3.1 A summary model for crop growth

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3.1.1 Introduction

As outlined in Section 1.3, different models of the same system may exist, all equally valid but differing in the purpose for which they were developed. One of the types of models discussed is the 'summary model', which in itself is relatively simple, but relies heavily for its functional relationships on more detailed process models.

In this section such a simple model is presented for the calculation of potential crop production at Production level 1 (Section 1.2), where water or plant nutrients are not limiting factors. It may be applied to different crops or plant species by introducing in the model the appropriate parameters and functions for each of these. It is to a large extent based on sections of the comprehensive model BACROS. In a sense, this section can also be seen as an introduction to that model. The summary model is fully explained here, but in a superficial way. More detail is given in the three following sections.

3.1.2 Description of the model

The model simulates the time course of dry matter production of a crop, from emergence till maturity, in dependence of daily total irradiation and air temperature. The dry matter produced is divided into roots (WRT), leaves (WLV), stems (WST) and storage organs (WSO). Partitioning factors are introduced as a function of the phenological state of the crop.

A complete listing of the program is given in Table 9. Parameter values for a wheat crop growing in Zambia are used. The abbreviations in the text refer to names used in the program and a complete list of them is given in Table 10. The program is structured in a logical way, which means a calculation of the principal variables is given first, followed by calculation of those variables that are required for the quantification of the principal ones.

This simple and universal crop growth model, named SUCROS, is written in CSMP (see Section 2.2); it can be easily translated into other computer languages.

CO_2 assimilation

The basis for the calculation of dry matter production is the rate of gross CO_2 assimilation of the canopy. This rate is obtained from the CO_2 assimilation-light response curve of individual leaves of the species, the total green (leaf) area of the canopy, the spatial arrangement of the leaves and on the one hand their op-

Table 9. A listing of the program of the model SUCROS.

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TITLE SUCROS - A SIMPLE AND UNIVERSAL CROP GROWTH SIMULATOR
***  DRY WEIGHT OF PLANT ORGANS, GROWTH RATES AND PARTITIONING

      WLV = INTGRL(WLVI,GLV-DLV)                                           101
      WST = INTGRL(0.,GST)                                                 102
      WSO = INTGRL(0.,GSO)                                                 103
      WRT = INTGRL(WRTI,GRT)                                               104
*  WEIGHTS OF LEAF BLADES, STEMS (TRUE STEMS AND LEAF SHEATHS), STORAGE
*  ORGANS AND ROOTS RESP., IN KG/HA
INCON WLVI=25., WRTI=25.                                                   105
*  WEIGHT OF LEAVES AND ROOTS AT EMERGENCE

      GTW=(GPHOT-MAINT)*CVF                                                106
*  GROWTH RATE OF ALL ORGANS COMBINED, IN KG/HA/DAY
      GRT=GTW*(1.-FSH)                                                     107
      GSH=GTW*FSH                                                          108
      GLV=GSH*FLV                                                          109
      GST=GSH*FST                                                          110
      GSO=GSH*FSO                                                          111
*  GROWTH RATES OF ROOTS AND SHOOTS (LEAVES,STEMS, STORAGE ORGANS)IN KG/HA/DAY
      DLV = WLV*RDR                                                        112
*  DEATH RATE OF LEAVES, IN KG/HA/DAY
      RDR = AFGEN(RDRTB,DVS)                                               113
FUNCTION RDRTB = 0.,0., 1.,0., 1.01,0.03, 2.,0.03                          114
      WLVD = INTGRL(0.,DLV)                                                115
*  DEAD MATERIAL (LEAVES) AT THE FIELD IN KG/HA

      FSH = AFGEN(FSHTB,DVS)                                               116
FUNCTION FSHTB=0.,0.5,   0.3,0.5, 0.45,0.775, 0.7,0.825, 1.,1., 2.,1.      117
*   FRACTION OF GROWTH OCCURING IN SHOOTS AS FUNCTION OF DEVELOPMENT STAGE
      FLV = AFGEN(FLVTB,DVS)                                               118
      FST = AFGEN(FSTTB,DVS)                                               119
      FSO = 1.-FLV-FST                                                     120
FUNCTION FLVTB = 0.,1., 0.45,1., 0.85,0.,            2.,0.                 121
FUNCTION FSTTB = 0.,0., 0.45,0., 0.85,1.,1.,1., 1.01,0., 2.,0.             122

***  CARBON BALANCE PROCESSES

      LAI = WLV*SLFA                                                       201
PARAM SLFA = 0.0020                                                        202
*  LEAF AREA INDEX IN HA/HA AND SPECIFIC LEAF AREA IN HA LEAF/KG LEAF WEIGHT

      GPHOT=DTGA*30./44.                                                   203
      DTGA = FOV*DGAO+(1.-FOV)*DGAC                                        204
*  GROSS PHOTOSYNTHESIS IN KG (CH2O AND CO2 RESP.) PER HA PER DAY, CALCULATED
*  FROM LEAF CHARACTERISTICS (AMAX, EFF), LAI AND ACTUAL DAILY RADIATION
*  (AVRAD), AND CORRECTED FOR DAYLENGTH (DL AND DLE):
   DGAC=INSW(LAI-5.,PHCL,PHCH)                                             205
   DGAO=INSW(LAI-5.,PHOL,PHOH)                                             206
   PHCH=0.95*(PHCH1+PHCH2)+20.5                                            207
   PHCH1=SSLAE*AMAX*DLE*X/(1.+X)                                           208
   X=ALOG(1.+0.45*DRC/(DLE*3600.)*EFFE/(SSLAE*AMAX))                       209
   PHCH2=(5.-SSLAE)*AMAX*DLE*Y/(1.+Y)                                      210
   Y=ALOG(1.+0.55*DRC/(DLE*3600.)*EFFE/((5.-SSLAE)*AMAX))                  211
   SSLAE=SIN((90.+DEC-LAT)*PI/180.)                                        212
   PHCL=AMIN1(PHC3,PHC4)*(1.-EXP(-(AMAX1(PHC3,PHC4)/AMIN1(PHC3,PHC4))))     213
   PHC3=PHCH*(1.-EXP(-0.8*LAI))                                            214
   PHC4=DL*LAI*AMAX                                                        215
   PHOH=0.9935*PHOH1+1.1                                                   216
   PHOH1=5.*AMAX*DLE*Z/(1.+Z)                                              217
   Z=DRO/(DLE*3600.)*EFFE/(5.*AMAX)                                        218
   PHOL=AMIN1(PHO3,PHC4)*(1.-EXP(-(AMAX1(PHO3,PHC4)/AMIN1(PHO3,PHC4))))     219
   PHO3=PHOH*(1.-EXP(-0.8*LAI))                                            220
   EFFE=(1.-REFLC)*EFF                                                     221
PARAM EFF= 0.5, AMAX = 30., REFLC=.08                                      221
*  INITIAL LIGHT USE EFFICIENCY AND LIGHT SATURATED CO2 ASSIMILATION RATE
*  OF INDIVIDUAL LEAVES. UNITS: KG CO2/HA/HR /(J/M2/S) AND KG CO2/HA LEAF/HR
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      FOV = (DRC-AVRAD)/(0.8◆DRC)                                             222
◆  AVERAGE FRACTION OF PERIOD OVERCAST DURING A DAY.
◆  CALCULATION OF DAILY RADIATION OF A CLEAR AND AN OVERCAST SKY (DRC
◆  AND DRO, P.A.R., IN J/M2) AND OF DAYLENGTH (IN HR) AS A FUNCTION OF
◆  LATITUDE (LAT, IN DEGREE), DECLINATION (DEC, IN DEGREE) AND DATE:
   DRC=0.5◆1300.◆RDN◆EXP(-0.1/(RDN/(DL◆3600.)))                               223
   DRO=0.2◆DRC                                                                224
   RDN=3600.◆(SINLD◆DL+24./PI◆COSLD◆SORT(1.-(SINLD/COSLD)◆◆2))                225
   SINLD=SIN(DEC◆PI/180.)◆SIN(LAT◆PI/180.)                                    226
   COSLD=COS(DEC◆PI/180.)◆COS(LAT◆PI/180.)                                    227
   DEC=-23.4◆COS(2.◆PI◆(DAY+10.)/365.)                                        228
   DL=12.◆(PI+2.◆ASIN(SINLD/COSLD))/PI                                        229
   DLE=12.◆(PI+2.◆ASIN((-SIN(8.◆PI/180.)+SINLD)/COSLD))/PI                    230
   DLP=12.◆(PI+2.◆ASIN((-SIN(-4.◆PI/180.)+SINLD)/COSLD))/PI                   231
CONSTANT PI = 3.1416                                                          232
PARAM LAT = -15.                                                              233

◆  MAINTENANCE RESPIRATION
      MAINT =AMIN1(GPHOT,MAINTS◆TEFF)                                         234
      MAINTS=WLV◆0.03+WST◆0.015+WSO◆0.01+WRT◆0.01                             235
      TEFF  =Q10◆◆(0.1◆TMPA-2.5)                                              236
PARAM Q10 = 2.                                                                237

◆   GROWTH EFFICIENCY
      CVF= (FLV◆0.72+FST◆0.69+FSO◆CVFSO)◆FSH+(1.-FSH)◆0.72                    238
PARAM CVFSO=0.73                                                              239

◆◆◆ DEVELOPMENT OF THE VEGETATION

      DVS = INTGRL(0.,INSW(DVS-1.,DVRV,DVRR))                                 301
FINISH DVS = 2.                                                               302
      DVRV= 0.0252 ◆ AFGEN(DVRTTB,TMPA) ◆ AFGEN(DVRDTB,DLP)                   303
      DVRR= 0.0477 ◆ AFGEN(DVRRTB,TMPA)                                       304
FUNCTION DVRTTB =10.,.63, 15.,.83, 20.,.92, 25.,.96, 30.,.98, 35.,.99         305
FUNCTION DVRRTB= 10.,.08, 15.,.38, 20.,.575, 25.,.71,30.,.80, 35.,.865        306
FUNCTION DVRDTB= 10.,0.223, 11.,0.425, 12.,0.575, 13.,0.685, ...              307
     14.,0.767, 15.,0.828, 16.,0.872, 17.,0.906                               307

◆◆◆  WEATHER DATA
      DAY   = AMOD(TIME,365.)                                                 401
      AVRAD = 0.5◆41820.◆AFGEN(AVRADT,DAY)                                    402
FUNCTION AVRADT = 1.,523., 15.,526., 46.,532., 74.,575., 105.,557.,...        403
      135.,509., 166.,466.,196.,482.,227.,545.,258.,611.,288.,644.,...        403
      319.,556.,349.,521.,365.,523.                                           403

      TMPA = 0.5◆(AFGEN(TMAXT,DAY)+AFGEN(TMINT,DAY))                          404
FUNCTION TMAXT = 1.,28.6, 15.,28.3, 46.,28.1, 74.,28.7,105.,28.9,...          405
                 135.,27.2,166.,24.9,196.,24.7,227.,27.4,258.,29.9,...        405
                288.,33.6,319.,31.3,349.,28.9,365.,28.6                       405
FUNCTION TMINT = 1.,18.2, 15.,18.2, 46.,18.2, 74.,16.3,105.,13.9,...          406
               135.,10.1,166., 8.5,196., 7.4,227., 9.7,258.,13.4,...          406
                 288.,16.6,319.,18.2,349.,18.2,365.,18.2                      406

◆◆◆  SIMULATION RUN SPECIFICATIONS
TIMER FINTIM = 1000.,DELT = 2.,PRDEL=2., OUTDEL= 2., TIME=300.                501
◆   INITIAL VALUE OF TIME INDICATES STARTING DAY OF SIMULATION
METHOD RKSFX                                                                  502
PRINT WLV,WLVD,WST,WSO,WRT,LAI,DVS,MAINT,DTGA,CVF                             503
   NWRT =-WRT                                                                 504
   WLVT =WLV+WLVD                                                             505
   WVEG =WLVT+WST                                                             506
   TADRW=WVEG+WSO                                                             507
PRTPLOT NWRT,WLV,WLVT,WVEG,TADRW                                              508
PAGE GROUP, NPLOT=5                                                           509
END
STOP
ENDJOB
```

Table 10. An explanation of the abbreviations used in the model SUCROS as listed in Table 9.

NAME	DESCRIPTION	UNIT
AMAX	CO2 ASSIMILATION RATE OF A LEAF AT LIGHT SATURATION	KG(CO2)/HA(LEAF)/H
AVRAD	ACTUAL DAILY RADIATION (400-700 NM)	J/M2/D
AVRADT	TABLE MEASURED GLOBAL RADIATION (CAL/CM2/D) VS DAYNUMBER	-
CVF	CONVERSION EFFICIENCY FOR GROWTH OF PLANT DRY MATTER	KG(DM)/KG(CH2O)
CVFSO	CONVERSION EFFICIENCY FOR FORMATION OF STORAGE ORGANS	KG(DM)/KG(CH2O)
DAY	NUMBER OF DAY IN THE YEAR FROM 1ST OF JANUARY	DAY
DEC	DECLINATION OF SUN WITH RESPECT TO THE EQUATOR	DEGREE
DGAC	DAILY GROSS CO2 ASSIMILATION -CLEAR SKY-	KG(CO2)/HA/D
DGAO	DAILY GROSS CO2 ASSIMILATION -OVERCAST SKY-	KG(CO2)/HA/D
DL	ASTRONOMICAL DAYLENGTH	H
DLE	EFFECTIVE DAYLENGTH	H
DLP	PHOTOPERIODIC DAYLENGTH	H
DLV	DEATH RATE OF THE LEAVES	KG/HA/D
DRC	PHOTOSYNTHETICALLY ACTIVE RADIATION -STANDARD CLEAR SKY-	J/M2/D
DRO	PHOTOSYNTHETICALLY ACTIVE RADIATION -STANDARD OVERCAST SKY-	J/M2/D
DTGA	ACTUAL DAILY GROSS CO2 ASSIMILATION	KG(CO2)/HA/D
DVRDTB	RELATION BETWEEN RATE OF DEVELOPMENT AND DAYLENGTH	-
DVRR	RATE OF DEVELOPMENT IN REPRODUCTIVE PHASE IN RELATION TO TEMPERATURE	1/D
DVRRTB	TABLE OF DVRR AS FUNCTION OF TEMPERATURE	-
DVRTTB	RELATION BETWEEN RATE OF DEVELOPMENT AND TEMPERATURE	-
DVRV	RATE OF DEVELOPMENT IN VEGETATIVE PHASE IN RELATION TO TEMPERATURE AND DAYLENGTH	1/D
DVS	DEVELOPMENT STAGE OF THE CROP	FRACTION
EFF	EFFICIENCY OF USE OF ABSORBED VISIBLE RADIATION FOR CO2 ASSIMILATION AT LOW LIGHT LEVELS	KG(CO2)/J/HA/H M2S
EFFE	EFF BASED ON INCIDENT RADIATION	KG(CO2)/J/HA/H M2S
FLV	FRACTION OF LEAVES IN SHOOT BIOMASS	-
FLVTB	TABLE FLV VS DEVELOPMENT STAGE	-
FOV	FRACTION OF TIME THAT SKY IS OVERCAST	-
FSH	FRACTION OF SHOOT IN TOTAL PLANT BIOMASS	-
FSHTB	TABLE FSH VS DEVELOPMENT STAGE	-
FSO	FRACTION OF STORAGE ORGANS IN SHOOT BIOMASS	-
FSOTB	TABLE FSO VS DEVELOPMENT STAGE	-
FST	FRACTION OF STEMS IN SHOOT BIOMASS	-
FSTTB	TABLE FST VS DEVELOPMENT STAGE	-
GLV	GROWTH RATE OF THE LEAVES	KG(DM)/HA/D
GPHOT	DAILY GROSS CO2 ASSIMILATION	KG(CH2O)/HA/D
GRT	GROWTH RATE OF THE ROOTS	KG(DM)/HA/D
GSH	GROWTH RATE OF THE SHOOT	KG(DM)/HA/D
GSO	GROWTH RATE OF THE STORAGE ORGANS	KG(DM)/HA/D
GST	GROWTH RATE OF THE STEMS	KG(DM)/HA/D
GTW	GROWTH RATE OF TOTAL PLANT BIOMASS	KG(DM)/HA/D
LAI	LEAF AREA INDEX	M2/M2
LAT	LATITUDE	DEGREE
MAINT	MAINTENANCE RESPIRATION OF THE VEGETATION	KG(CH2O)/HA/D
MAINTS	MAINTENANCE RESPIRATION AT STANDARD TEMPERATURE (25 C)	KG(CH2O)/HA/D
NWRT	NEGATIVE WEIGHT OF ROOTS (OUTPUT VARIABLE)	KG(DM)/HA
PI	CIRCUMFERENCE OF A CIRCLE, DIVIDED BY ITS DIAMETER	-
Q10	INCREASE IN RATE OF MAINTENANCE PROCESSES PER 10 DEGR. C	-
RDN	AVERAGE LEVEL INCOMING PHOTOSYNTHETIC ACTIVE RADIATION	J/M2/S
RDR	RELATIVE DEATH RATE OF THE LEAVES	1/D
RDRTB	TABLE RDR VS DEVELOPMENT STAGE	-
REFLC	REFLECTION COEFFICIENT OF THE CANOPY	(FRACTION)
SLFA	SPECIFIC LEAF AREA	HA(LEAF)/KG(LEAF)
TADRW	TOTAL ABOVE-GROUND BIOMASS	KG/HA
TEFF	EFFECT OF TEMPERATURE ON RATE OF MAINTENANCE RESPIRATION	-
TIME	SIMULATED TIME	DAY
TMAXT	TABLE MAXIMUM TEMPERATURE VS DAYNUMBER	-
TMINT	TABLE MINIMUM TEMPERATURE VS DAYNUMBER	-
TMPA	AVERAGE AIR TEMPERATURE	DEGREE C
WLV	WEIGHT OF THE GREEN LEAVES	KG/HA
WLVD	WEIGHT OF THE DEAD LEAVES	KG/HA
WLVI	INITIAL WEIGHT OF THE LEAVES	KG/HA
WLVT	WEIGHT OF THE GREEN PLUS DEAD LEAVES (OUPUT VARIABLE)	KG/HA
WRT	WEIGHT OF THE ROOTS	KG/HA
WRTI	INITIAL WEIGHT OF THE ROOTS	KG/HA
WSO	WEIGHT OF THE STORAGE ORGANS	KG/HA
WST	WEIGHT OF THE STEMS	KG/HA
WVEG	WEIGHT OF THE VEGETATIVE PARTS (OUTPUT VARIABLE)	KG/HA

tical properties, and from the incident irradiation, on the other. A method to calculate daily values of gross CO_2 assimilation for any day as a function of daily total irradiation and geographical latitude was worked out by de Wit (1965) and amended and summarized by Goudriaan & van Laar (1978). In the model presented here, the Goudriaan & van Laar procedure is imitated very accurately with a small group of statements (Lines 203-221). It is described further in Subsections 3.2.3 and 3.2.4. For wheat, a value of the light saturated assimilation rate of individual leaves in terms of mass of CO_2 per leaf area (AMAX) of 30 kg ha^{-1} h^{-1} is introduced, in combination with an initial light use efficiency (EFF) of 0.5 kg ha^{-1} h^{-1} per Joule per square metre per second of absorbed visible irradiation. When based on incident irradiation, this efficiency is somewhat lower due to reflection. (Note that the variable named AMAX is completely different from the CSMP function AMAX1 (see Section 2.2, Table 3)). Such values are normal for C_3 type cereals. The rates of CO_2 assimilation of the canopy under completely clear and completely overcast conditions (DGAC and DGAO, respectively) that are computed with this group of equations reproduce accurately data that were established with a large computer model (Goudriaan & van Laar, 1978). The actual rate of CO_2 assimilation of the canopy (DTGA) is an average of both assimilation rates, weighted according to the actual fraction of the specific day that happened to be 'overcast'. The procedure also takes into consideration the reduced light interception and reduced CO_2 assimilation at incomplete soil cover. After multiplication of the rate of CO_2 assimilation by 30./44., (Line 203), gross photosynthesis (GPHOT) is expressed in glucose (CH_2O).

The fraction of the day that the sky is overcast (FOV) is calculated by comparing the measured level of incoming photosynthetically active radiation (AVRAD) to that on a completely clear and on a fully overcast day. The level of irradiance on completely clear days is computed from equations that integrate solar height as a measure of irradiation, multiplied with a solar constant, and corrected for day length (Lines 223-233, Goudriaan, personal communication). Photosynthetically active irradiation on overcast days is assumed to be 20% of that value.

The combination of both procedures for obtaining standardized daily totals for photosynthetically active irradiation and CO_2 assimilation are quite flexible, and they can be used with a high degree of accuracy in both hemispheres between 70°N and 70°S for crops with an LAI between 0.1 and 10.

Exercise 24

Use these procedures to compute the daily total of photosynthetically active irradiation and the daily gross CO_2 assimilation at your latitude today, assuming that the sky is fully clear.

Respiration and growth

Part of the carbon fixed by the assimilation process is respired to provide energy for biological functioning of the organism. The remainder is the carbon incorporated in structural dry matter. Maintenance respiration is considered explicitly, growth respiration only implicitly.

Maintenance respiration provides energy to maintain cells and their biostructure and ionic gradients. Although accurate data on maintenance requirements are scarce, reasonable estimates can be made on the basis of the composition of the biomass present. In the present model, the maintenance requirements for leaf, stem and root tissue are expressed in mass of glucose and are set at 0.03, 0.015 and 0.01 kg kg^{-1} d^{-1}, respectively (Line 235). These values hold at 25 °C; the effect of other temperatures is taken into account with a Q_{10} value of 2 (Lines 236, 237). For all types of storage organs, a value of 0.01 at 25 °C is adopted. For further detail, see Subsection 3.3.5.

Growth implies the conversion of primary photosynthates into structural plant material. The efficiency of the conversion depends on the chemical composition of the dry matter formed. In the model, average conversion factors of 0.72, 0.69 and 0.72 kg kg^{-1} are used for leaf, stem and root biomass, respectively, and 0.73 kg kg^{-1} for grains of wheat. The latter value depends on the nature of the storage organ, and its value is specific for each type of crop. In this model, a weighted average (CVF) of these organ specific conversion factors is calculated (Line 238) by multiplying the organ specific values with the fractions that these organs obtain from total weight increment. Multiplication of the amount of carbohydrates available for growth with this CVF value yields the total increase in dry matter of the crop per day (GTW, Line 106). All carbohydrates formed during that day and not consumed in maintenance processes are available for growth.

The amount of CO_2 lost as a result of growth processes (the growth respiration) also depends on the composition of the biomass formed (Subsection 3.3.4). The complement of CVF represents – roughly – the extent of growth respiration, but this is not modelled explicitly here.

Partitioning of dry matter

The increase in total dry weight (GTW), in kg ha^{-1} d^{-1}, of the crop is partitioned over the plant organs: roots, leaf blades, stems and leaf sheaths and the storage organ (grains, beets, pods, etc.). This is correct simulation of what occurs during the vegetative phase. Storage organs, however, may not only be formed from current photosynthates but also from carbohydrates and proteins that have been stored temporarily in vegetative parts and are redistributed during the reproductive stage. In this model, the latter process is not yet incorporated: the total growth of the crop is partitioned among the plant organs according to partitioning factors that are introduced as forcing functions; their values change with the development stage of the crop.

In allocating the biomass formed, first assimilates are diverted to the roots

(Lines 116 and 117). In general, it is difficult to obtain reliable data for assimilate supply to below ground organs, the more so since the processes of growth and decay may proceed concurrently, so that weights determined at any particular point may not be indicative for the amount of material invested in the roots. The function specified in this model is based on data supplied by Jonker (1958) for wheat. This description, in which biomass is first partitioned between shoot and root, is chosen to provide the option of modification of the biomass distribution values when stress conditions develop (Section 4.1; see Figure 33a, Section 3.3).

To obtain the increase in dry weight of leaves, stems and storage organs, the total shoot growth is multiplied by the appropriate factors. The partitioning between leaf blades and other vegetative structures (sheaths, true stems) is strongly schematized. For wheat, for example, it is assumed that only leaf blades are being formed until the development stage reaches 0.45, after which stem elongation starts and more of the assimilates are invested in these structures (Lines 121 and 122, cf. Rawson & Hofstra, 1969; Spiertz, 1977). After flowering, all available carbohydrates are used for grain formation (Line 120; see Figure 33a, Section 3.3).

As already stated, any contribution of pre-anthesis carbohydrates to grain yield is disregarded in this approach, which certainly is an oversimplification (Stoy, 1965; de Vos, 1975; Vos, 1981). We have not included even a simple description of this process, to avoid compromising the nature of the model: a summary of well known processes. As a result the prediction of economic yield can be up to 10-20% too low, depending upon crop type and growth conditions. Users are invited to improve on this (Subsection 3.4.9 provides an example). The model in its present form is essentially a source-oriented model in which dry matter accumulation is governed by the availability of assimilates. However, in reality, situations may occur for which the size of the sink, characterized in wheat by the number of grains present and the potential growth rate per individual grain, limits the rate of accumulation of dry matter in the grain (Section 3.4). Since actual grain numbers are not simulated in the model such a phenomenon cannot properly be taken into account. For application in particular situations adaptation of the model may then be necessary.

Leaf area growth

The increase in photosynthesizing surface, i.e. green area of the canopy (Line 201), follows directly from the growth rate of the leaf blades, by assuming a constant specific leaf area (SLFA) to mass of dry matter of 0.002 ha kg^{-1} (leaf dry matter) (Aase, 1978). In this description the area of green sheaths and stems is not taken into account separately, but it is generally a negligible fraction of the total green surface during the vegetative phase (Fisher, 1982).

Exercise 25
Why are results of simulation with this model sensitive to changes in the value of SLFA? Is there positive or negative feedback?

Leaves only have a limited life-span, and some of the earlier formed leaves will die even during the vegetative stage of the canopy. In the model, senescence is taken into account only after flowering, when the sink action of the developing grain accelerates leaf deterioration. Leaf death is effectuated by assuming a relative death rate of the green area as a function of crop development stage (Lines 112-115). The values introduced here lead to reasonably realistic simulations of decline in green area, such that sometimes physiological maturity is reached before all assimilating tissue has stopped functioning, whereas in other cases the reverse is happening. In this schematized description, the contribution to the assimilation process of green tissue other than leaf blades, which may be important after flowering, is also included. Note that this formulation of senescence has no fundamental basis, and is therefore descriptive rather than explanatory.

Crop phenology
The development pattern of a growing plant is characterized by the rate and order of appearance of vegetative and reproductive plant organs. The rate of development, that is the inverse of the duration of a particular growth stage, is determined by genetic properties as well as by environmental conditions. Genetic properties account for differences in growth duration among cultivars growing at a given time at a certain location (short vs. long duration cultivars), whereas environmental conditions, notably temperature and day length, cause variations in growth duration for one cultivar at different locations and/or seasons. In the model, the phenological state of the canopy is characterized by its development stage (DVS), a variable having the value 0. at emergence and 1. at flowering. Intermediate values are obtained by integration of the rate of development (DVR), which depends on the average daily temperature and day length in the vegetative phase, and on temperature only afterwards (Lines 301-307). Differences in temperature sensitivity between species and cultivars may exist, associated with photoperiodic influences (Angus et al., 1981). This is discussed further in Subsection 3.3.2.

After flowering, the crop is allowed to proceed until the development stage (DVS) of maturity is reached, which is introduced as a cultivar specific value (Line 302).

3.1.3 Application of the model

The model can be executed with time steps of one day with the simple rectilinear method of integration (RECT), or time steps of 10 days with the integration method RKSFX (Section 2.3). The latter method is used here (Line 502), but to obtain more detailed output, a time step of two days (Line 501) is specified in Table 9. End of execution is achieved via a FINISH statement, which is operative when the crop reaches maturity.

When appropriate parameters and functions are available, the model may be used to predict potential productivity of different crops under varying conditions and at different locations. It should be kept in mind that its applicability is restricted by the assumptions underlying the present description, i.e. no constraining factors are present other than the level of irradiance. To achieve the productions as predicted by the model in the real situation for validation purposes, growing conditions should be optimal in terms of supply with water and plant nutrients, weeds should not seriously interfere with crop production and the crop should be free of pests and diseases. It may be problematic, even under experimental conditions, to create such an ideal situation, but then the model may indicate the scope for improvement that is still possible.

The model is thought to be valid universally where potential growth conditions can exist, including climate rooms, but with exception of extremely high and low temperatures, or very low light levels and with exception of situations where considerable relocation from vegetative to reproductive organs occurs. The user is advised not to modify structure or data, with the exception of those indicated in the next paragraph, unless he is very familiar with the subject. In some of the following sections, examples will be given how this simple model can be expanded by adding more detail to the description of certain processes, and by including other aspects of crop growth and other growth limiting factors.

Input data requirements

Specific for each situation are the latitude (LAT, negative values for the Southern Hemisphere) and the date at which the crop emerges. The latter can be defined by giving the variable TIME (Line 501) an initial value equal to the day number of the Julian calender. DAY equals TIME up to Day 365, after which DAY equals TIME − 365. This is achieved by means of the AMOD function (Table 2 of Section 2.2). The example chosen refers to wheat growth in Zambia (LAT = −15 °) starting on October 27 (Day 300).

The next group of data concern the initial conditions. For this purpose, 'initial' is defined as the moment at which the contribution of seed reserves to the young plants becomes negligible, which for wheat is about 10 days after sowing. In the example of Table 9, 50 kg of plant material is present per hectare, of which half is root (WRTI) and half leaf (WLVI, Line 105). This corresponds roughly to 85 kg of seed. These figures are of course specific for the particular plant type and seed rate used.

The next group of data required are physiological characteristics: CO_2 assimilation, respiration and partitioning. CO_2 assimilation is characterized only with a constant initial light use efficiency for all species and the maximum rate of

CO_2 assimilation per unit leaf area at light saturation. This value is about 30 kg ha^{-1} h^{-1} for many C_3 plants. It is an important parameter, and considerable attention should be given to its quantification. The formulation of respiration processes in the model is sufficiently general to require little attention from the user. Only the conversion factor to form the reproductive organs from photosynthates is specific for each crop. Such data, for 23 different crops, have been reported by Penning de Vries et al. (1982). Since the partitioning of biomass over plant organs with respect to development stage is specific for species and cultivars, such data need to be specified. Three examples (wheat, potato and soybean) are given in Figure 33 of Section 3.3. The rate of development of the crop, including the effects of temperature and day length is also specific and not predictable from basic data, and need thus to be specified. In many cases, this will require at least one good field experiment with the very crop plant or a similar one in the very environment or something that resembles it closely.

The specific leaf weight is an important parameter. Its value varies little between species, but as this factor is an important one in the model, attention should be paid to it. The decline in green leaf area at the end of the crop growth cycle has to be defined, but there are many similarities between groups of species, and users are not encouraged to use other data unless specific information is available.

The environmental conditions of the crop are specified by daily irradiation, and daily minimum and maximum temperatures, or average daily temperatures. All environmental conditions may be specified per day or as monthly means; in the first case the time step of the model should be reduced so that it equals or is smaller than the input data interval.

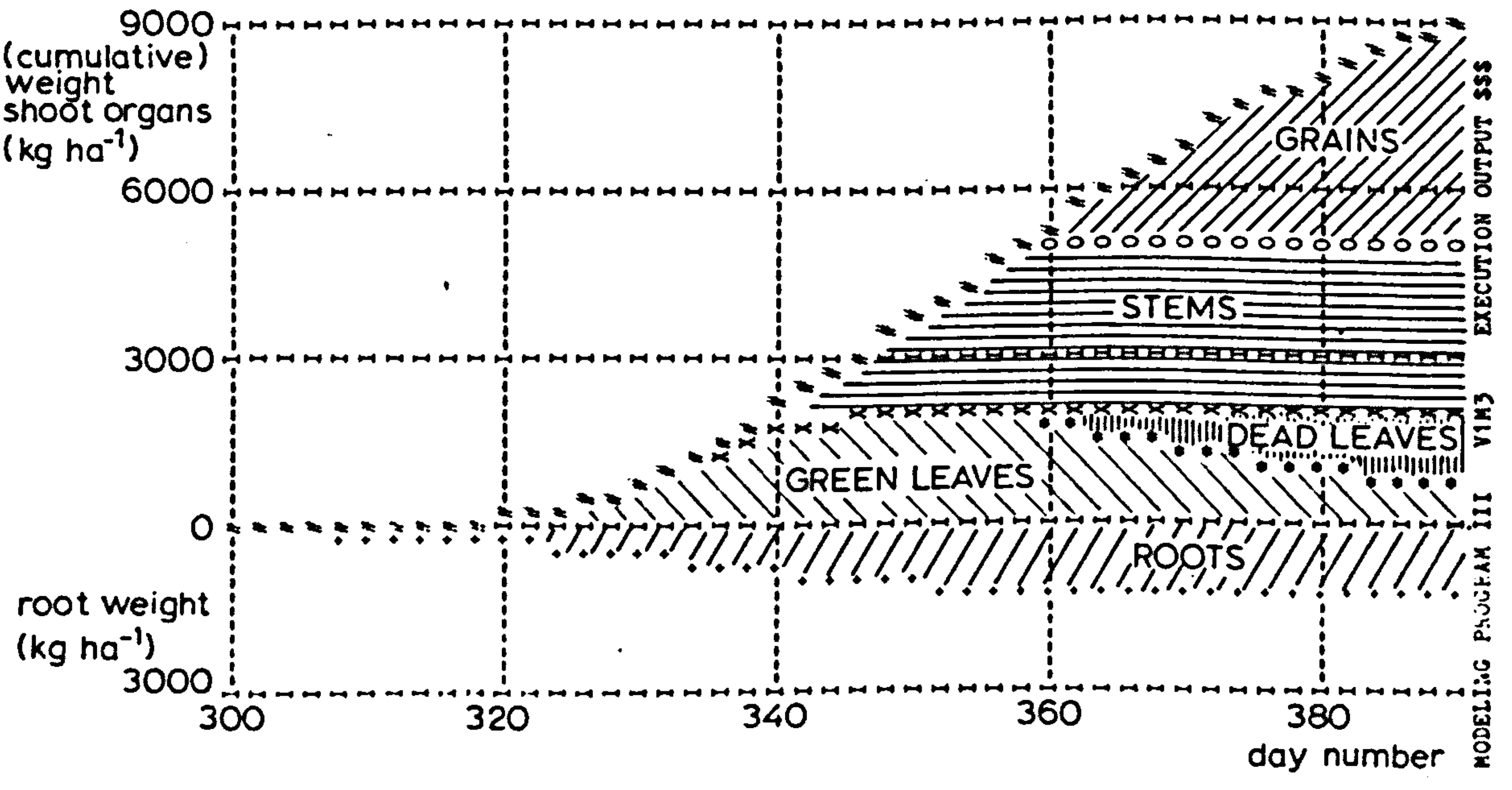

Figure 24. An adapted reproduction of the CSMP PRinTPLOT of the cumulative weight of the shoot organs and of the roots, as these develop during a growing season. The results were obtained with the SUCROS model as listed in Table 9.

An example of the use of SUCROS with the data as given in the program of Table 9 is given in Figure 24. It is basically the output generated by CSMP by the Lines 503-508.

Exercise 26

a. Run the model SUCROS, and check that your results are identical to those of Figure 24.

b. Simulate wheat production for your own latitude.

c. Run the model for another crop with other characteristics for partitioning of assimilates, for instance those of Figure 33b or 33c, Section 3.3.

d. It is not realistic to run SUCROS for other crops by changing only assimilate partitioning. Suggest reasonable values for other important parameters of these crops.