSN * PHTCAR - GROWTH - RESP),ICHO)
      PHTCAR = 30. / 44.
'  SOLUBLE CARBOHYDRATES (FREELY MOBILE, AS METABOLIC RESERVES)        '
'     (KG/SQUARE METER)                                                '
'                                                                      '
      GROWTH = TOPGRO + TOTRG
'  TOTAL GROWTH OF BOTH SHOOT AND ROOT SYSTEM                          '
'                                                                      '
'                    **    PHOTOSYNTHETIC ACTIVITY    **               '
'                                                                      '
      PHOTSN =  RADN * MAXFOT * LAIFAC(LAI) * WATRST(POTCR) / MAXRAD
'  PHOTOSYNTHETIC RATE (NET CARBON FIXATION, KG/SQUARE METER/SECOND    '
      RADN = AMAX1( 0.0 , SIN(2 * PI * (DAY - 0.250))) * MAXRAD
'                                                                      '
'                                                                      '
'       **            ROOT AND SHOOT RESPIRATION          **           '
'                                                                      '
      RESP = RESPSH + RESPRT
'  TOTAL RESPIRATION, INCLUDING BOTH SHOOT AND ROOT SYSTEM             '
      RESPSH = SHMRES + SHGRES
'  RATE OF SHOOT RESPIRATION (KG/SQ METER/SEC)                         '
'    (SUM OF GROWTH RESPIRATION AND MAINTENANCE RESPIRATION)           '
      SHMRES = SHOOTW * TMPFCS * RSPFAC
      CSTMRS = INTEG( SHMRES,0.0)
'  SHOOT MAINTENANCE RESPIRATION                                       '
    SHGRES = TOPGRO * CONVRT
' SHOOT GROWTH RESPIRATION                                             '
      RESPRT = RTMRES + RTGRES
'  RESPIRATION OF ROOT SYSTEM                                          '
      RTMRES = ROOTW * RSPFAC * TMPFCR
      CRTMRS = INTEG(RTMRES,0.0)
'  ROOT MAINTENANCE RESPIRATION                                        '
      RTGRES = TOTRG*CONVRT
'  ROOT GROWTH RESPIRATION, INCLUDING CHEMICAL CONVERSION AND TRANSPORT'
'                                                                      '
'           **   GROWTH AND DEATH OF SHOOT TISSUE       **             '
```

```
'                                                                        '
      SHOOTW = INTEG( (TOPGRO - SHOOTD),ISHOOT)
'   WEIGHT OF LIVING SHOOT TISSUE (KG/SQ METER)                          '
'                                                                        '
      POTCRD = INTEG((POTCR-POTCRD)/DLAY,10.)
'     DELAYED CANOPY WATER POTENTIAL                                     '
      POTCRE = AMIN1(POTCR,POTCRD)
'     EFFECTIVE CANOPY WATER POTENTIAL                                   '
      FRAC = FRACTB(POTCRE)
      TOPGRO = TMPFCS * GROFAC * SOLCHO * FRAC
'     TOPGRO = TMPFCS * GROFAC * SOLCHO * FRG                            '
'    RATE AS (KG/SQ METER/SEC) OF SHOOT (STEMS, LEAVES, AND FRUIT)      '
      SHOOTD = SHOOTW * TMPFCS * DTHBGN(LAI) * AGING
'   SHOOT DEATH RATE (PRINCIPALLY LEAF-DROP DUE TO AGE AND WATER STRESS)'
      AGING = AGFAC * (DAY/30.)
      LAI = SHOOTW * LEAFTH
'   LEAF AREA INDEX, DIMENSIONLESS (AREA OF LEAF SURFACE/UNIT LAND AREA)'
'                                                                        '
'            **        GROWTH AND DEATH OF AGGREGATED ROOT SYSTEM   *'
'                                                                        '
      ROOTW = INTEG((TOTRG-ROOTDY),IROOT)
'   WEIGHT OF LIVE ROOT TISSUE(ALL SOIL LAYERS)                          '
      TOTRG = (1.0 - FRAC) * SOLCHO * GROFAC * TMPFCR
'     TOTRG = (1.0 - FRG) * SOLCHO * GROFAC * TMPFCR                     '
'   TOTAL ROOT GROWTH, SUM OF ROOT WEIGHT IN ALL SOIL LAYERS             '
      ROOTDY = ROOTW / RESL* DTHFAC * TMPFCR
'   RATE OF DYING FOR TOTAL ROOT SYSTEM -- MODULATED IN SUMMATION  OF    '
'     DEATH RATES FOR ROOTS IN EACH SOIL LAYER IN A LATER SECTION.       '
'INVERSELY PROPORTIONAL TO CARBOHYDRATE RESERVES--DYING OFF WHEN HUNGRY'
'   (RATE EXPRESSED AS KG ROOTS/SQUARE METER/SECOND -- WHOLE PLANT)      '
'                                                                        '
'                                                                        '
'          **  TRANSPIRATION AND WATER LOSS FROM SOIL SURFACE  **        '
'                                                                        '
      TRANSP = WATRST(POTCR) * PET * LAIFAC(LAI)
'   TRANSPIRATION LOSSES, AS METERS/SECOND                               '
'                                                                        '
      PET =AMAX1(0.01 * DTRDEM / 86400., PI * RADN * MPANEV / MAXRAD)
'   POTENTIAL EVAPOTRANSPIRATION, BASED ON TEMPERATURE (+ RADIATION)     '
'    (NOT LESS THAN 1= OF AVERAGE TRANSP. DEMAND--NEGATIVES ELIMINATED) '
'                                                                        '
       CUMPET = INTEG(PET,0.0)
'   CUMULATIVE POTENTIAL EVAPOTRANSPIRATION -- COMPARE OUTPUT WITH AVPET'
'                                                                        '
     MPANEV = AVPET(JDAY) / 86400.
'   MEASURED POTENTIAL EVAPOTRANSPIRATION IN FIELD (METERS PER DAY)      '
      SLEVAP = PET * (1.0 - LAIFAC(LAI))
'  SOIL EVAPORATION (METERS/SEC), PET REDUCED BY LEAF SHADING            '
'                                                                        '
'                                                                        '
'                  **  SOIL WATER MOVEMENT CALCULATIONS **               '
'                                                                        '
      VOLW   = INTVC   ( NFLW ,IVOLW)
'   VOLUME OF WATER STORED IN EACH SOIL LAYER                            '
```

```
'                                                                        '
'      **  OOMPUTE SOIL WATER CONTENT, POTENTIALS, AND CONDUCTIVITY      '
'                                                                        '
PROCEDURAL(THETA, POTM, POTH,  MPOT, RK, COND                        ...
      = TIME, PB)
      DO 100 I = 1,NJ
      THETA(I) = VOLW(I)/TCOM(I)
      POTM(I)=-SUCTB(THETA(I))
      POTH(I) =POTM(I)  - DEPTH(I)
 100..CONTINUE
'                                                                        '
'                    **  COMPUTE SOIL HYDRAULIC CONDUCTIVITY  **         '
'                                                                        '
      DO 85 I = 1, NJ
      MPOT = -POTM(I) * 100.0
      IF (MPOT.LE. 0.0) GO TO 84
      RK(I) = (PB/MPOT) ** ETA
'   RELATIVE CONDUCTIVITY (AS A FRACTION OF SATURATED CONDUCTIVITY)      '
      GO TO 87
  84..RK(I) = 1.0
'  RELATIVE CONDUCTIVITY CAN NEVER BE MORE THAN 1.0;                     '
' THUS, SATURATED CONDUCTIVITY APPLIES IF MATRIC POTENTIAL IS POSITIVE '
  87..CONTINUE
      RK(I) = AMIN1(1.00, RK(I))
'  CONDUCTIVITY IS LIMITED TO A MAXIMUM OF THE SATURATED CONDUCTIVITY   '
      COND(I) = RK(I) * SATCON / 8.6400E06
'  SOIL HYDRAULIC CONDUCTIVITY, METERS/SECOND                            '
  85..CONTINUE
END $ 'PROCEDURAL'
'                                                                        '
'    ** COMPUTE VERTICAL SOIL WATER FLOW (DARCIAN)     **                '
'                                                                        '
PROCEDURAL(AVCOND, FLW, NFLW= POTH)
      DO 110 I = 2,NJ
      AVCOND(I) = .5 * (COND(I-1) + COND(I))
      FLW(I) = AVCOND(I) * (POTH(I-1)-POTH(I)) / DIST(I)
 110..CONTINUE
      IF (POTM(1) .GT. -10.0) FLW(1)=-SLEVAP
      IF (POTM(1) .LE. -10.) FLW(1)=FLW(2)
' WATER FLOW OUT THE TOP IS LIMITED BY SUPPLY IF TOP LAYER IS DRY        '
      FLW(NJJ) = 0.000000
      DO 120 I = 1,NJ
         NFLW(I) = FLW(I) - FLW(I+1) - RTEX(I)
 120..CONTINUE
END $ 'PROCEDURAL'
'                                                                        '
'   **  PARTITIONING AGGREGATE ROOT GROWTH BETWEEN SOIL LAYERS    **     '
'                                                                        '
      PRTL = INTVC(NETGRO,IPRTL)
'  PARTIAL ROOT LENGTH, IN EACH SOIL LAYER -- SUM OF GROWTH LESS DEATH '
'                                                                        '
PROCEDURAL(BIRTH,EXTENS,RTGRO,SUMRG,RTDTH,SUMRD,NETGRO, ...
  W,SUMRTG,SUMRTD = POTM)
'                                                                        '
```

```
'              **                ROOT GROWTH IN EACH LAYER               **  '
'                                                                            '
'                                                                            '
      W =  AMAX1(0.0,  (POTM(2) - EXTMIN))
      DO  1010  I=1,NJ
      X =  AMAX1(0.0,  (POTM(I) - BRMIN))
      XX =  AMAX1(0.0,  (POTM(I) - EXTMIN))
      BIRTH(I) = BR * ( 1.0 - EXP ( -AA*X**BB )    )
1010..EXTENS(I) = EXTNRT * ( 1.0 - EXP ( -AA*XX**BB )   )
      RTGRO(1) = PRTL(1) * BIRTH(1)
      SUMRG = RTGRO(1)
'  SUMMATION OF INSTANEOUS ROOT GROWTH RATES, OVER ALL SOIL LAYERS          '
'   (EXPRESSED AS METERS ROOTS/SQUARE METER SURFACE/SECOND)                 '
      DO 647 I = 2,NJ
      RTGRO(I) = (PRTL(I-1)*EXTENS(I) + PRTL(I)*BIRTH(I))
'  GROWTH EXPRESSED AS METERS/SEC IN EACH SQUARE METER OF EACH LAYER        '
 647..SUMRG = RTGRO(I) + SUMRG
'  TOTAL INCREASE, WHOLE PLANT, IN METERS/SQ. METER/SECOND                  '
'                                                                            '
      SUMRTG = 0.0
      DO 648 I = 1,NJ
      IF (SUMRG.EQ.0.00) GO TO 648
      RTGRO(I) = RTGRO(I) * TOTRG/SUMRG * LNGFAC
'  (BRINGS ACTUAL ROOT GROWTH IN EACH LAYER INTO LINE WITH TOTAL            '
'    PHOTOSYNTHATE AVAILABLE AT ANY GIVEN TIME).                             '
      SUMRTG = SUMRTG + RTGRO(I)
 648..CONTINUE
'                                                                            '
'                  **        ROOT DEATH IN EACH LAYER          **            '
'                                                                            '
      SUMRD = 0.0
      DO 649 I = 1, NJ
      RTDTH(I) =PRTL(I) * DTHFAC * TMPFCR
'  ROOT DEATH, AS METERS/SECOND LOST FROM EACH LAYER                        '
 649..SUMRD = SUMRD + RTDTH(I)
      SUMRTD = 0.0
      DO 651 I = 1, NJ
      IF (SUMRD.EQ.0.) GO TO 651
      RTDTH(I) = RTDTH(I) * ROOTDY/SUMRD * LNGFAC
'  SCALES ACTUAL DEATH RATE TO TOTAL AGGREGATE REQUIRED FOR C-BALANCE       '
      SUMRTD = SUMRTD + RTDTH(I)
'  TOTAL FOR PLANT, AS METERS/SQ. METER/SECOND                              '
 651..CONTINUE
'                                                                            '
'            **          SUMMARY OF GROWTH AND DEATH IN EACH LAYER         *'
'                                                                            '
      DO 653 I = 1,NJ
 653..NETGRO(I) = RTGRO(I) - RTDTH(I)
'  NET CHANGE IN ROOT LENGTH, AS METERS/SECOND CHANGE IN EACH LAYER.        '
END $ 'PROCEDURAL'
'                                                                            '
'               ** ROOT SYSTEM RESISTANCE AND WATER UPTAKE **                '
'                                                                            '
PROCEDURAL(RSSL, PTOTL, RSRT = COND,SUMRG)
```

```
      DO 102 I = 1,NJ
      RSSL(I) = 1./(B*COND(I)*PRTL(I))
      PTOTL(I) = POTH(I)
'  NOTE THAT PTOTL IS THE SAME AS HYDRAULIC POTENTIAL IN THIS VERSION  '
      RRS(I) = URRS / PRTL(I)
'  RADIAL RESISTANCE TO WATER FLOW IN THE ROOT                          '
      ARS(I) = UARS * DEPTH(I) / PRTL(I)
'  AXIAL RESISTANCE -- ALONG THE XYLEM TRANSPORT SYSTEM                 '
      RSRT(I) = RRS(I) + ARS(I)
'  COMBINED AXIAL AND CONDUCTIVE RESISTANCE OF ROOTS IN THIS LAYER      '
 102..CONTINUE
END $ 'PROCEDURAL'
'                                                                       '
'                                                                       '
'       **   CALCULATION OF POTCR AND PARTITIONING OF ROOT WATER UPTAKE '
'                                                                       '
      CUMREM = INTEG(SUMR,0.0)
'  CUMULATIVE WATER REMOVAL (BY ROOT SYSTEM) FROM ALL SOIL LAYERS       '
'                                                                       '
PROCEDURAL(  SUMR,DIFF,DIF,RTEX,POTRT =...
           POTH, TRANSP, RUN, RSRT)
      COUNT = 0.0
      FLPFLP = -FLPFLP
 115..CONTINUE
      COUNT = COUNT  +  1.0
      IF  (  COUNT .LT.  100.0  )  GO TO 116
      GO TO 165
'   IN CASE THE LOOP DOES NOT CONVERGE IN 100 TRIES, GO AHEAD ANYWAY    '
 116..CONTINUE
      SUMR =  0.0
      DO 150 J = 1,NJ
      I = J
      IF ( FLPFLP .EQ. 1.0 )  I = NJ - J + 1
      RTEX(I) = AMAX1(0.0 ,(POTH(I) - POTCR) / (RSSL(I) + RSRT(I) ) )
'  ROOT EXTRACTION, M/SECOND                                            '
      SUMR = SUMR + RTEX(I)
'  SUM OF WATER REMOVALS BY ROOTS IN ALL LAYERS                         '
      DIFF = TRANSP - SUMR
      IF (SUMR .LT. TRANSP) RTEX(I) = AMIN1(RTEX(I),DIFF)
 150..CONTINUE
'                                                                       '
'  FOR EACH LAYER, WATER EXTRACTION IS ASSUMED ON THE BASIS OF CURRENT '
'  VALUE FOR CANOPY POTENTIAL.  ITERATION WILL CONTINUE UNTIL EQUAL.    '
      DIF = (SUMR - TRANSP) / TRANSP
      IF (COUNT.GT.5.0) GO TO 165
      IF ( ABS(DIF) .LE. ERROR ) GO TO 165
      IF ( DIF )  160 , 165 , 160
'  ADJUSTMENT OF CANOPY WATER POTENTIAL UP OR DOWN AS NEEDED TO BALANCE'
 160..POTCR = AMIN1((POTCR - DIF*POTCR*CF),MAXPOT)
      GO TO 115
 165..CONTINUE
      DO 170 I = 1,NJ
      POTRT(I) = POTCR + RTEX(I) * RSRT(I)
 170..CONTINUE
```

```
END $ 'PROCEDURAL'
'                                                                        '
'      **   SUMMARY OF WATER MOVEMENT AND EVAPORATIVE LOSSES            '
'                                                                        '
      CRTEX  =  INTVC  (  RTEX ,IRTEX)
'  CUMULATIVE ROOT EXTRACTION                                            '
'                                                                        '
      EVAP = AMIN1(-FLW(1), SLEVAP)
'  EVAPORATION FROM SOIL SURFACE - LIMITED BY AVAILABILITY OF WATER     '
' (COMING FROM DEEPER SOIL LAYERS) OR BY THERMAL INSOLATION AT SURFACE '
      CEVAP = INTEG( EVAP,0.0)
'  CUMULATIVE EVAPORATION FROM SOIL SURFACE                              '
      FLW8P = AMAX1 (0.0,FLW(8))
      DRAIN = INTEG  (FLW8P,0.0)
'  INTERNAL DRAINAGE, AS WATER PASSES THE BOTTOM OF THE 7TH LAYER       '
      FLW8N = - AMIN1(0.0,FLW(8))
      CAPRIS = INTEG (FLW8N,0.0)
'  CAPILLARY RISE, PAST THE 8TH LAYER                                    '
      CUMTRN = INTEG (TRANSP,0.0)
      DRAING = FLW8P
'  CUMULATIVE TRANSPIRATION, AS M/SQUARE METER                           '
'                                                                        '
'     XYZ=DEBUG(02,0.0)'
'     ZYX=DEBUG(01,3600.)'
END$'DERIVATIVE'
TERMT(HOURC.GT.120.0.OR.POTCR.LT.-300..OR.SOLCHO.LT.1.0E-07.OR....
     SHOOTW.LT.0.0001.OR.TOPGRO.LT.-1.0E-10.OR.TOTRG.LT.-1.0E-18)
'  THE SIMULATION WILL TERMINATE WHEN THE PLANT WATER POTENTIAL DROPS'
' BELOW -300 METER WATER POTENTIAL(OR -30 BAR),OR WHENEVER ALL        '
' SOLUBLE CARBOHYDRATE IS EXPENDED ( NO FOOD IN STORAGE)              '
'                                                                     '
'            **  VERTICAL GRADIENT PLOTTING INSTRUCTIONS **             '
'                                                                        '
PROCEDURAL(YY,Y=OUTF,THETA,POTM,CRTEX,PTOTL,FLW,PRTL,TCOM)
      YY = PULSE ( 0.0   ,  OUTF  , 600.  )
      IF (  YY   .EQ.  0.0   ) GO TO 1200
      IF (TIME.LT.OUTF) GO TO 1200
      IF (KEEP.NE.1) GO TO 1200
      OUTF = OUTF + OUTF
      RUNS = 1
      COUNT = 1
'  FOR VARIABLE-FREQUENCY OUTPUT PLOTS                                   '
      DO 1000 IFUN = 1,6
' THE ORDER WILL BE THETA PPOTM CRTEX PTOTL FLW PRTL                     '
      GO TO  ( 500,550,650,700,750,850 ) , IFUN
 500..DO 505 I=1,NJ
 505.. Y(I) = THETA(I)
      WRITE(6,1505)
1505..FORMAT('1', /, 56X, 'THETA VS. DEPTH', /)
      GO TO 900
 550..DO 555 I=1,NJ
 555..Y(I) = - POTM(I)
      WRITE (6, 1555)
1555..FORMAT('1',/,56X,'-POTM (METERS) VS. DEPTH', /)
```

```
      GO TO 900
 650..DO 655 I=1,NJ
 655..Y(I) = CRTEX(I)
      WRITE(6,1655)
1655..FORMAT('1',/,56X,'CUMULATIVE ROOT EXTRACTION, METERS VS. DEPTH',/)
      GO TO 900
 700..DO 705 I = 1, NJ
 705..Y(I) =-PTOTL(I)
      WRITE(6,1705)
1705..FORMAT('1',/,56X,'TOTAL WATER POTENTIAL AS A FUNCTION OF DEPTH',/)
      GO TO 900
 750..DO 755 I = 1, NJ
 755..Y(I) = FLW(I)
      WRITE(6,1755)
1755..FORMAT('1',/, 56X, 'VERTICAL WATER FLUX RATE, POSITIVE DOWN',/)
      GO TO 900
 850..DO 855 I=1,NJ
 855..Y(I) = PRTL(I)/TCOM(I)
      WRITE(6,1855)
1855..FORMAT('1',/, 41X, 'PARTIAL ROOT LENGTH, METERS/SQ. METER ', ...
       'IN EACH LAYER', /)
 900..CONTINUE
      WRITE(6,905) HOURC, RUN, IFUN
 905..FORMAT(3X,'TIME IS ',F06.2,'   RUN = ',F8.0, /, '   IFUN = ', ...
        I2, //)
      SCAAL (IFUN) = (SMAX(IFUN) - SMIN(IFUN)) / 75.0
      DO 950 I = 1,NJ
      IL = ( Y(I) - SMIN(IFUN) ) / SCAAL(IFUN)  + 2.0
      IF (IL.LE.2)  IL = 2
      IF (IL .GE. 101 ) IL = 101
      J = 0.5 + TCOM(I) * 100.0 / 4.0
      LINE(IL) = IX
 922..J = J-1
      IF (J) 931,931,925
 925..WRITE(6,926)
 926..FORMAT('          1'  )
      GO TO 922
 931..WRITE (6,935) DEPTH(I),(LINE(K),K=1,101), Y(I)
 935..FORMAT(2H  , F9.4,3X,101A1,2X,E12.5 )
      LINE(IL) = IB
 950..CONTINUE
1000..CONTINUE
1200..CONTINUE
      RUNS = RUNS + 1
END$'PROCEDURAL'
END$'DYNAMIC'
'                                                                       '
'* * * * * * * * TERMINAL SEGMENT * * * * * * * * * * * * * * * * '
'                                                                     '
TERMINAL
END$' TERMINAL                                                            '
END$' OF PROGRAM                                                          '
//GO.FT99F001 DD SYSOUT=(C,,1111)
//GO.SYSIN DD *
```

```
PREPAR TIME,HOURC,RADN,POTCR,SOLCHO,SHOOTW,ROOTW,PHOTSN,POTCRE,...
      TOPGRO,TOTRG,SHOOTD,ROOTDY,NETGRO,CUMREM,CUMTRN,CEVAP,DRAIN,...
      RESP,FRAC,THETA,SHMRES,SHGRES,RTMRES,RTGRES
SET TITLE= ' WATER UPTAKE AND ROOT GROWTH IN A HOMOGENEOUS SOIL PROFILE'
OUTPUT TIME,HOURC,RADN,PHOTSN, POTCR, SOLCHO, SHOOTW,                ...
ROOTW,'NCIOUT'=10
START
SET CALPLT=.TRUE.,PENCPL=.TRUE.,XINCPL=10.0,YINCPL=7.5,NPCCPL=50,...
      TTLCPL=.TRUE.,SYMCPL=.TRUE.
SET TITLE = ' NET-PHOTOSYNTHESIS AND RESPIRATION      (KG/M2/SEC)        '
PLOT 'XAXIS' = HOURC,'XHI' = 120.,PHOTSN,RESP,'SAME',SOLCHO
SET TITLE = 'SHOOT MAINTENANCE AND GROWTH RESPIRATION                    '
PLOT 'XAXIS' = HOURC,'XHI'=120.,SHGRES,RTGRES,RTMRES,SHMRES,'SAME'
SET TITLE = 'FACTORS INFLUENCING BIOMASS PARTITIONING                    '
PLOT 'XAXIS' = HOURC,'XHI'=120.,POTCR,POTCRE,'SAME',FRAC
SET TITLE = ' TISSUE GROWTH AND BIOMASS PARTITIONING                     '
PLOT 'XAXIS' = HOURC,'XHI'=120.,TOPGRO,TOTRG,SHOOTD,ROOTDY,'SAME'
SET TITLE = ' NET INCREASE IN ROOT LENGTH             (METER/METER2)     '
PLOT 'XAXIS' = HOURC,'XHI'=120.,NETGRO(10),NETGRO(9),NETGRO(8),...
  NETGRO(7),NETGRO(6),NETGRO(5),NETGRO(4),NETGRO(3),NETGRO(2),...
  NETGRO(1),'SAME'
SET TITLE = 'SOIL WATER CONTENT                                          '
PLOT 'XAXIS' = HOURC,'XHI'=120.,THETA(04),THETA(3),THETA(2),...
  THETA(1),THETA(10),THETA(9),THETA(08),THETA(7),THETA(6),...
  THETA(5),'SAME'
SET TITLE = ' SIMULATED CUMULATIVE WATER BALANCE :   TRANSPIRATION...
 AND UPTAKE'
PLOT 'XAXIS' = HOURC,'XHI'=120.,CUMREM,CUMTRN,CEVAP,DRAIN,'SAME'
STOP
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APPENDIX D

GLOSSARY OF TERMS USED IN SIMULATION MODEL

VARIABLE	DESCRIPTION	UNIT
AA	Coefficient for sigmoid root generation curve	(dimensionless)
AAA	Procedure statement	-
ABS	FORTRAN function - absolute value	-
ABSERR	Absolute error (CSMP variable for integration control)	-
AFGEN	CSMP function generator (CSMP library linear interpolation)	-
AGE	Cumulative days of simulation time	day
AGFAC	Aging factor, parameter controlling leaf aging	kg/(kg s)
AGING	Relative aging factor, modifying shoot death rate	day/day
ALPHA	Constant in relative conductivity equation	1/m
ALOG	FORTRAN function - natural logarithm	-
AMAX1	FORTRAN function - maximum real number variable	-
AMIN1	FORTRAN function - minimum real number variable	-
AMOD	FORTRAN function - remaindering function	-
AND	CSMP function - logic AND function	-
ARS	Axial resistance to water flow through roots (xylem flow resistance)	sec
ATAN	FORTRAN function - ARCTANGENT	-
AVCOND	Average conductivity for water flow between soil compartments	m/sec
AVPET	Average potential evapotranspiration, as measured daily	m/day
B	Constant, relating soil-root conductivity to length of root	1/m
BB	Coefficient for sigmoid generation curve	-
BGNDAY	Julian date at the beginning of the simulation run	day
BIRTH	Branching rate (Formation of new roots in same soil layer)	m/sec
BR	Branching rate parameter	m/sec
BRMIN	Lowest soil water potential at which root branching occurs (new root tissue)	m (kPa*10)
BULKDS	Bulk density of the soil	kg/m^3
BULKF	Table for bulk density as a function of depth	-

CAPRIS	Cumulative capillary rise (past the bottom layer)	m
CEVAP	Cumulative evaporation from soil surface	m
CF	Correction factor - iteration loop	-
CLOCK	Clock time	
CMRAIN	Measured daily rainfall	m/day
COND	Soil hydraulic conductivity	m/sec
CONVRT	Relative growth efficiency (kg biomass/kg carbohydrate respired)	kg/kg
COS	FORTRAN function - cosine	-
COUNT	Counter for iteration loop	-
CRC	Current radiation under a clear sky	Joule/(m^2 sec)
CRO	Current radiation under an overcast sky	Joule/(m^2 sec)
CRTEX	Cumulative root extraction	m
CRTMRS	Cumulative root maintenance respiration	kg/m^2
CSDC	Cosine of declination	-
CSLT	Cosine of latitude	-
CSTMRS	Cumulative shoot maintenance respiration	kg/m^2
CTRAN	Cumulative transpiration	m (H_2O)
CUMPET	Cumulative potential evapotranspiration	m (H_2O)
CUMRAD	Cumulative daily total radiation	Joule/m^2
CUMREM	Cumulative water removal (by root system) from all soil layers	m (H_2O)
C0	Auxiliary variable for the calculation of photosynthesis under a clear sky	kg CO_2/(m^2 sec)
C1	Auxiliary variable for the calculation of photosynthesis under a clear sky	kg CO_2/(m^2 sec)
C2	Auxiliary variable for the calculation of photosynthesis under a clear sky	kg CO_2/(m^2 sec)
DATA	FORTRAN statement - data input	
DAY	Day of the year during simulation	day
DAYRAD	Daily total radiation	Joule/(m^2 day)
DAYRAI	Daily total rainfall	m/day
DAYS	Table for number of days per month	-
DEBUG	CSMP statement - controls error debugging	-
DEC	Declination of the sun with respect to the equator	degree
DELAY	Delay time for computation of effective canopy water potential	sec
DELMAX	Maximum time-step for integration routine	sec
DELMIN	Minimum time-step for integration	sec
DELT	Timestep for integration	sec
DEPTH	Depth to midpoint of soil layer, measured from soil surface	m
DEPTHG	Factor accounting for increased resistance to soluble carbohydrates with deeper roots	m/m
DFCLTB	Table for diffuse visible radiation under a standard clear sky	-
DFOVTB	Table for diffuse visible radiation under a standard overcast sky	-
DIF	Difference between root extraction rate and transpiration rate	m/sec

DIFCL	Diffuse visible radiation under a standard clear sky	Joule/(m^2 sec)
DIFF	Relative difference between root extraction rate and transpiration rate	(dimensionless)
DIFON	Diffuse near-infrared radiation under a standard overcast sky	Joule/(m^2 sec)
DIFOV	Diffuse visible radiation under a standard overcast sky	Joule/(m^2 sec)
DIMENSION	(FORTRAN-statement to define arrays)	-
DIST	Distance of flow between two adjacent soil layers	m
DKPHOT	Dark respiration rate of the leaves	kg/(m^2 sec)
DLLA	Leaf area of shaded leaves	m^2/m^2
DLYTOT	MACRO for the computation of daily totals	-
DRAD	Daily total calculated radiation	Joule/m^2
DRADI	Initial daily total calculated radiation	Joule/m^2
DRAIN	Cumulative internal drainage (past bottom of lowest soil layer)	m
DRAING	Instantaneous drainage rate (past bottom of lowest soil layer)	m/sec
DRC	Daily total global radiation under a clear sky	Joule/m^2
DRCI	Initial daily total global radiation under a clear sky	Joule/m^2
DRCP	Daily total global radiation under a clear sky of previous day	Joule/m^2
DRO	Daily total global radiation under an overcast sky	Joule/m^2
DROI	Initial daily total global radiation under an overcast sky	joule/m^2
DROP	Daily total global radiation under an overcast sky of previous day	joule/m^2
DRYWT	Total dry matter of the plant	kg/m^2
DTBL	Table of shoot death versus leaf area index	
DTHBGN	Relative shoot death rate	kg/(kg sec)
DTHFAC	Relative root death rate	kg/(kg sec)
DTR	Daily total global radiation measured (constant over a day)	Joule/(m^2 day)
DTRDEM	Daily transpiration demand (average, parameter for minimum)	m/day
DTRR	Daily total global radiation measured	Joule/(m^2 day)
ECON	Base of natural logarithm , 'e'	-
EFF	Efficiency of photosynthesis at light compensation point	kg/(J s)
ERROR	Maximum allowable error in iteration loop (POTCR computation)	%
ETA	Soil porosity	m^3/m^3
EVAP	Evaporation from soil surface	m/sec
EXP	FORTRAN function - exponentiation	-
EXTENS	Extension rate for root growth into the next soil layer	m/sec
EXTMIN	Threshold soil water potential for root extension into next soil layer	m (kPa*10)
EXTNRT	Extension rate parameter, for root growth into adjacent layer	m/sec

FCL	Fraction of the time that the sky is clear	-
FGLOAD	CMSP Function - input for function generator table	-
FINISH	Conditions for termination of simulation run	-
FINT	Extension coefficient for light in canopy	(dimensionless)
FINTIM	Total duration of simulation run	sec
FLPFLP	Flipflop control statement for iteation loop	-
FLW	Flow of water past bottom of each soil layer	m/sec
FLWNJN	Capillary rise (Past the bottom soil layer, negative flow up)	m
FOV	Fraction of time that the sky is overcast	-
FRAC	Fraction of carbohydrates remaining in the shoot (computed)	kg/kg
FRACTB	Table for carbohydrate partitioning based upon canopy water potential	-
FRG	Set constant for fraction of carbohydrates remaining in the shoot	-
GROFAC	Relative consumption rate of reserves	kg/(kg sec)
GROWTH	Total growth rate of both root and shoot systems	kg/(m^2 sec)
HOUR	Clock time	hour
HOURS	Cumulative hours of simulation time	hour
HSUN	Height of the sun	degree
I	Index of soil layer (ordinal number)	-
IB	Index for gradient plotting	-
ICHO	Initial mass of carbohydrates	kg/m^2
IFUN	Index for gradient plotting	-
IDAY	Age of the plant at start of simulation	day
IL	Index for gradient plotting	-
IMPULS	CSMP function - impuls generator	-
INSW	CSMP function - input switch generator	-
INTLZ	Procedure statement	-
IPER	Initial fraction of soluble carbohydrates	-
IPRTL	Initial root length per layer	m/m^2
IRFAC	Minimum soil water potential to trigger irrigation	kPa
IRMIN	Minimum soil water potential to trigger irrigation (same as IRFAC, but in m)	m
IROOT	Initial root mass	kg/m^2
IRQUAN	Volume of water applied during irrigation pulse	cm^3/(m^2 sec)
IRTL	Initial total root length	m/m^2
IRTVL	Initial total root volume	m^3/m^2
IRTWT	Initial total root mass	kg/m^2
ISHOOT	Initial shoot mass	kg/m^2
ITHETA	Initial volumetric water content of the soil	m^3/m^3
IVOLW	Initial amount of water in each layer	m^3/m^2
IX	Index for gradient plotting	-

J	Index of soil layer (ordinal number)	-
JDAY	Day of the year during simulation (integer number)	day
JJ	Day of the month during simulation	day
JULIAN	Day of the year during simulation	day
K	Runner in DO loop	-
KEEP	CSMP integration control statement (0 = trial integration, 1 = advance time step)	-
LAI	Leaf area index	m^2/m^2
LAIFAC	Leaf area index factor for partitioning of water loss between plant and soil	(dimensionless)
LAITBL	Table relating leaf area index and water loss between plant and soil	-
LAT	Latitude of experimental plot	degree
LEAFTH	Specific leaf area	m^2/kg
LEAFW	Mass of the leaves	kg/m^2
LFCL	Fraction of time that the sky is clear, restrained between 0 and 1	(dimensionless)
LFOV	Fraction of time that the sky is overcast, restrained between 0 and 1	(dimensionless)
LIMIT	CSMP function - defining limitation or saturation of a system	-
LINE	Variable for gradient plotting	-
LNGFAC	Length/mass ratio of the roots	m/kg
LSNHS	Sine height of the sun of the previous day	degree
MAXPOT	Maximum allowable canopy water potential	m ($MPa*10^2$)
MAXRAD	Maximum light flux density (during a day)	$J/(m^2$ sec)
MAXSTM	Measured maximum soil temperature	degree(°C)
MAXTEM	Measured maximum air temperature	degree(°C)
MAXTMP	Measured maximum air temperature table	-
MINRTL	Minimum root length for root expansion between two adjacent soil layers	m
MINSTM	Measured minimum soil temperature	degree(°C)
MINTEM	Measured minimum air temperature	degree(°C)
MINTMP	Measured minimum air temperature table	-
MNSTMP	Measured minimum soil temperature table	-
MONTH	Integer number presentation of month	-
MPANEV	Estimated pan evaporation (a scaling factor for PET)	m/day
MPOT	Matric potential of the soil in each layer (computed from soil water content)	m (kPa*10)
MTH	Real number presentation of month	-
MTIME	Macro for the computation of day and month	-
MXPHOT	Maximum photosynthetic rate	$kg/(m^2$ sec)
MXSTMP	Measured maximum soil temperature table	-
MU	Constant 'm' in relative conductivity equation	(dimensionless)

NALARM	CSMP flag	-
NETGRO	Net change in root length per layer (growth - death)	m/sec
NETVLG	Net change in root volume per layer	m^3/sec
NETWTG	Net change in root mass per layer	kg/sec
NFLW	Net flow of water into each soil layer (Darcian movement only)	m/sec
NJ	Number of layers comprising the soil profile	-
NJJ	Number of layers in the soil profile plus one	-
NNJ	Number of layers in the soil profile minus one	-
NOT	CSMP Function	-
NU	Constant 'n' in relative conductivity equation	(dimensionless)
OUTDEL	Time interval for output points on CSMP plots	sec
OUTF	Output function for vertical gradient plotting	sec
O0	Auxiliary variable to calculate photosynthesis under an overcast sky	kg/(m^2 sec)
O1	Auxiliary variable to calculate photosynthesis under an overcast sky	kg/(m^2 sec)
O2	Auxiliary variable to calculate photosynthesis under an overcast sky	kg/(m^2 sec)
PARTDS	Particle density	kg/m^3
PB	Bubbling pressure (air entry value for saturated soil)	cm (kPa*10^{-1})
PET	Potential evapotranspiration	m/sec
PEV	Measured pan evaporation table	-
PEVAP	Measured pan evaporation	m/day
PEVV	Measured pan evaporation	m/day
PEVVV	Measured pan evaporation (constant over a day)	m/day
PHOTC	Photosynthetic rate under a completely clear sky	kg/(m^2 sec)
PHOTD	Photosynthetic rate under a completely clear sky for diffuse radiation	kg/(m^2 sec)
PHOTS	Photosynthetic rate under a completely clear sky for direct radiation	kg/(m^2 sec)
PHOTSH	Photosynthetic rate under a completely overcast sky	kg/(m^2 sec)
PHOTSM	Maximum daily photosynthetic rate (net fixation)	kg/(m^2 sec)
PHOTSN	Photosynthetic rate (net carbon fixation)	kg CO_2/(m^2 sec)
PHTCAR	Photosynthetic carbon conversion factor (molecular weight ratio)	(dimensionless)
PI	Circumference of a circle, divided by its diameter	-
POROS	Porosity of the soil	m^3/m^3
POTCR	Canopy plant water potential	m (MPa*10^{-2})
POTCRD	Delayed canopy water potential	m

POTCRE	Effective canopy water potential	m
POTH	Hydraulic potential head in each soil layer	m
POTM	Matric potential of the soil in each layer	m
POTMAR	Minimum matric potential of top soil layer	m
POTRT	Water potential of the roots	m
POVC	Auxiliary variable to calculate photosynthesis	-
PRDEL	Time interval for outputting print results	sec
PROC1	Procedure statement	-
PROC2	Procedure statement	-
PROC3	Procedure statement	-
PROC4	Procedure statement	-
PROC5	Procedure statement	
PRTL	Root length per layer	m/m^2
PS	Auxiliary variable for the calculation of photosynthesis	(dimensionless)
PSH	Auxiliary variable for the calculation of photosynthesis	(dimensionless)
PTOTL	Total soil water potential (grav. + osm. + matric) for each soil layer	m (kPa*10)
PULSIR	Pulse to trigger irrigation after a defined time interval	-
PULSSW	Switch to trigger irrigation after soil water potential has dropped below a minimum value	-
RAD	1 degree in radians (180/PI)	radians
RADCAL	Current global radaition	$Joule/(m^2\ sec)$
RADCPH	Photosynthetic active radiation under a clear sky	$Joule/(m^2\ sec)$
RADFCN	Measured daily total global radiation table	
RADIAT	Total incoming radiation	$Joule/(m^2\ sec)$
RADN	Radiation generating function	$Joule/(m^2\ sec)$
RADOPH	Photosynthetic active radiation under an overcast sky	$Joule/(m^2\ sec)$
RAIN	Rainfall intensity	m/sec
RANGE	Range between average and minimum or maximum air temperature	degree(°C)
RANGES	Range between average and minimum or maximum soil temperature	degree(°C)
REFT	Reference or average air temperature	degree(°C)
REFTS	Reference or average soil temperature	degree(°C)
RELERR	CSMP statement - variable for integration control	
RESL	Reserve level of carbohydrates in the plant	kg/m^2
RESP	Total respiration of both root and shoot systems	$kg/(m^2\ sec)$
RESPRT	Total root respiration	$kg/(m^2\ sec)$
RESPSH	Total shoot respiration	$kg/(m^2\ sec)$
RISE	Time of sunrise	hour
RISEI	Initial value of sunrise	hour
RK	Relative soil conductivity	
RNF	Measured daily total rainfall table	
RNFALL	Measured daily total rainfall	m/day
ROOTDY	Root death rate	$kg/(m^2\ sec)$
ROOTL	Total root length of living root tissue	m/m^2

ROOTVL	Volume of living root tissue (by layer)	m^3/m^2
ROOTW	Total mass of living root tissue	kg/m^2
ROOTWT	Mass of living root tissue (by layer)	kg/m^2
RRL	Relative root length per layer	(dimensionless)
RRLL	Relative root mass per layer	gram/m
RRS	Radial resistance to root water uptake	sec
RSPFAC	Relative shoot maintenance respiration rate	kg/(kg sec)
RSRT	Root system resistance to water flow, total for each layer	sec m/m
RSSL	Soil resistance to water flow, total for each layer	sec m/m
RTDTH	Root death rate per layer	m/sec
RTDWPC	Percentage dry matter in the roots	(dimensionless)
RTEX	Root extraction rate for soil moisture from each layer	m/sec
RTGRES	Root growth respiration	$kg/(m^2$ sec)
RTGRO	Root growth rate per soil layer	m/sec
RTMRES	Root maintenance respiration rate	$kg/(m^2$ sec)
RUN	Real number counting variable for printer output	-
RUNS	Integer number counting variable for printer output	-
SATCON	Saturated conductivity	$m*10^{-2}/day$
SCALE	Scale factor for vertical gradient plots	
SHGRES	Shoot growth respiration rate	$kg/(m^2$ sec)
SHMRES	Shoot maintenance respiration rate	$kg/(m^2$ sec)
SHOOTD	Shoot death rate	$kg/(m^2$ sec)
SHOOTW	Mass of living shoot tissue	kg/m^2
SIMDAY	Calendar day for input date	day
SIN	FORTRAN sine function	-
SLEVAP	Soil evaporation rate	m/sec
SLLA	Sun lit leaf area index	m^2/m^2
SMAX	Scaling factors for verticle gradient plotting	-
SMIN	Scaling factors for vertical gradient plotting	-
SNDC	Sine declination of the sun	(dimensionless)
SNHS	Sine of height of sun, but zero when sun below horizon	(dimensionless)
SNHSS	Sine of height of sun, also when negative	(dimensionless)
SNLT	Sine of latitude of experimental plot	(dimensionless)
SOLCHO	Soluble carbohydrate reserves (starch) in the plant	kg/m^2
SQRT	FORTRAN function - square root	-
START	Beginning day for simulation run	day
STEMP	Temperature of the soil	degree(°C)
STEMW	Mass of the stem	kg
STORAGE	CSMP statement - allocation of memory locations	-
STWTR	Fraction of shoot dry matter, partitioned into the stem	-
SUMR	Sum of water removal by roots in all layers	m
SUMRD	Estimated root death rate for the whole plant	$m/(m^2$ sec)
SUMRG	Estimated root grwoth rate for the whole plant	$m/(m^2$ sec)
SUMRTD	Corrected root death rate for the whole plant	$m/(m^2$ sec)
SUMRTG	Corrected root growth rate for the whole plant	$m/(m^2$ sec)

SUNDCL	Direct visible radiation under a standard clear sky	Joule/(m^2 day)
SUNTB	Direct visible radiation under a standard clear sky table	-
SUTB	Suction table (volumetric water content versus soil suction, in meter (kPa*10))	-
T	Real number representation for month	
TCOM	Thickness of a soil layer (vertical direction)	m
TEMP	Temperature of the air	degree(°C)
THETA	Volumetric water content of each soil layer	m^3/m^3
THTAIR	Minimum volumetric water content of top soil layer	m^3/m^3
TIME	CSMP variable for simulation, initiating starting time	sec
TITLE	CSMP-statement	
TMPFCR	Biological Q_{10}-value - temperature factor for the roots	(dimensionless)
TMPFCS	Biological Q_{10}-value - temperature factor for the shoot	(dimensionless)
TOPGRO	Total growth of the shoot system	kg/(m^2 sec)
TOTRG	Total growth of the root system	kg/(m^2 sec)
TRANSP	Transpiration loss	m/sec
TRNTBL	Transpiration table	-
TT	Integer number representation for month	-
UARS	Unit axial resistance per unit root surface	sec m/m
UPDATE	Name of FORTRAN program generated to update integration	-
URRS	Unit radial resistance per unit root surface	sec m
VOLW	Voume of water in each compartment	m^3/m^2
W	Water potential difference for extension of new roots in second soil layer	m (kPa*10)
WATER	Measured daily total rainfall (constant over a day)	m/day
WATRST	Water stress in plant tissue (relative 0 - 1 factor, based on canopy water potential)	(dimensionless)
WAVE	Macro for the computation of temperature along sine profile	-
X	Water potential difference for branching rate of new roots	m (kPa*10)
XOVC	Auxiliary variable to calculate photosynthesis (fraction overcast)	(dimensionless)
XS	Auxiliary variable to calculate photosynthesis	(dimensionless)
XSH	Auxiliary variable to calculate photosynthesis (fraction sunshine)	(dimensionless)
XX	Water potential difference for extension of new roots	m (kPa*10)
Y	Vertical gradient plotting variable	-
YY	Runner for vertical gradient plotting	-

ZHOLD	CSMP function - storing integration value	-
ZLAM	Z(lambda), parameter to compute soil hydraulic conductivity	(dimensionless)
ZYX	Debug statement argument	-
ZYY	Debug statement argument	-
ZZZ	Debug statement argument	-