SBFLEVO and WWFLEVO

Growth models to simulate crop growth, optical reflectance and radar backscatter of sugar beet and winter wheat, calibrated for Flevoland

B.A.M. Bouman

cabo-dlo

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1 Introduction

This report contains a description and a FORTRAN-listing of the growth model FLEVO that simulates crop growth, optical reflectance and radar backscatter of sugar beet and winter wheat, calibrated for Flevoland in The Netherlands: SBFLEVO for sugar beet, WWFLEVO for winter wheat. FLEVO consists of the crop growth model SUCROS87 (van Keulen et al., 1982; Spitters et al., 1989) that is extended with the model EXTRAD (Goudriaan, 1977) for optical reflectance, and with the 'Cloud' model (Attema & Ulaby, 1978) for radar backscatter. The above model components were especially calibrated and validated on experiments that were conducted in Flevoland: ROVE 1980-1981 (de Loor et al., 1982), "HSM-1983" (de Boer et al., 1988) and Agriscatt 1987-1988 (Attema, 1988). Experiments on other locations were included for verification, or for calibration when not enough data were present from Flevoland itself. Flevoland was chosen for model calibration because this area is a main test site for past, current and future international remote sensing campaigns and experiments (e.g. Agrisar-86, Agriscatt 87-88, Maestro-89, Maceurope-91, ERS-1, X-SAR/SIR-C). Moreover, Flevoland has a long history as national test site for radar campaigns (ROVE). A map of Flevoland is given in Figure 1, and a description of the area (in relation to airborne radar campaigns) is given by Stolp et al. (1988).
In the above remote sensing campaigns, crop growth monitoring has been, and continues to be a major research topic. The growth model FLEVO is unique in combining knowledge on the process of crop growth and development with knowledge on the interaction of optical radiation and microwaves with crop canopies. With FLEVO, crop growth and development can be studied in relation to optical reflectance and radar backscatter in various frequency bands (from 1.2 to 17.3 GHz). FLEVO also offers the possibility to study the value of synergy between optical remote sensing and radar remote sensing.

In Chapters 2 to 4, the FLEVO model components for crop growth, optical reflectance and radar backscatter are explained respectively. Since the SUCROS model for crop growth has already been described extensively elsewhere (Spitters et al., 1989), the remote sensing model components are described in relatively more detail. Chapter 5 explains how the total model FLEVO is structured and how the input and output of the model is controlled. Chapter 6 presents some notes on the validity of the model and of the model components. In Chapter 7, simulations of crop growth, optical reflectance and radar backscatter are presented for the 1991 growing season in Flevoland. The simulations of yield are compared to actually obtained yields of ten farmers in the area. These simulations are meant to support, and to help interpret the optical and radar remote sensing data collected with the ERS-1 and with the airborne instruments during the Maceurope-91 campaign. The simulation of radar backscatter in the JERS-1 SAR configuration is also included for future comparison (from 1992 on).

The appendices contain the complete listings of the models SBFLEVO and WWFLEVO, together with a listing of the input files. FLEVO is written in the programming language FORTRAN 77; the program was developed on a DEC-μVAX 3600 (operating system VMS 5.4, compiler VAX-FORTAN v 5.6-199).

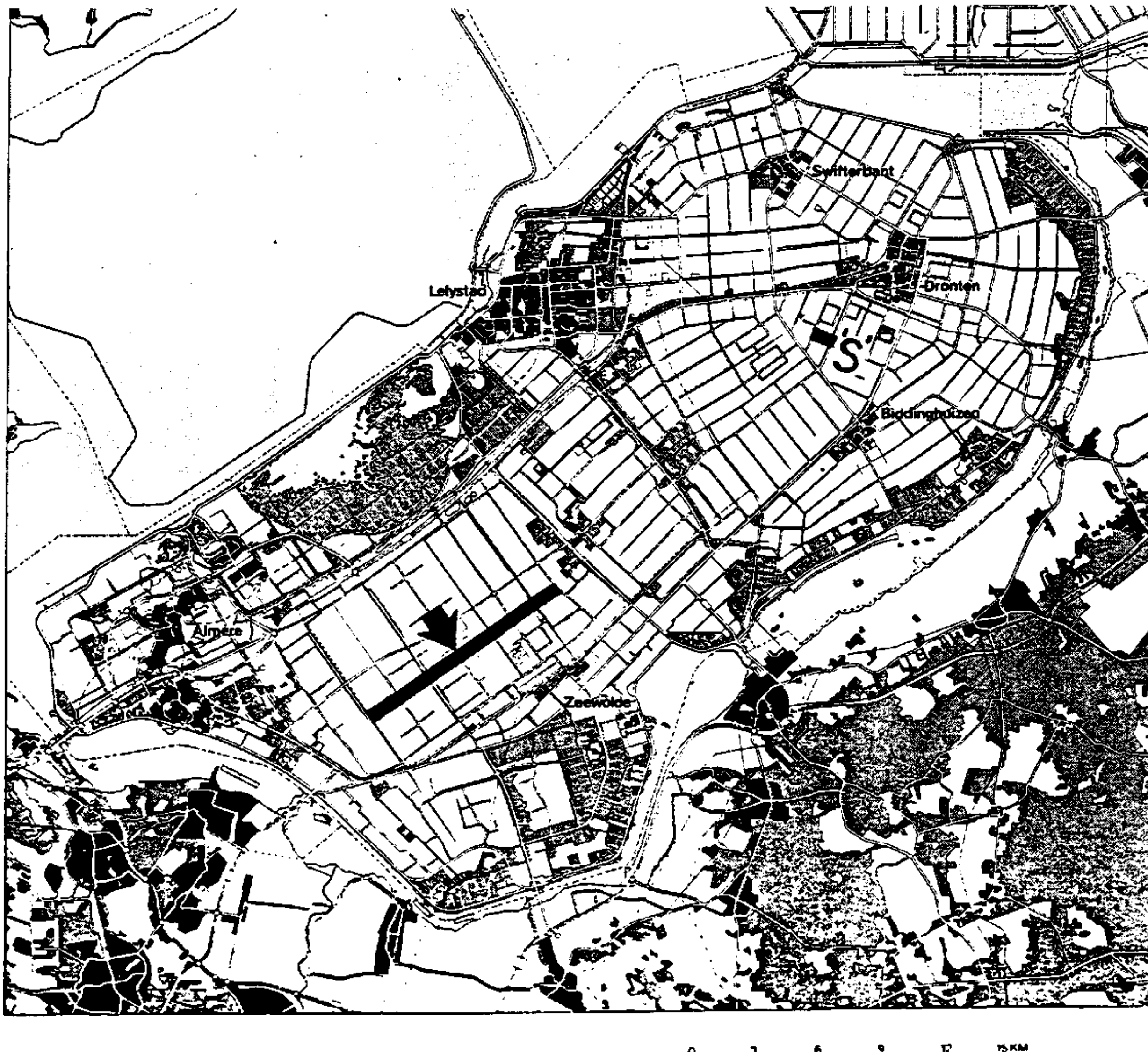


Figure 1. Flevoland in The Netherlands. The broad arrow points to the main test site (black strip) of the Agriscatt campaign; the 'S' near Dronten indicates the location of test farm "De Schreef" where the experiments of ROVE (1980, 1981) and of "HSM" (1983) were carried out.

2 SUCROS

SUCROS (Simplified and Universal Crop Growth Simulator) is a mechanistic crop growth model that describes the potential growth of a crop from irradiation, air temperature and crop characteristics. Potential growth means the accumulation of dry matter under ample supply of water and nutrients, in an environment that is free from pests and diseases.

A schematic illustration of the model is given in Figure 2. The light profile within a crop canopy is computed on the basis of the Leaf Area Index (LAI) and the extinction coefficient (based on the formulations in EXTRAD, Chapter 3.1). At selected times during the day and at selected depths within the canopy, photosynthesis is calculated from the photosynthesis-light response of individual leaves. This response curve is characterized with its initial slope (the initial light use efficiency) and the asymptote (the light saturated photosynthesis). Integration over the canopy layers and over time within the day gives the daily assimilation rate of the crop (partly from Spitters, 1990).

Assimilated matter is first used to maintain the present biomass (maintenance respiration) and for the remainder converted into new, structural plant matter (with loss due to growth respiration). The newly formed dry matter is partitioned to the various plant organs through partitioning factors introduced as a function of the phenological development stage of the crop. Multiplication of the simulated leaf dry matter with the specific leaf area of new leaves gives the increase in leaf area (LAI). The increase in leaf area contributes to next day's light interception and hence to next day's rate of assimilation.

The parameters of the model can be divided into species parameters (e.g. partitioning factors, light use efficiency), location parameters (latitude), initialization parameters (e.g. sowing date, number of plants/m^2) and driving variables (daily irradiance, daily maximum and minimum temperature). Species parameters have to be estimated from field and laboratory measurements. Location and initialization parameters have to be known for each simulation condition, and driving variables have to be measured daily throughout the growing season.

SUCROS was calibrated, i.e. the species parameters were determined, by Spitters et al. (1989) on a number of Dutch field experiments, and by taking parameter values from literature. Spitters et al. also updated and improved the SUCROS version as published by van Keulen et al. (1982) and named their version SUCROS87. This version is taken with minor adaptions as the basic crop growth module in the model FLEVO. A good description of SUCROS87 with an explanation of the abbreviations (parameter and variable names) is presented in 'Simulation and systems management in crop protection (Eds: R. Rabbinge, S.A. Ward and H.H. van Laar; PUDOC, Wageningen, 1989), Chapter 4 (pp. 147-181).

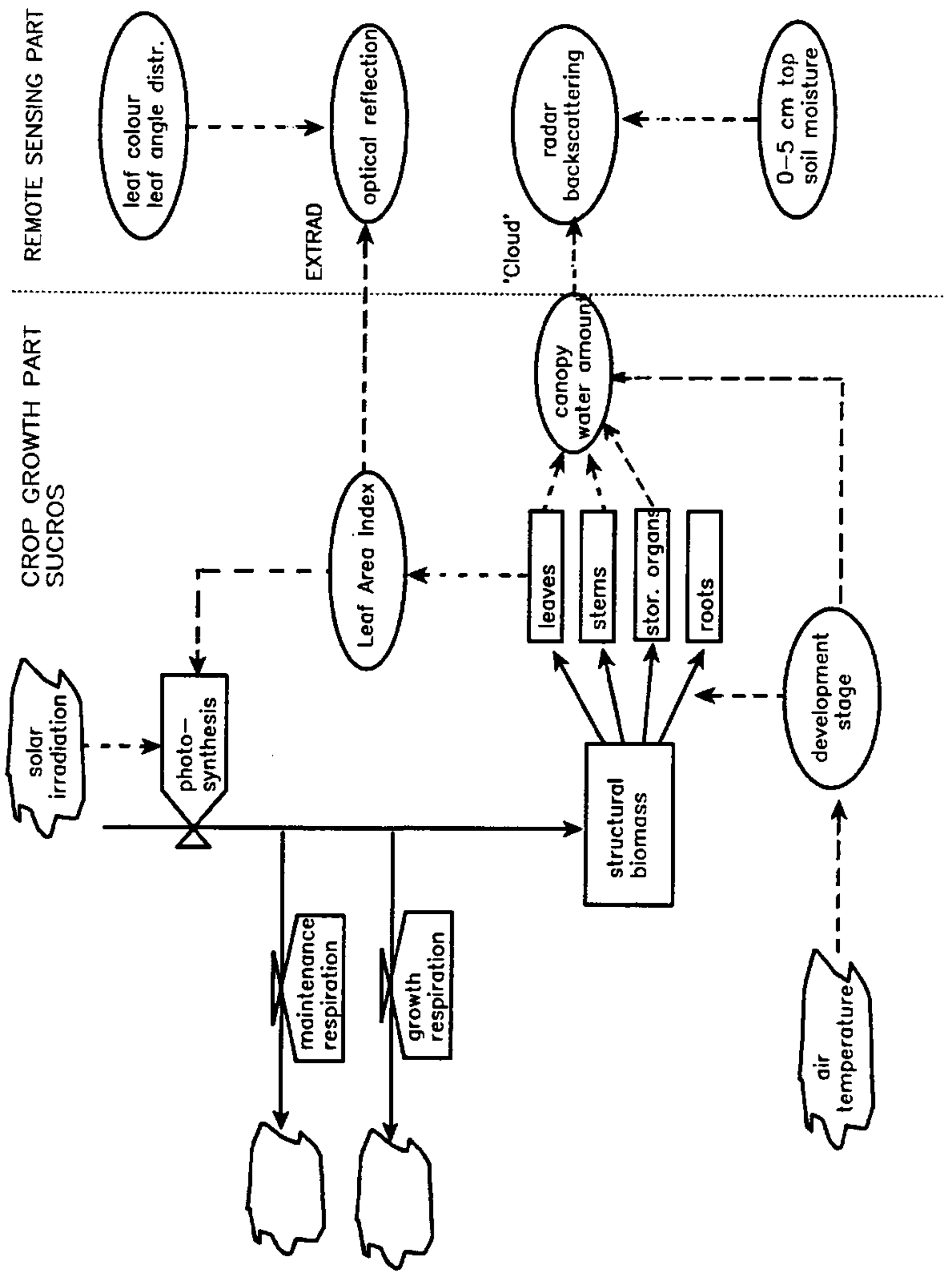


Figure 2. Functioning of the crop growth model SUCROS87, and the linkage with the remote sensing models 'Cloud' (radar backscatter) and EXTRAD (optical reflectance). Rectangles represent quantities, valve symbols represent flows, circles represent auxiliary variables and clouds the atmosphere; drawn lines represent flows of material and broken lines flows of information. Source: Bouman, 1991.

Important variables in SUCROS are:

```
TIME   = day number during simulation (timer parameter)
LAI    = leaf area index
COVER  = soil cover (fraction)
TADRW  = total above ground dry weight (kg/ha)
WSO    = dry weight of storage organs (kg/ha);
         in winter wheat, this is the grain weight (econ. product);
         in sugar beet, this is the 'main' under-ground tuber
TUBER  = dry weight of 'total' tuber of sugar beet (kg/ha)
         (= tuber + crown + roots)
WTUBER = fresh weight of TUBER (ton/ha) (economic product)
```

Specifically for winter wheat:

```
LAIH   = leaf area index of leaves
EAI    = area index of ears
LAI    = leaf area index of leaves (LAIH) + area index of ears (EAI)
```

(Note: the definitions of TUBER and WTUBER differ slightly from those given by Spitters et al., 1989; the variable COVER is introduced by the author)

SUCROS was calibrated (by the author) for sugar beet and winter wheat in Flevoland on data acquired on fields of farmers during the Agriscatt campaign in 1987 and 1988. The number of fields that was used in the calibration was six for sugar beet and eight for winter wheat. The cultivars (cvs) were, for sugar beet: Regina, Accord, Salohil and Univers, and for winter wheat: Arminda, Kraka, Granta and Obelisk. In the calibration, no differentiation was made to cultivar. During Agriscatt, the following crop variables were measured: fresh and dry weights of leaf blades, of leaf stems, of stems, of ears (cereals), of tubers (sugar beet), of soil cover and LAI. The measurements were carried out at intervals of about 2 weeks during the growing season. The measurement procedures and the measured data are given by Stolp et al. (1988) and Vissers et al. (1989). The calibration procedure was based on a controlled random search algorithm as developed by Price (1979) and extended by Klepper (1989) and Rouse (Stol et al., 1992).

The calibration resulted in the following, *site-specific* adaptions in the species parameters of SUCROS, and in some changes in the main program for sugar beet and for winter wheat:

Sugar beet

New parameter values:

```
NPL = 9.0
FLVTB: 0.0 0.65  370.0 0.65  665.0 0.44  820.0 0.29  3000.0 0.29
FSTTB: 0.0 0.30  370.0 0.30  665.0 0.47  820.0 0.61  3000.0 0.61
```

New parameters:

```
LAISHAD = value of LAI above which leaves die due to internal
shading
LAISHAD = 4.5
```

```
TEMERG  = temperature sum after sowing needed for emergence
TEMERG  = 105
```

Replacements in main programme:

```
- replace: RDRSH = 3.0*(MAX(0.,(LAI-4)/4)
  by     : RDRSH = 3.0*MAX(0.,(LAI-LSHAD)/LSHAD)
- replace: IF(EMERG.LT.200)GO TO 100
  by     : IF(EMERG.LT.TEMERG)GO TO 100
- replace: RDRV = LINT(RDRT,IRDRN,TSUM2)*DTSUM2
  by     : RDRV = 0.
- replace: AMAX = AMX*AMDVS*AMTMP
  by     : AMAX = AMX * AMTMP
```

Winter wheat

New parameter values:

```
data AMDVST: 0.0 1.0  1.0 1.0  2.0 1.0  2.5 0.0
data DVRTV :-30.0 0.0  0.0 0.0  30.0 0.0280
data FLVTB : 0.0 0.66  0.1 0.66  0.25 0.66  0.5 0.63  0.7 0.29
             0.95 0.0  2.5 0.0
data FSTTB : 0.0 0.34  0.1 0.34  0.25 0.34  0.5 0.37  0.7 0.71  0.95
             1.0  1.07 0.0  2.5 0.0
data RDRDN : 0.0 0.0  0.59 0.0  0.6 0.0  1.04 0.0  1.05 0.5
             1.54 0.5 1.55 1.0  2.5 1.0
```

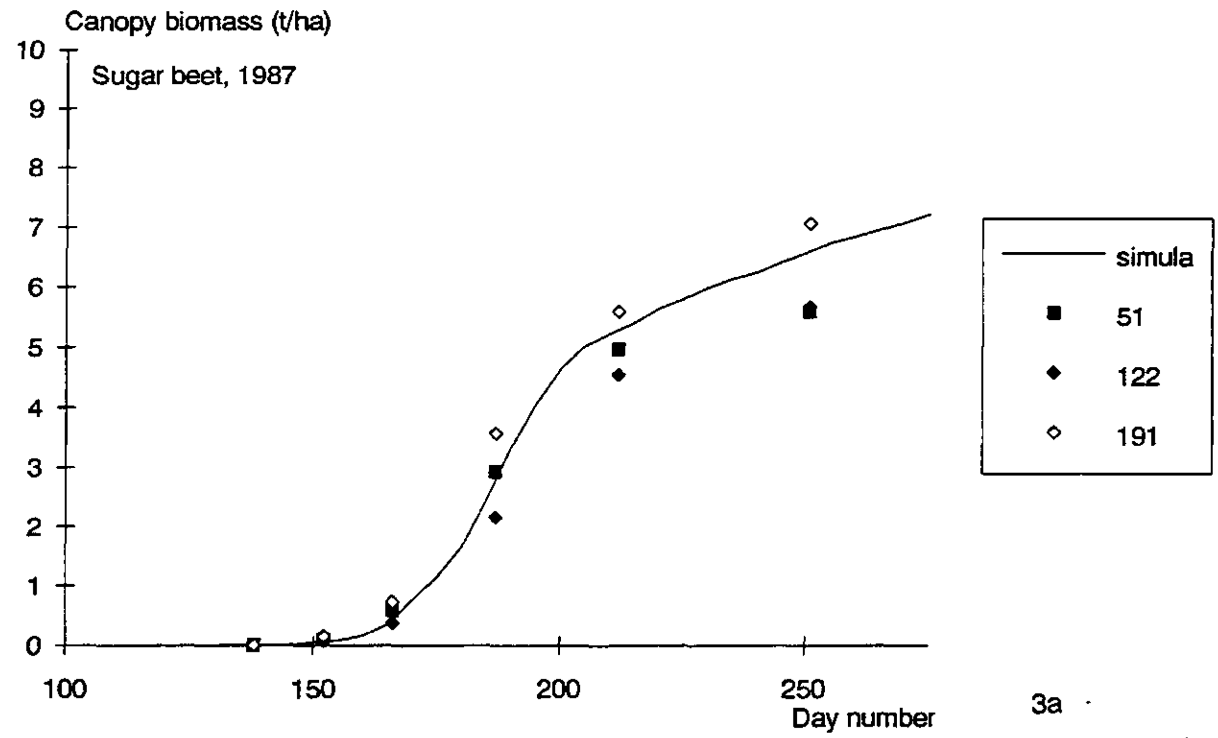
New parameter:

```
TEMERG = temperature sum needed to 're-start' crop growth after
winter
TEMERG = 156
```

Replacements in main programme:

```
replace: IF (TSUMEM.LT.200) GO TO 15
by     : IF (TSUMEM.LT.TEMERG) GO TO 15
```

The results of the calibration are illustrated in Figures 3 and 4 for sugar beet, and in Figures 5 and 6 for winter wheat.



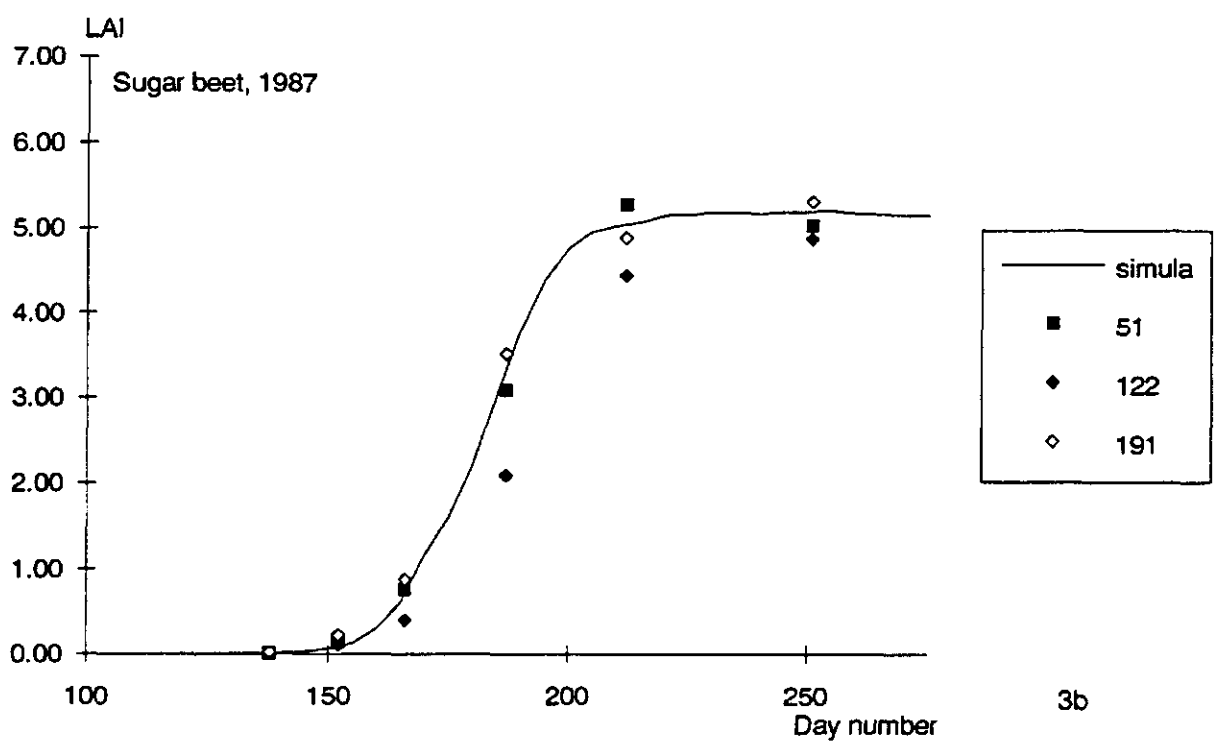
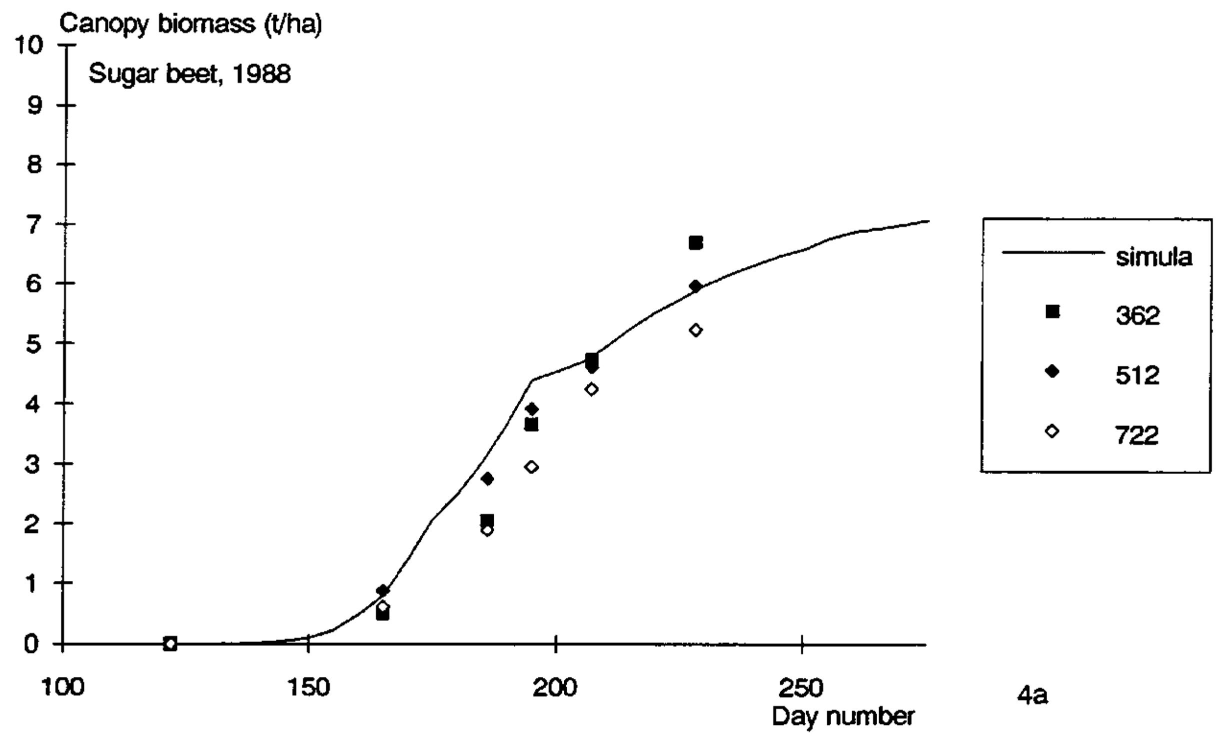
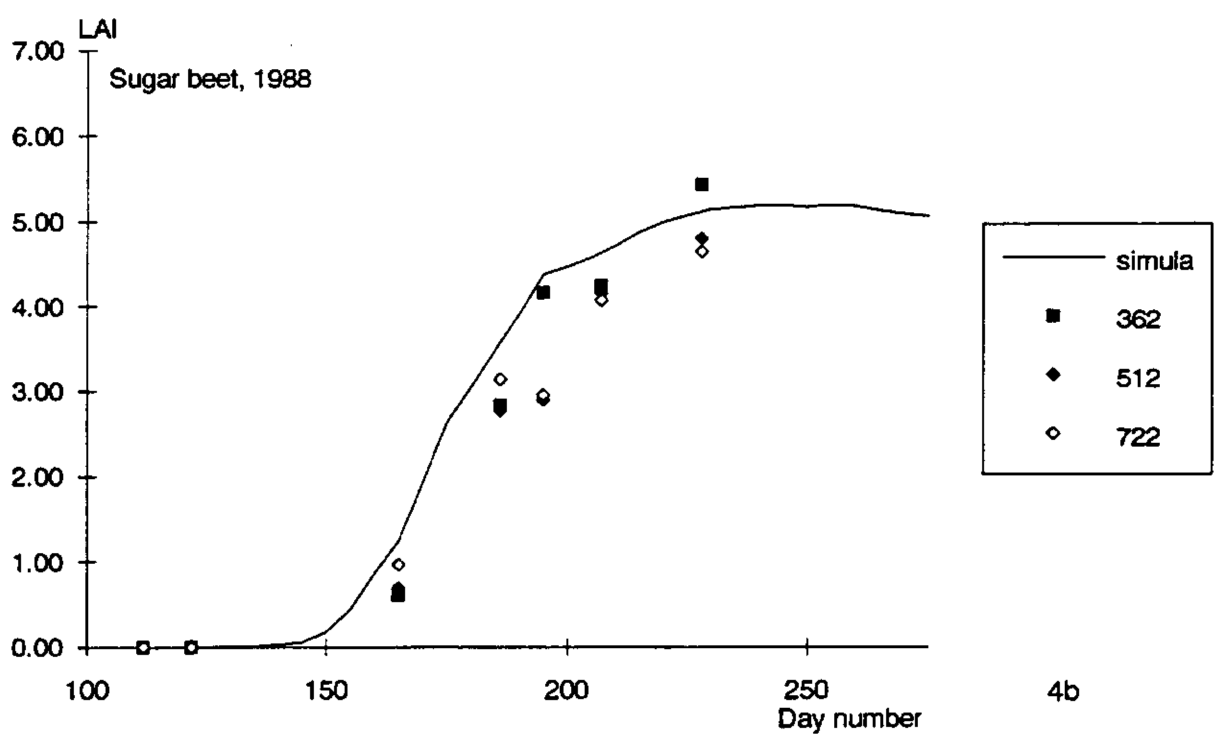


Figure 3. Measured and simulated canopy biomass (3a) and LAI (3b) for sugar beet, Flevoland 1987. The drawn line is the calibrated SUCROS simulation (with one average sowing date for all fields), the symbols are the measured data (different symbols indicate different fields). N = six observations per field during the growing season.


Canopy biomass (t/ha)
Sugar beet, 1988
10
9
8
7
6
5
4
3
2
1
0
100
150
200
250
Day number
simula
362
512
722

4a


LAI
Sugar beet, 1988
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
100
150
200
250
Day number
simula
362
512
722

4b

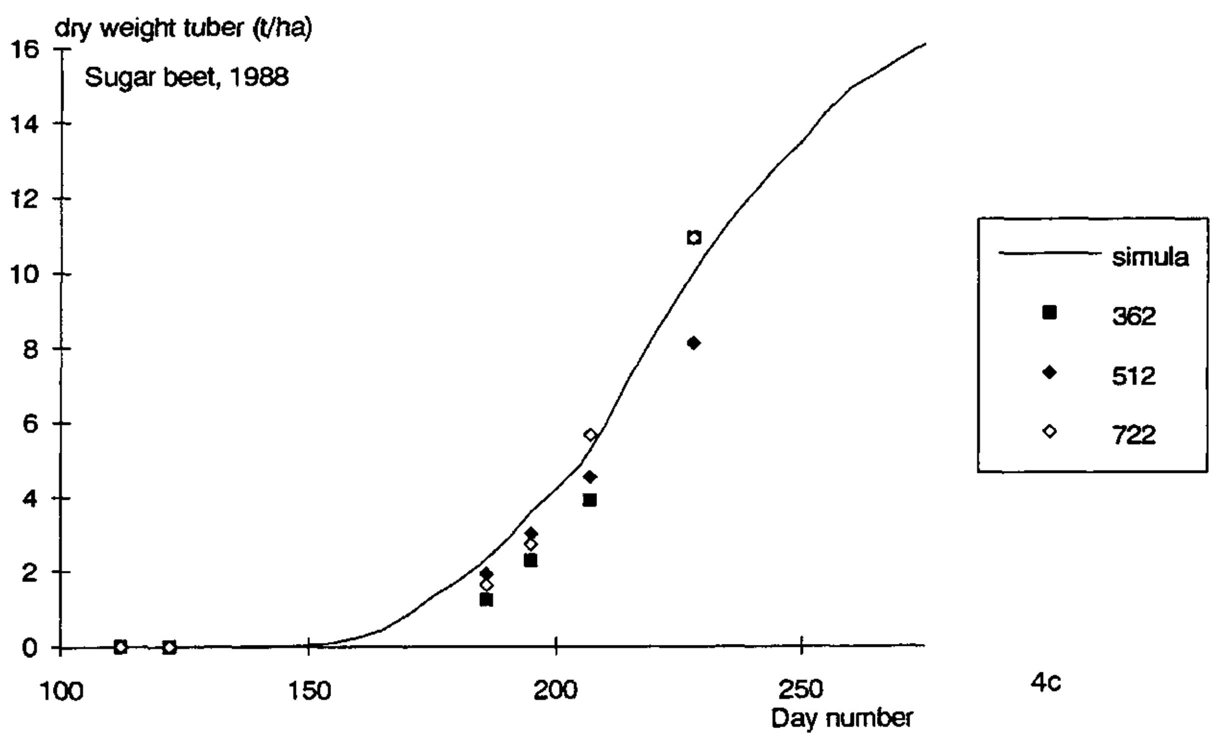
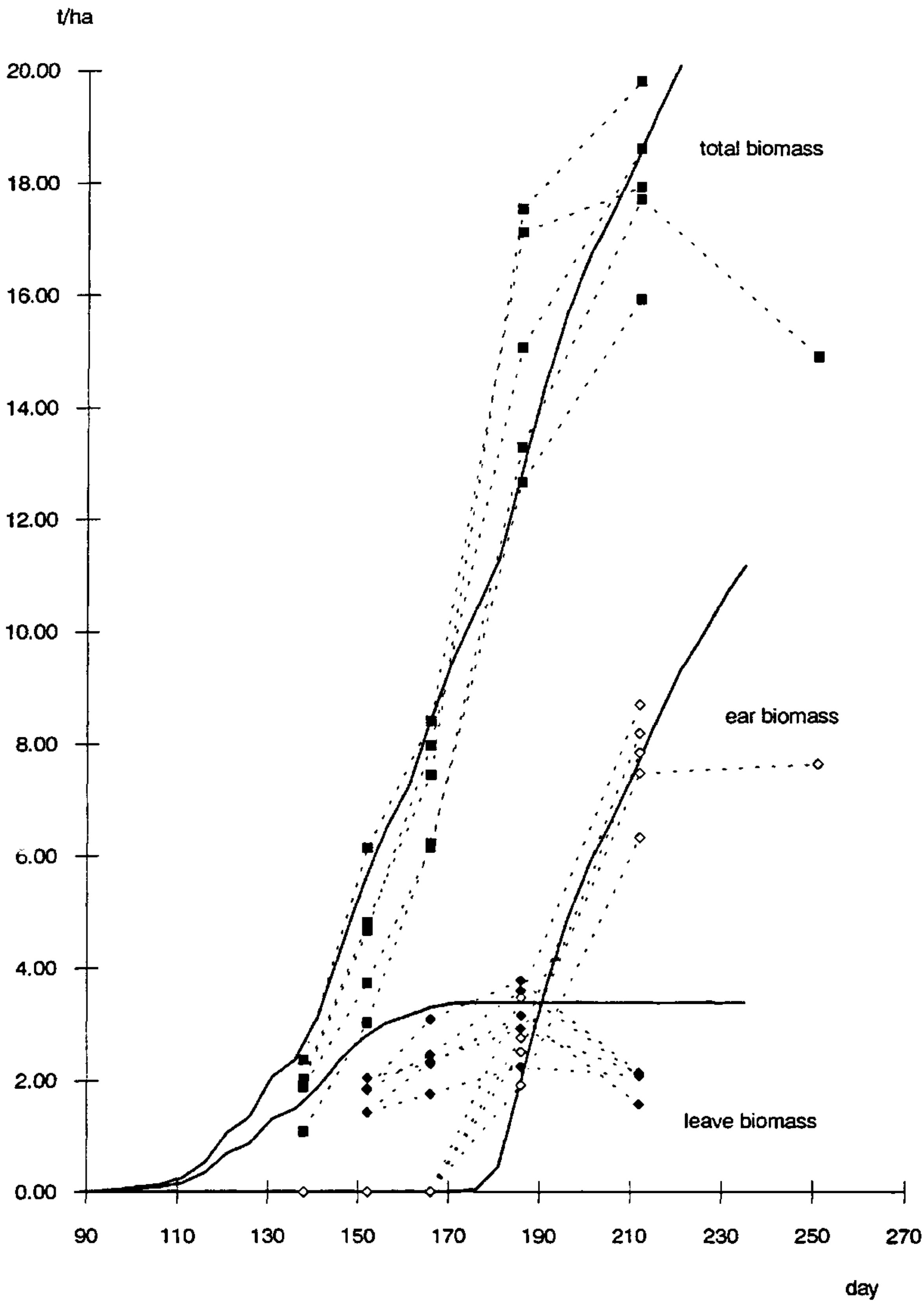
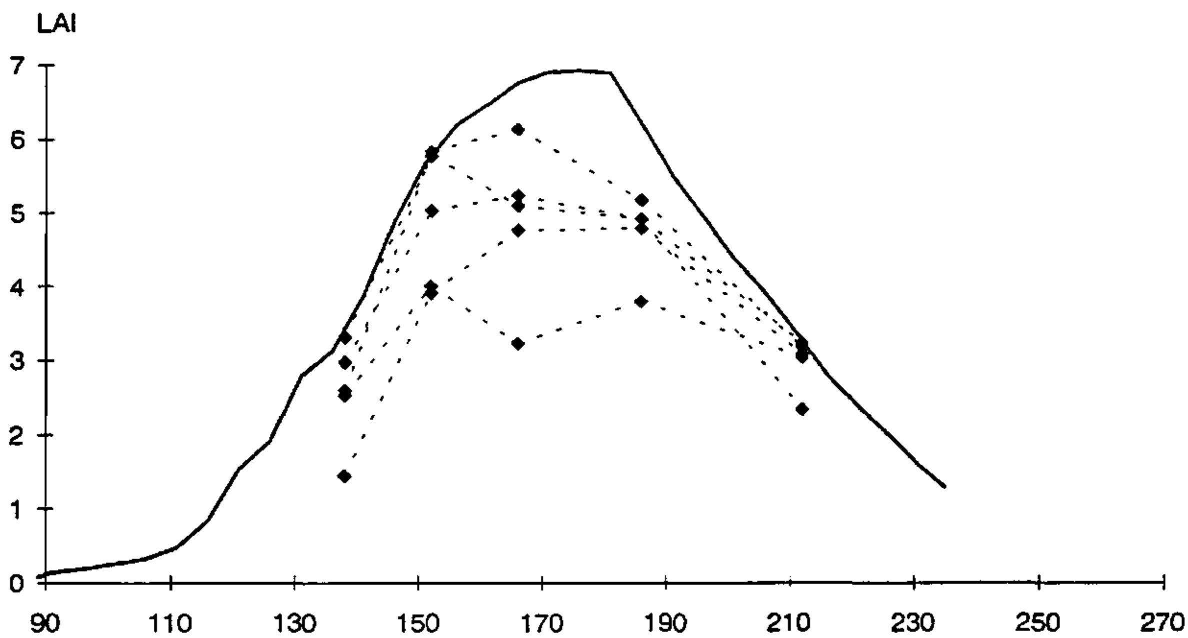


Figure 4. Measured and simulated canopy biomass (4a), LAI (4b) and tuber weight (4c) for sugar beet, Flevoland 1988. The drawn line is the calibrated SUCROS simulation (with one average sowing date for all fields), the symbols are the measured data (different symbols indicate different fields). N = six observations per field during the growing season.

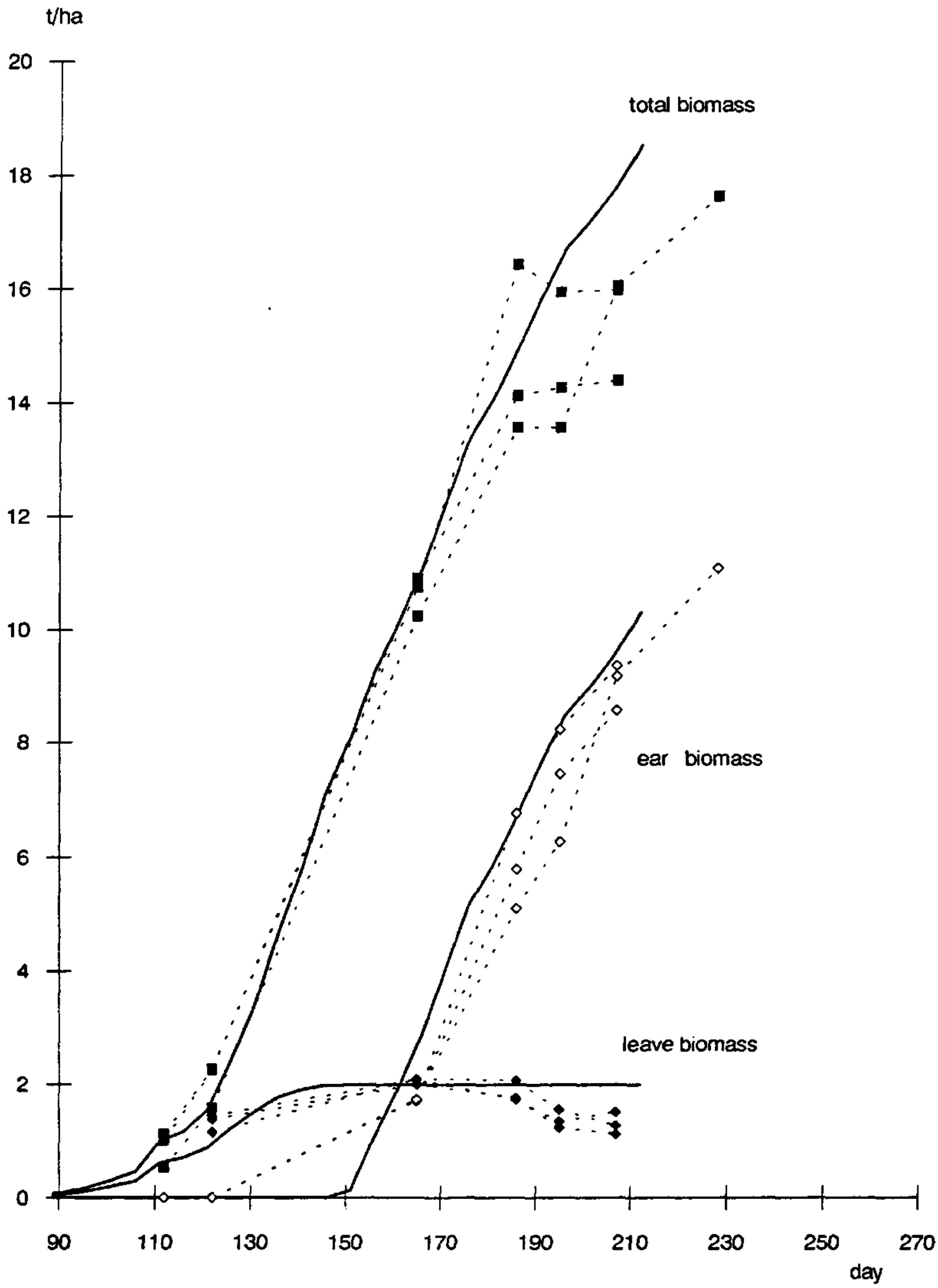

t/ha
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
90
110
130
150
170
190
210
230
250
270
day
total biomass
ear biomass
leave biomass

5a

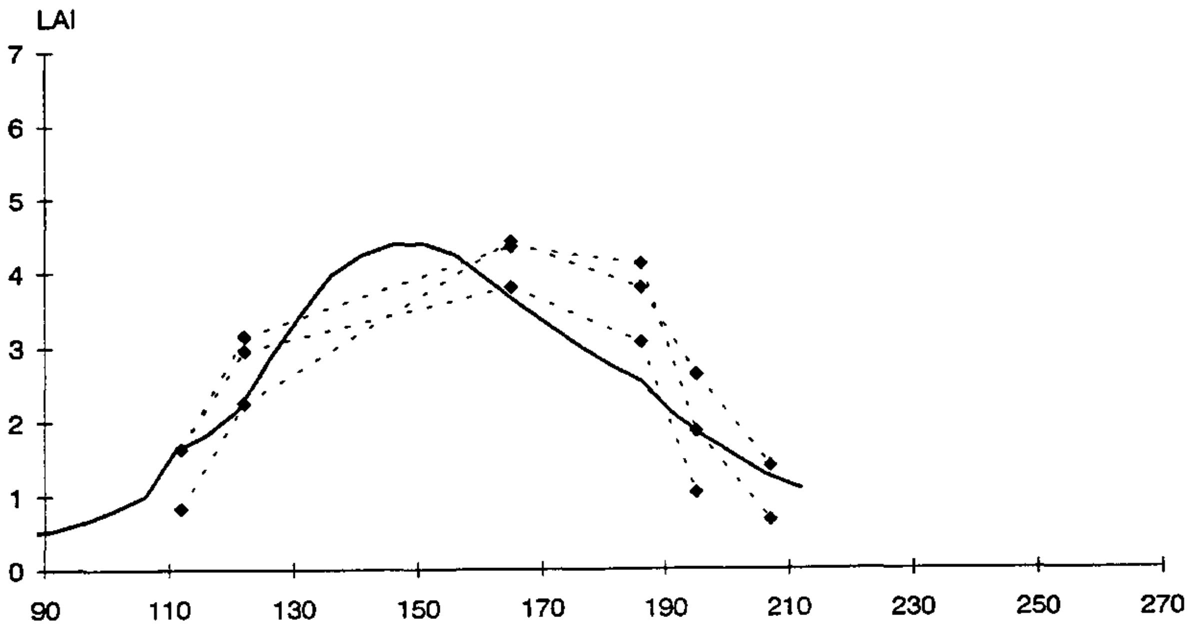


5b

Figure 5. Measured and simulated canopy biomass, differentiated in total canopy biomass, ear biomass and green leaf biomass (5a), and measured and simulated LAI (5b) for winter wheat, Flevoland 1987. The drawn lines are the calibrated SUCROS simulations, the symbols are the measured data. N = five to six observations per field during the growing season.


t/ha
20
18
16
14
12
10
8
6
4
2
0
total biomass
ear biomass
leave biomass
90
110
130
150
170
190
210
230
250
270
day

6a



6b

Figure 6. Measured and simulated canopy biomass, differentiated in total canopy biomass, ear biomass and green leaf biomass (6a), and measured and simulated LAI (6b) for winter wheat, Flevoland 1988. The drawn lines are the calibrated SUCROS simulations, the symbols are the measured data. N = five to six observations per field during the growing season.

3 Optical reflectance

Three options are introduced in the main module SUCROS to simulate optical reflectance and/or the Weighted Difference Vegetation Index (WDVI; Clevers, 1988, 1989): 1) the EXTRAD model, developed by Goudriaan (1977), 2) a simple physical metamodel for WDVI, and 3) empirical relations for WDVI. The modelling of the vegetation index WDVI was chosen (from other Vegetation Indices known in literature) because it was found to give the most stable relationship with LAI (the key driving variable of canopy reflectance) under wide ranges of 'disturbing' influences (e.g soil moisture, canopy architecture, illumination conditions). The WDVI gave especially relative stable relationships with LAI with changes in leaf optical properties (Bouman, 1991).

3.1 EXTRAD

EXTRAD (Extinction of radiation) was developed by Goudriaan (1977) to calculate the (solar) radiation profile in crop canopies. A simplified version of EXTRAD is used in the photosynthesis subroutine of SUCROS to compute the extinction of photosynthetically active radiation (~ 400-700 nm wavelengths). However, the original, more detailed model was needed to calculate the directional reflectance from crop canopies at specific wavelengths up to the infrared region.

In EXTRAD, the canopy is subdivided into a number of horizontal infinitely extended layers. The leaves in these layers are assumed to have Lambertian scattering properties, and to have a uniform azimuthal distribution. The angle distribution of the leaves is described by nine inclination intervals from 10° each. The radiation profile in the canopy is then calculated with a relaxation method. The canopy reflectance in a given direction (in our study: nadir) is computed from the total radiance leaving the top layer of the canopy in that direction.

The input of the model are crop parameters (LAI, leaf scattering coefficient at specific wavelength, leaf angle distribution function), soil parameters (hemispherical reflection coefficient at specific wavelength) and illumination parameters (solar elevation angle, fraction diffuse sky irradiance). In principle, each parameter can be physically measured. Because a constant value is used as input for the reflection coefficient of bare soil, the influence of top soil (~ 0-1 cm) moisture content on the reflectance of a crop-soil system is not modelled. The abbreviations of the model parameters are:

```
LAI     = leaf area index
SCATG   = green scattering coefficient leaves
SCATR   = red      "          "          "
SCATIR  = infrared "          "          "
RHOSG   = green hemispherical reflection coefficient bare soil
RHOSR   = red         "           "           "          "
RHOSIR  = infrared    "           "           "          "
BETA    = solar elevation angle
F       = leaf angle distribution
FRDIF   = fraction diffuse sky irradiance
```

For Flevoland, EXTRAD was calibrated on reflectance measurements made with a portable reflectance meter during the Agriscatt campaign. The reflectance meter operated in the green band (band centre = 548 nm, band width = 10 nm) and in the infrared band (band centre = 823 nm; band width = 31 nm) [the reflectance meter did not have a red band]. The calibration was performed on the same fields and cultivars that were used to calibrate SUCROS (see Chapter 2). The calibrated model parameters for sugar beet and winter wheat were the green and infrared scattering coefficients of the leaves, and the green and infrared hemispherical reflection coefficients of the bare soil. The calibrated values for the leaf scattering coefficients compared well with laboratory measurements on individual leaves. Therefore, the leaf red scattering coefficient (at ~ 650 nm) was taken from the laboratory measurements. The red reflection coefficient of bare soil was derived from field reflectance measurements with another reflectance meter in earlier years in Flevoland.

	Sugar beet	Winter wheat
SCATG	0.294	0.341
SCATR	0.079	0.123
SCATIR	0.974	0.960
RHOSG	0.146	0.134
RHOSR	0.166	0.145
RHOSIR	0.199	0.174

For both sugar beet and winter wheat, the leaf angle distribution was chosen spherical. The solar elevation was fixed on 60° (though, in principle, this value can be set to any actual condition during remote sensing observations).

The results of the calibration are illustrated by the LAI-WDVI relationship of the calibrated model for sugar beet in Figure 7 and for winter wheat in Figure 8.

The calculations of EXTRAD are performed by a call to the subroutine REFLEX in the main module SUCROS. The EXTRAD model parameters SCATG, SCATR, SCATIR, RHOSG, RHOSR, RHOSIR, BETA and F are read from input file, and the LAI and the fraction diffuse sky irradiance (FRDIF) are daily calculated in SUCROS and passed to REFLEX. The main linking parameter between SUCROS and EXTRAD is the LAI (see also Figure 2). In REFLEX, the nadir canopy reflectances are calculated in the green, red and infrared pass-bands: NADG, NADR and NADIR respectively. Furthermore, the following Vegetation Indices (VI's) are calculated: Infrared/green ratio (RATIO; first used by Jordan, 1969), Normalized Difference Vegetation Index (NDVI; Rouse, 1973) and the Weighted Difference Vegetation Index (WDVI; Clevers, 1988):

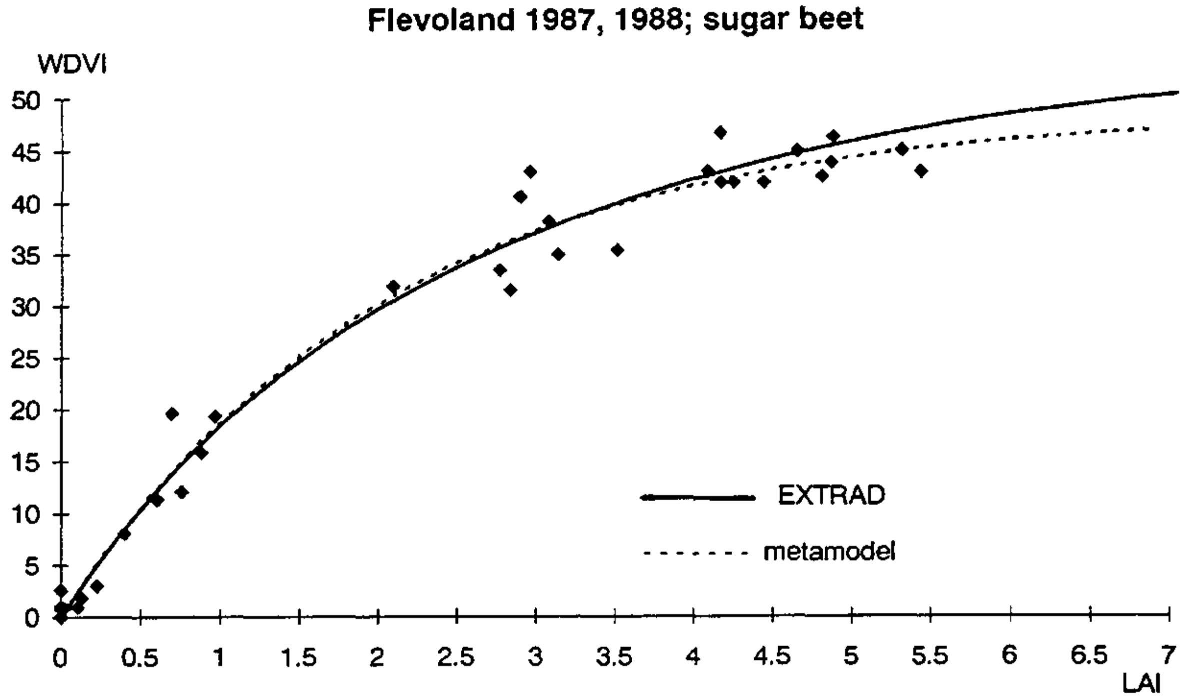


Figure 7. Measured and calculated values of WDVI versus LAI for sugar beet. The solid line is the calibrated EXTRAD model, the dotted line is the calibrated metamodel, and the diamonds are the measured data in Flevoland during Agriscatt 1987 and 1988 (N = 33).

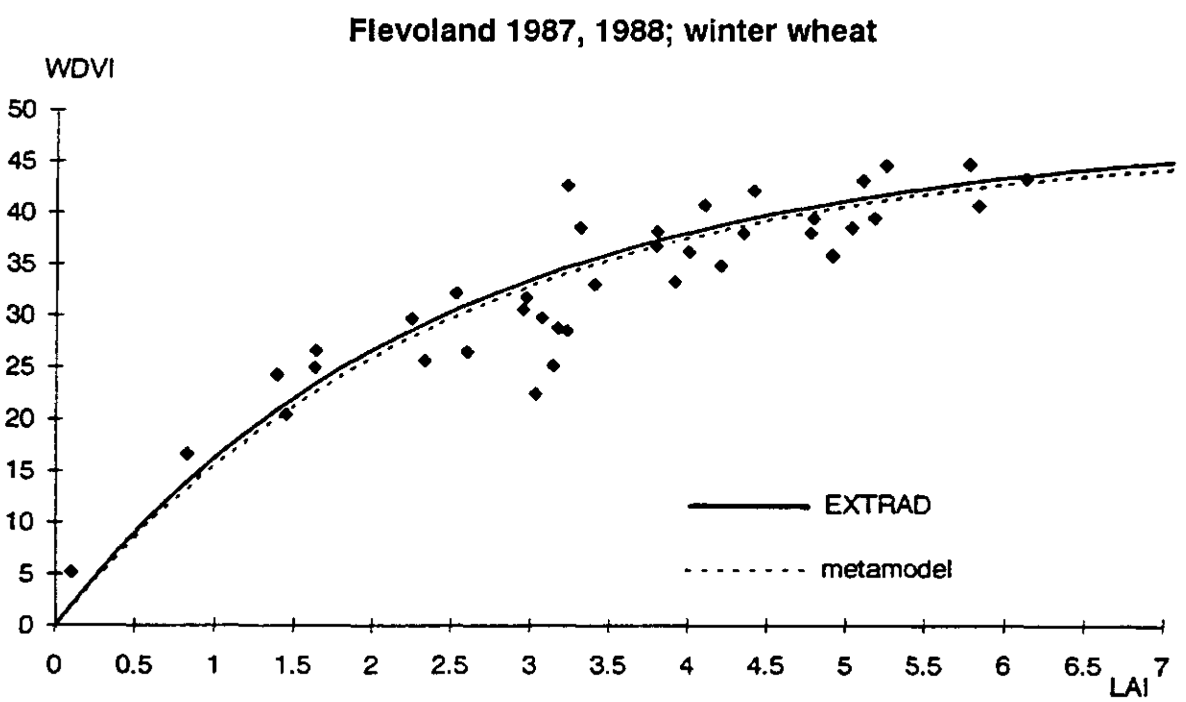


Figure 8. Measured and calculated values of WDVI versus LAI for winter wheat. The solid line is the calibrated EXTRAD model, the dotted line is the calibrated metamodel, and the diamonds are the measured data in Flevoland during Agriscatt 1987 and 1988 (N = 42).

RATIO = IR/GR ratio
NDVI = (IR-GR)/(IR+GR)
WDVI = IR-(IR_s/GR_s).GR

where GR_s and IR_s is the green and infrared reflectance of the bare soil, and GR and IR is the green and infrared reflectance of the crop. In the calculation of the WDVI, the IR_s/GR_s ratio in Flevoland is typically 1.3 (and the IR_s/R_s ratio 1.2). Here, the calculation of the VI's is performed with green and infrared reflectance values, instead of with red and infrared reflectance values as is done in the original descriptions of the VI's. The choice for green reflectances was guided by the availability of a green band in the reflectance meter that was used in the calibration years 1987 and 1988 (see above). However, in the calculations of the VI's in the subroutine REFLEX, the calculated reflectance in the green band (NADG) can easily be replaced by the calculated reflectance in the red band (NADR).

The subroutine REFLEX is especially suitable to study effects of changes in leaf colour, in canopy structure, in soil background or in illumination conditions on the reflectances of the simulated crop.

3.2 Metamodel for WDVI

The Weighted Difference Vegetation Index can also be calculated directly from the simulated LAI in the main module SUCROS with a metamodel (Bouman et al, 1992 in prep.):

WDVIM = WMAX.(1-exp(-WEXT.LAI))

where WDVIM = WDVI (the suffix 'M' refers to 'metamodel' and is meant to distinguish the WDVI calculated here from the WDVI calculated in REFLEX); WMAX = the asymptotic value of WDVI at infinite LAI; and WEXT = an extinction coefficient. This metamodel is the same as the CLAIR model developed by Clevers (1988, 1989).

This metamodel was calibrated for sugar beet on the same 'Flevoland-data' that were used to calibrate EXTRAD, and for winter wheat also on reflectance measurements made at various other locations in The Netherlands (Uenk et al., 1992). In the calibration set, WDVI was again calculated from green and infrared canopy reflectance. The calibrated model parameters are read from input file:

	Sugar beet	Winter wheat
WMAX	48.64	47.00
WEXT	0.485	0.400

Figures 7 and 8 illustrate the calibrated relationship of the metamodel for sugar beet and winter wheat respectively. As can be seen, the curves of the metamodel are very similar to the curves of the calibrated EXTRAD model. The metamodel is included in the main module SUCROS as a faster alternative to the more elaborate computations in REFLEX when the calculation of only WDVI is the objective.

3.3 Empirical relationship for WDVI

For winter wheat, a third option for the calculation of WDVI consists of a combination of empirical linear relations between WDVI and LAI, and is again incorporated in the main module SUCROS. To get reliable relationships, the regression was performed on reflectance measurements from a large number of experiments using various varieties in different years and on different locations (Uenk et al., 1992). The WDVI was again calculated from green and infrared reflectance. The relationships were only derived for winter wheat because the number of data was too low for sugar beet to get reliable regression coefficients.

The relationship for winter wheat is:

```
for    0 < LAI < 0.6   : WDVIE = 20.LAI
for 0.6 < LAI < 4.06 : WDVIE = 7.463.(LAI+1.03)
for        LAI > 4.06 : WDVIE = 2.645.(LAI+10.44)
```

where WDVIE = WDVI (the suffix 'E' refers to 'empirical' and is meant to distinguish the WDVI calculated here from the WDVI calculated in REFLEX). Figure 9 illustrates this relationship between WDVI and LAI for winter wheat.

This empirical relation was found to give a (slightly) more accurate description of the relationship between LAI and WDVI than either the model EXTRAD or the metamodel of option 2 (Uenk et al., 1992). The empirical relationship can again be used in SUCROS as a faster alternative to the more elaborate computations in REFLEX when the calculation of only WDVI is the objective. The disadvantage of this method is, of course, its strictly empirical nature.

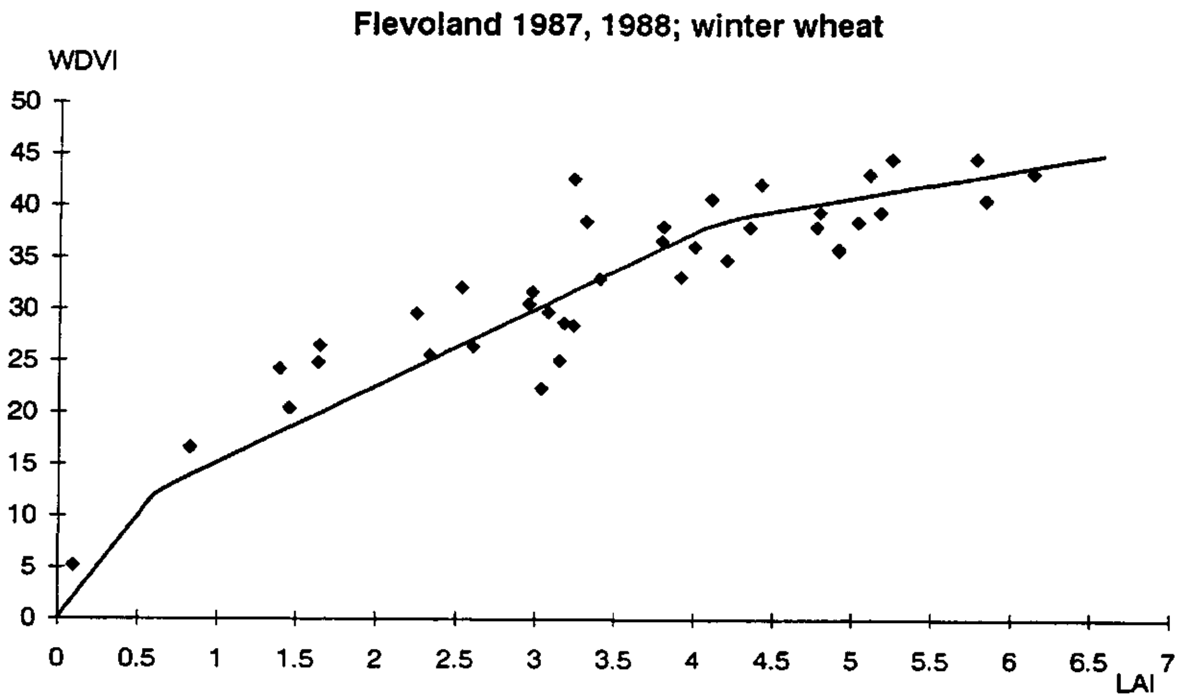


Figure 9. Measured and calculated values of WDVI versus LAI for winter wheat. The solid line represents the empirical linear relation between WDVI and LAI, and the diamonds are the measured data in Flevoland during Agriscatt 1987 and 1988 (N = 42).

4 Radar backscatter

The radar backscatter is calculated using the 'Cloud' model developed by Attema and Ulaby (1978). For sugar beet, the original one-layer 'Cloud' model is used, and for winter wheat, the two-layer 'Cloud' model developed by Hoekman et al. (1982):

Sugar beet:

$\gamma = C(\theta).[1\text{-}\exp(\text{-}D.W/\cos\theta)] + G(\theta).\exp(m.K\text{-}D.W/\cos\theta)$ (m^2/m^2)

where γ = radar cross section per unit projected area (m^2/m^2), W = amount of water in the canopy per unit soil surface (kg/m^2), m = volumetric soil moisture content (%), θ = incidence angle (°), D = coefficient of attenuation, K = soil moisture coefficient, $C(\theta)$ = backscatter of an optically thick crop cover, $G(\theta)$ = backscatter of dry soil.

C, G, D and K are model parameters (per angle of incidence), and W and m are the driving variables of the model.

Winter wheat:

$$\gamma = C2(\theta).[1\text{-}\exp(\text{-}D2.W2/\cos\theta)] + C1(\theta).[1\text{-}\exp(\text{-}D1.W1/\cos\theta)].\exp(\text{-}D2.W2/\cos\theta) + G(\theta).\exp(m.K).\exp([(\text{-}D2.W2+D1.W1)/\cos\theta]) \quad (m^2/m^2)$$

where the symbols have the same meaning as above, with the suffix 1 to denote the vegetative layer of the canopy, and 2 to denote the ear-layer of the canopy.

Two options are introduced to calculate the radar backscatter with the 'Cloud' model in the main module SUCROS: the subroutine CLOUDX, with 'Cloud' calibrated on ground-based X-band data, and the subroutine CLOUDM, with 'Cloud' calibrated on multifrequency measurements performed with DUTSCAT during Agriscatt. The model parameters of 'Cloud' (C, G, D and K) and the soil moisture content (m) are read from file. For both subroutines, the amount of water in the canopy (W) is calculated from the simulated dry canopy weight in the main module SUCROS times the water content of the canopy (defined as fresh canopy weight minus dry canopy weight, divided by fresh weight). The water content is calculated as a function of the development of the crop, i.e. as a function of temperature sum for sugar beet, and as a function of development stage for winter wheat. This function was derived (by the author; not originally in SUCROS) from measurements of fresh and dry weights of the crop canopies in the ROVE and Agriscatt campaigns in Flevoland. For sugar beet, the water content proved to be stable throughout the growing season (average 90.8%; Figure 10), but for winter wheat, the water contents of both the vegetative layer and the ear-layer distinctly changed with development stage (Figure 11).

Thus, the main linking variables between SUCROS and 'Cloud' are the amount of canopy water, and the development stage.

The volumetric soil moisture content is read from input file. When measurements of soil moisture content have actually been performed, these data can be entered in the data file (see section 5.1: controlling input). On the days of the measurement, the 'Cloud' subroutines take the actually measured moisture contents; for days between the measurements, linear interpolation is used to derive an input for soil moisture content. When no measurements of soil moisture content are available, any hypothetical value can be entered in the input file.

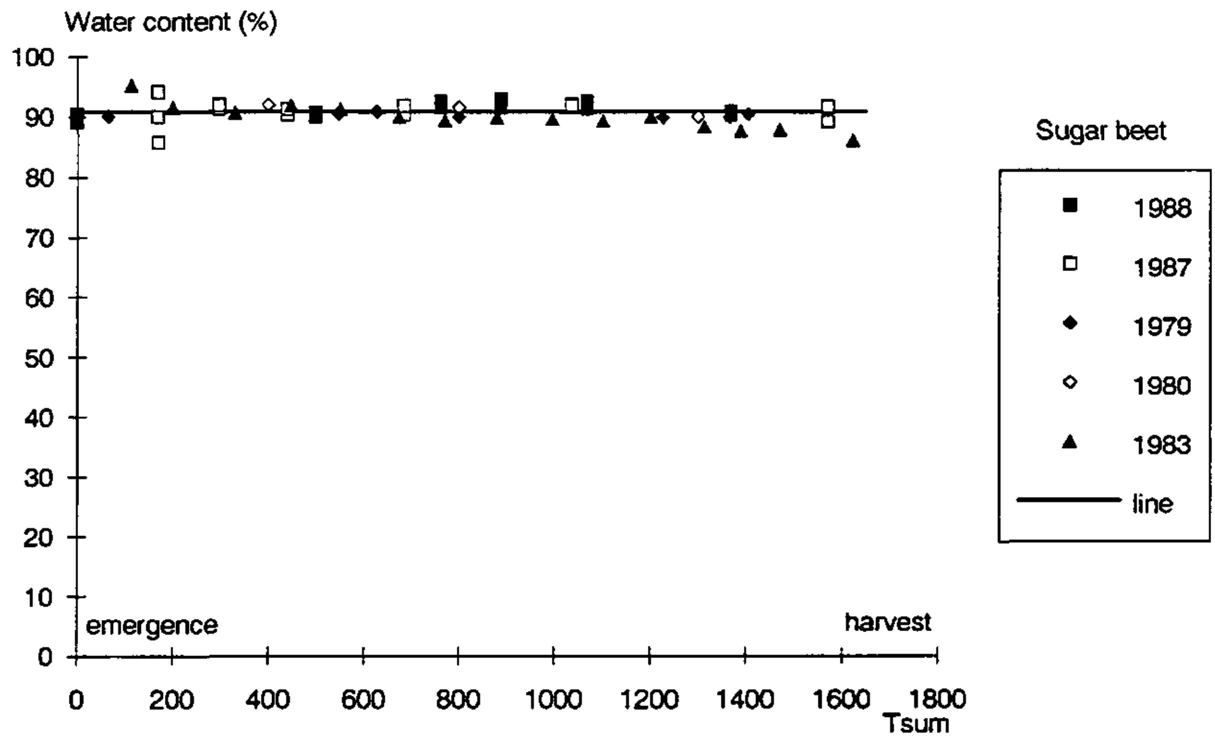


Figure 10. Water content of the canopy of sugar beet versus temperature sum after sowing. The drawn line gives the relationship as included in SUCROS, the different symbols represent measurements of different fields in different years: 1979 at Droevendaal, 1980, 1983 at De Schreef, 1987, 1988 Agriscatt fields (Ntotal = 61).

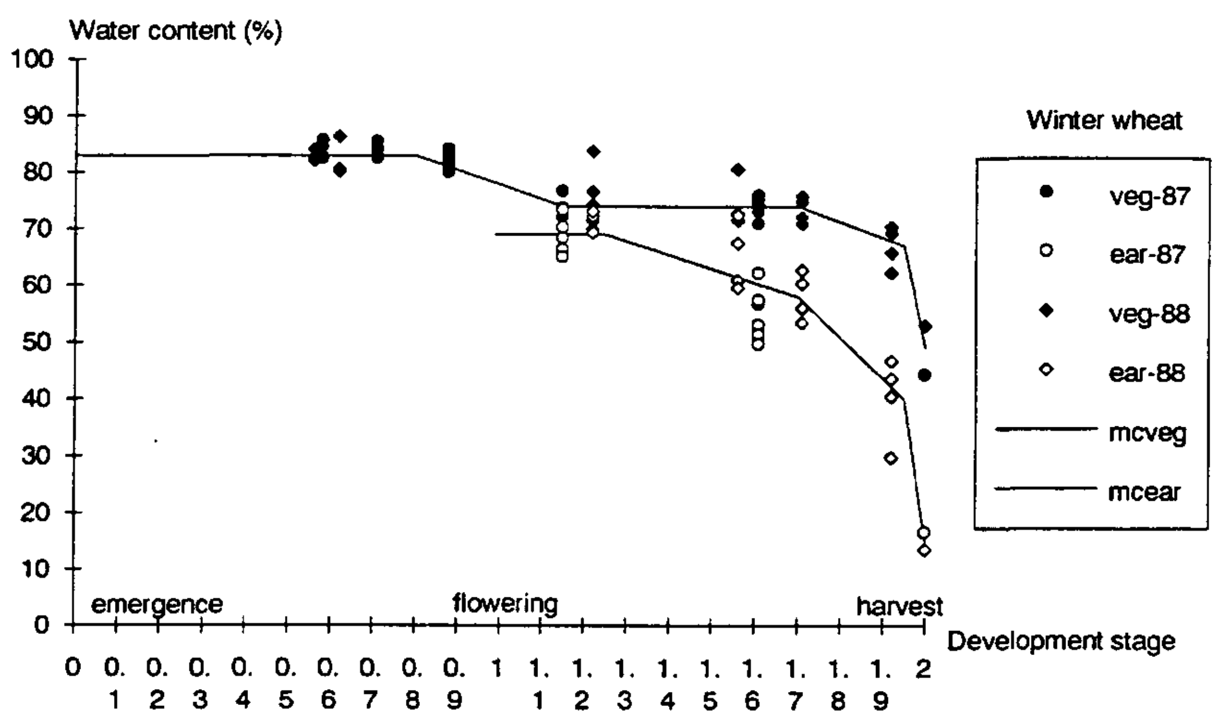


Figure 11. Water content of the vegetative layer and of the ear-layer of winter wheat versus development stage. The drawn lines give the relationships as included in SUCROS, the symbols represent measurements from the Agriscatt campaign (Ntotal = 55 for the vegetative layer and 30 for the ear-layer).

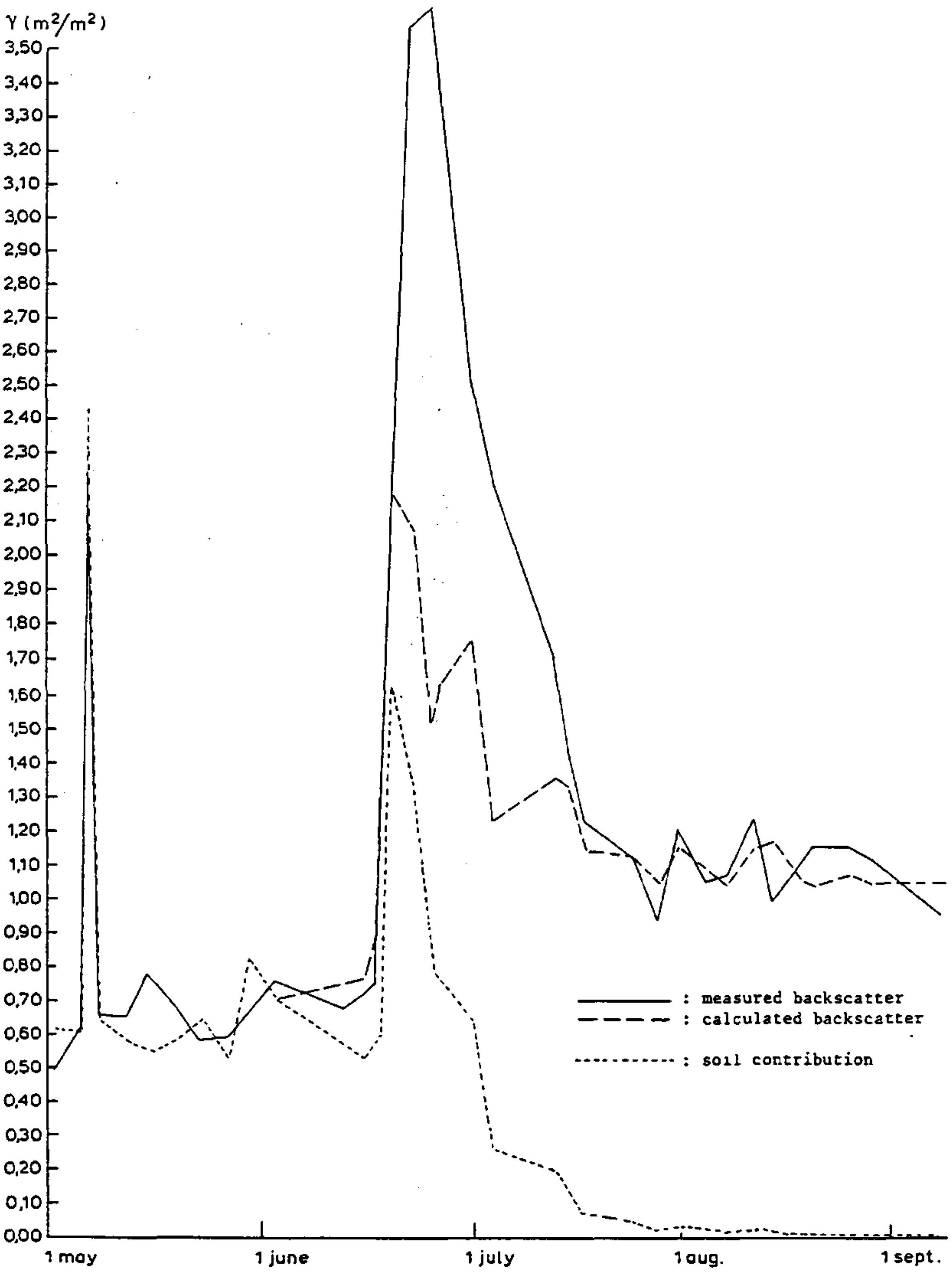
4.1 X-band radar backscatter

With the subroutine CLOUDX, the X-band radar backscatter is calculated with the 'Cloud' model calibrated on ground-based X-band (9.5 GHz) measurements in VV polarization, performed by the ROVE team in 1979 and in 1980 (de Loor et al., 1982). For sugar beet, 'Cloud' was calibrated on the data collected on test farm 'De Schreef' in Flevoland, 1980 (Bouman , 1987), and for winter wheat - by lack of good data on 'De Schreef'- on data collected on test farm 'Droevendaal' at Wageningen, 1979 (Hoekman, 1981). For sugar beet, the cv was Monohil, for winter wheat the cv was Okapi.
The model parameters are read from input file:

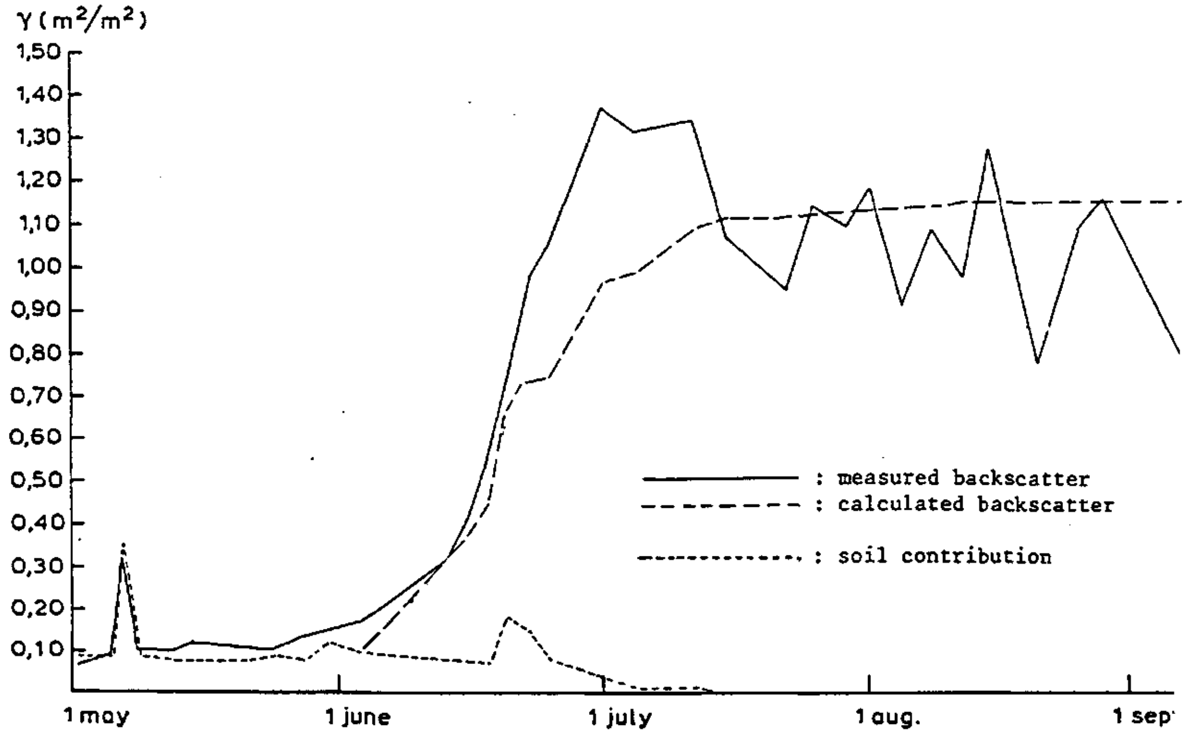
Incidence angle:		10°	20°	30°	40°	50°	60°	70°	75°
Sugar beet	C	1.060	1.190	1.200	1.150	1.170	1.150	0.980	0.930
	G	0.525	0.174	0.120	0.095	0.076	0.065	0.055	0.042
Winter wheat	C2	0.101	0.048	0.039	0.040	0.054	0.079	0.130	0.172
	G	0.344	0.326	0.088	0.057	0.019	0.010	0.012	0.009

```
D (sugar beet)      = 0.46
D1 (winter wheat) = 1.153
D2 (winter wheat) = 2.0565
C1 (winter wheat) = 0.1850
K (sugar beet and winter wheat) = 0.06
```

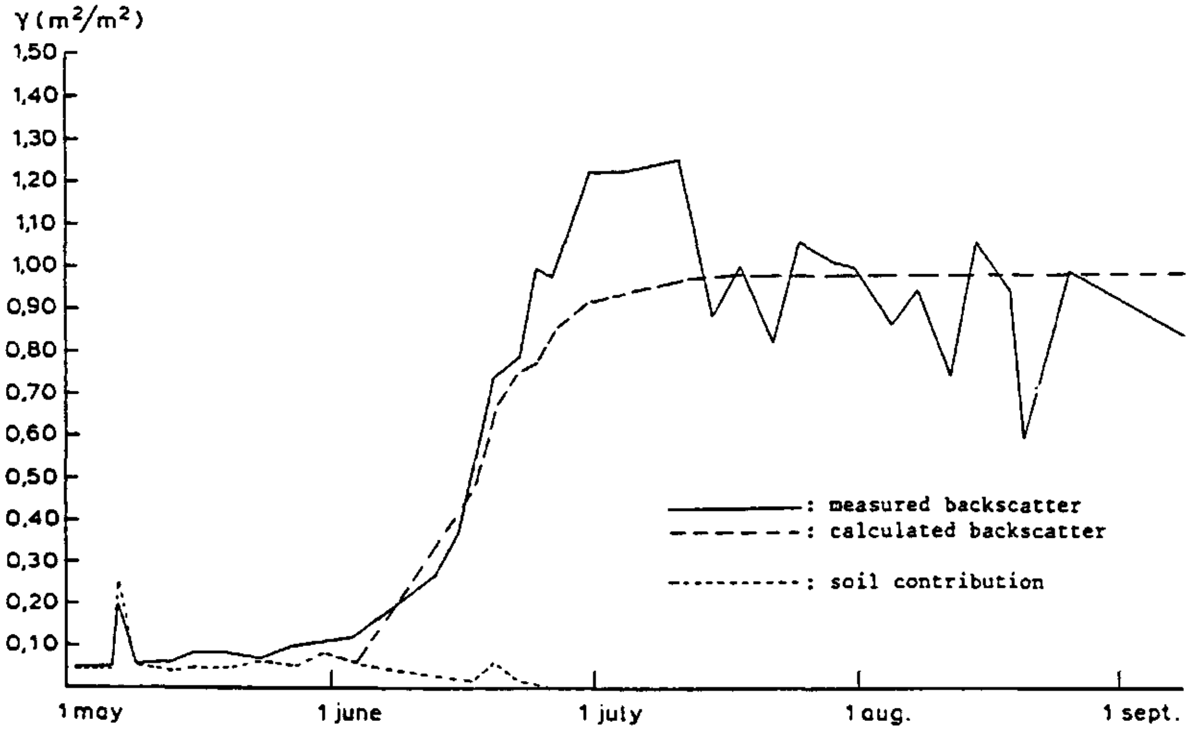
The results of the calibration are depicted in Figure 12 for sugar beet and in Figure 13 for winter wheat.


γ (m²/m²)
3,50
3,40
3,30
3,20
3,10
3,00
2,90
2,80
2,70
2,60
2,50
2,40
2,30
2,20
2,10
2,00
2,90
1,80
1,70
1,60
1,50
1,40
1,30
1,20
1,10
1,00
0,90
0,80
0,70
0,60
0,50
0,40
0,30
0,20
0,10
0,00
1 may
1 june
1 july
1 aug.
1 sept.
: measured backscatter
: calculated backscatter
: soil contribution

12a



12b



12c

Figure 12. Measured and calculated radar backscatter with the calibrated 'Cloud' model at 10° (12a), at 50° (12b) and at 70° (12c) incidence angle of sugar beet at test farm "De Schreef" in 1980, N = 36 per angle of incidence. Note that the radar backscatter is given in m^2/m^2! Source: Bouman, 1987.

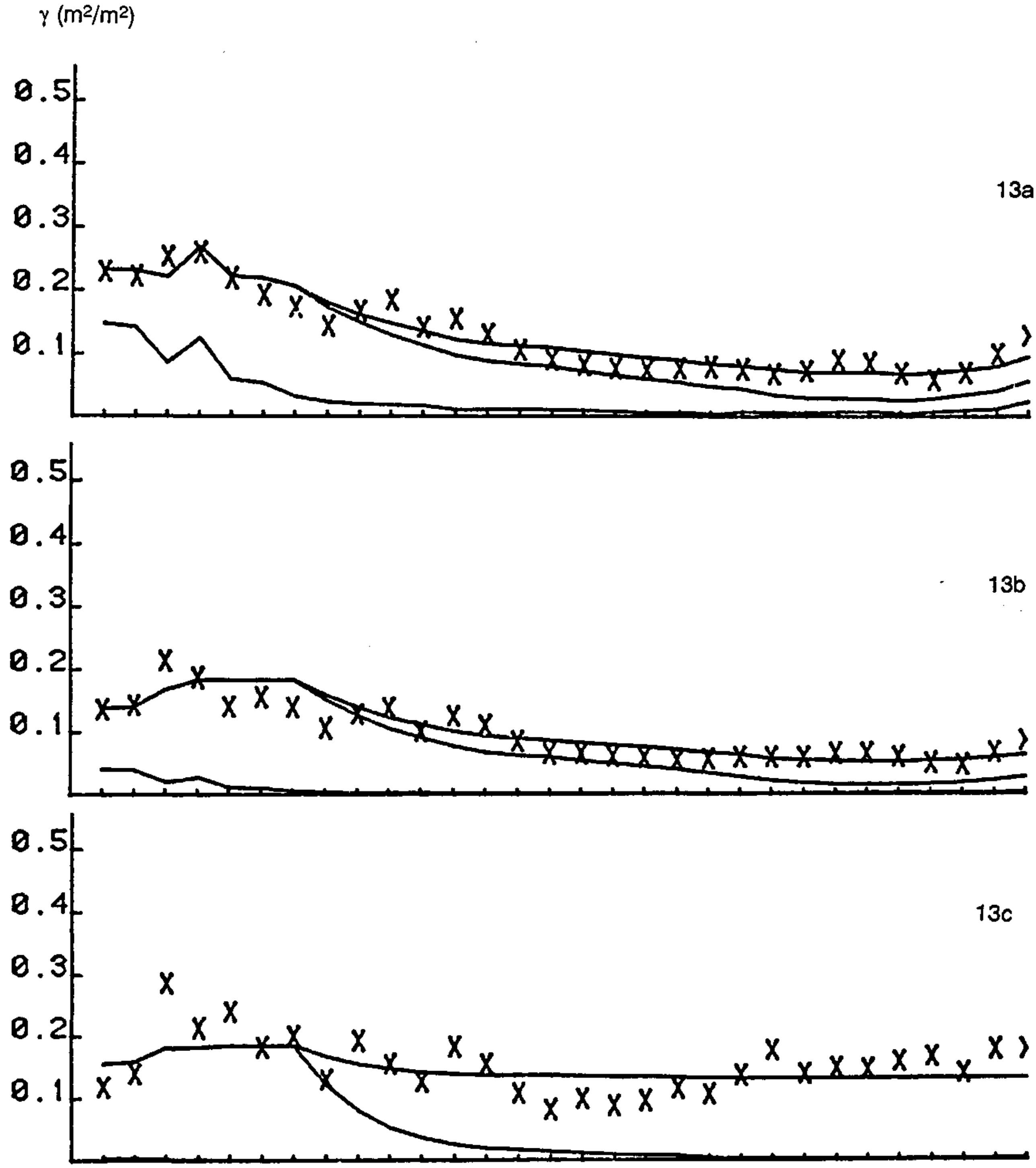


Figure 13. Measured and calculated radar backscatter with the calibrated 'Cloud' model at 20° (13a), at 40° (13b) and at 60°(13c) incidence angle of winter wheat (cv Okapi) at test farm "Droevendaal" in 1979. The crosses indicate the measurements, the drawn lines indicate the simulated radar backscatter (total backscatter, contribution of vegetative layer and soil contribution), N = 39 per angle of incidence. Note that the radar backscatter is given in m^2/m^2! Source: Hoekman, 1981.

In the subroutine CLOUDX, the following abbreviations are used:

```
GAMMA(I) = X-band radar backscatter at inci. angle denoted by I; dB
MCCROP   = water content whole canopy; %
PLWCROP  = amount of water in the whole canopy (W); kg/m²
MS       = volumetric top soil moisture content (M); %
INC(I)   = incidence angle denoted by I
CPL(I)   = 'Cloud' parameter C at incidence angle denoted by I
GS(I)    = 'Cloud' parameter G at incidence angle denoted by I
DPL      = 'Cloud' parameter D
KS       = 'Cloud' parameter K
```

I = counter to denote angle of incidence, read from data file:

I :	1	2	3	4	5	6	7	8
Incidence angle:	10°	20°	30°	40°	50°	60°	70°	75°

And specifically for winter wheat:

```
MCVEG    = water content vegetative layer in canopy; %
MCEAR    = water content ear layer in canopy; %
PLWVEG   = amount of water in the vegetative layer of the canopy
           (W1); kg/m²
PLWEAR   = amount of water in the ear layer of the canopy
           (W2); kg/m²
CVEG     = 'Cloud' parameter C1
CEAR(I)  = 'Cloud' parameter C2 at incidence angle denoted by I
DVEG     = 'Cloud' parameter D1
DEAR     = 'Cloud' parameter D2
```

Note that the simulated output, i.e. the radar backscatter, is given in dB!

4.2 L-, S-, C-, X-, Ku1- and Ku2-band radar backscatter

With the subroutine CLOUDM, the L-, S-, C-, X-, Ku1- and Ku2-band radar backscatter is calculated with the 'Cloud' model calibrated on airborne DUTSCAT measurements made during Agriscatt-1988 (Bouman et al., 1990b). [In 1987, the DUTSCAT measurements were considered too unreliable for model calibration; Bouman et al., 1990a)]. The calibration was performed on the same fields of 1988 that were used to calibrate SUCROS and EXTRAD. The values for the C, D and K parameters were derived by van Leeuwen (van Leeuwen, 1991; pers. comm.), and the values for the G-parameters were derived by the author. The DUTSCAT bands had the following frequency centres: L-band = 1.2 GHz; S-band = 3.2 GHz; C-band = 5.3 GHz; X-band = 9.7 GHz; Ku1-band = 13.7 GHz and Ku2-band = 17.3 GHz. For sugar beet, the 'Cloud' model was calibrated on HH polarized data, and for winter wheat on VV polarized data. The model parameters are read from input file:

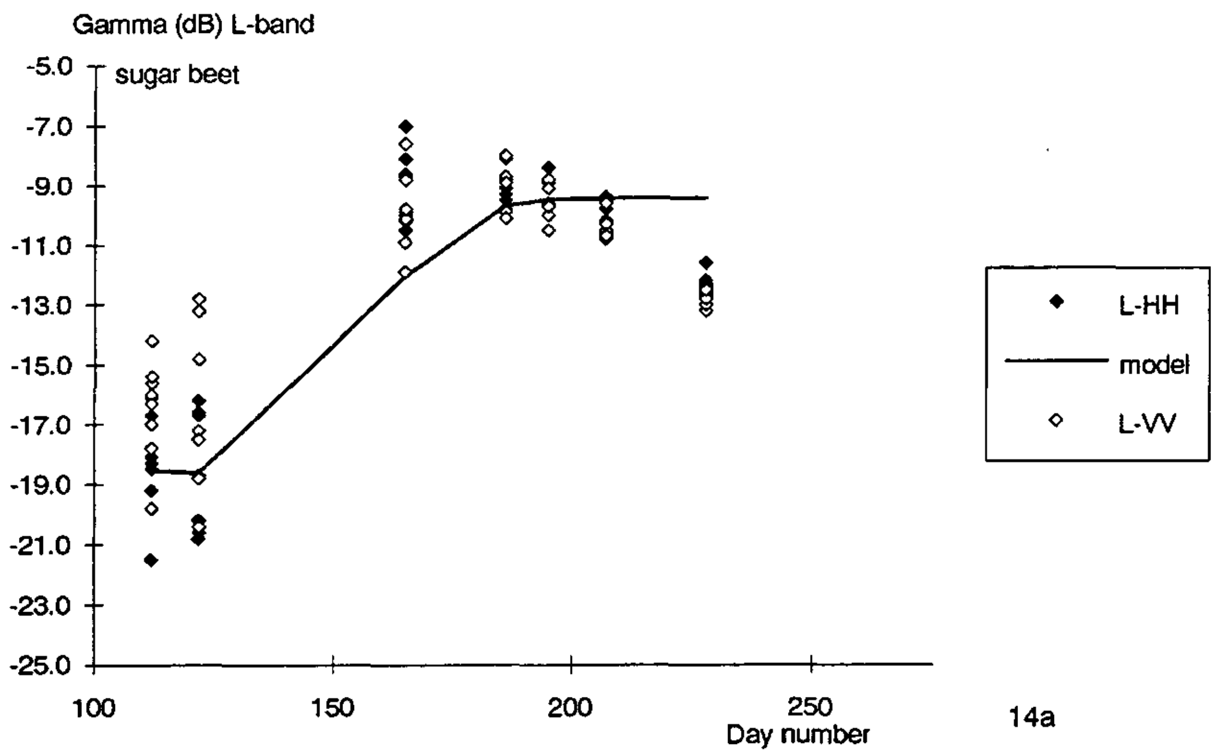
Sugar beet

		L	S	C	X	Ku1	Ku2
C-parameter							
	20°	.19115	.32000	.58845	1.04065	1.94800	1.37346
	30°	.12776	.27578	.50725	.83942	2.66803	1.14837
	40°	.11424	.30995	.44199	1.22765	2.57024	1.14212
	50°	.11386	.34963	.32138	1.13502	2.59050	1.33077
	60°	.10328	.36640	.49978	.96138	1.95570	1.20513
G-parameter							
	20°	0.00190	.01302	.01964	.12578	.16330	.077177
	30°	0.00085	.00914	.01146	.06729	.10215	.074368
	40°	0.00070	.00445	.04918	.03464	.12071	.076001
	50°	0.00082	.00374	.00458	.02186	.06557	.070116
	60°	0.00079	.00293	.00391	.02583	.10719	.029653
D-parameter		1.1025	.2314	.1009	.2099	1.0000	1.0000
K-parameter		.100	.069	.058	.048	.044	.041

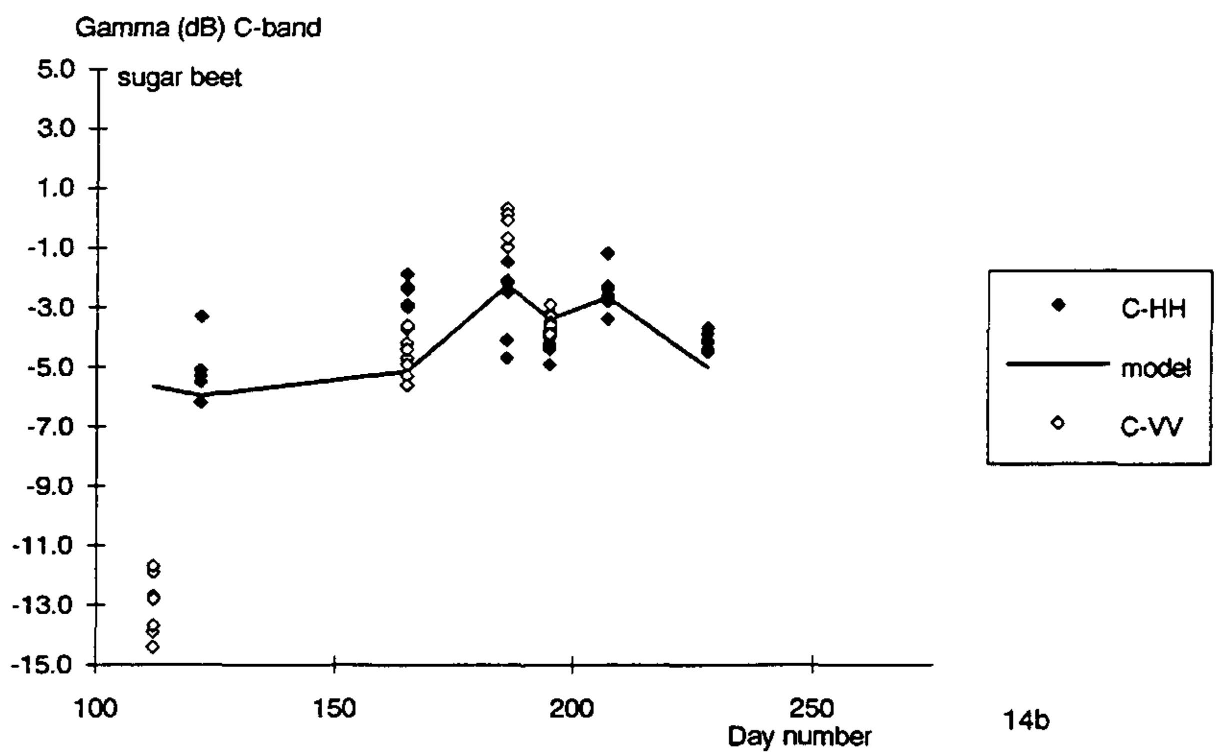
Winter wheat

		L	S	C	X	Ku1	Ku2
C2-parameter							
	20°	.0556	.4861	.2249	.1230	.3919	.2661
	30°	.0698	.2771	.2086	.1331	.4379	.2975
	40°	.0676	.2203	.1302	.1191	.4188	.2954
	50°	.0868	.1996	.1547	.1001	.4843	.3103
	60°	.1150	.3009	.2795	.2298	.3302	.3623
G-parameter							
	20°	.0061	.0255	.0200	.0400	.1100	.0800
	30°	.0047	.0150	.0190	.0250	.0700	.0850
	40°	.0022	.0080	.0090	.0104	.0750	.0980
	50°	.0012	.0067	.0110	.0005	.0900	.0900
	60°	.0016	.0090	.0110	.0400	.0600	.0600
C1-parameter		.0486	.1566	.1727	.2099	.1904	.1813
D1-parameter		.2678	.0047	.0033	.5568	.5568	.5847
D2-parameter		2.0789	1.9799	.0717	.0009	.1491	.4810
K-parameter		.100	.069	.058	.048	.044	.041

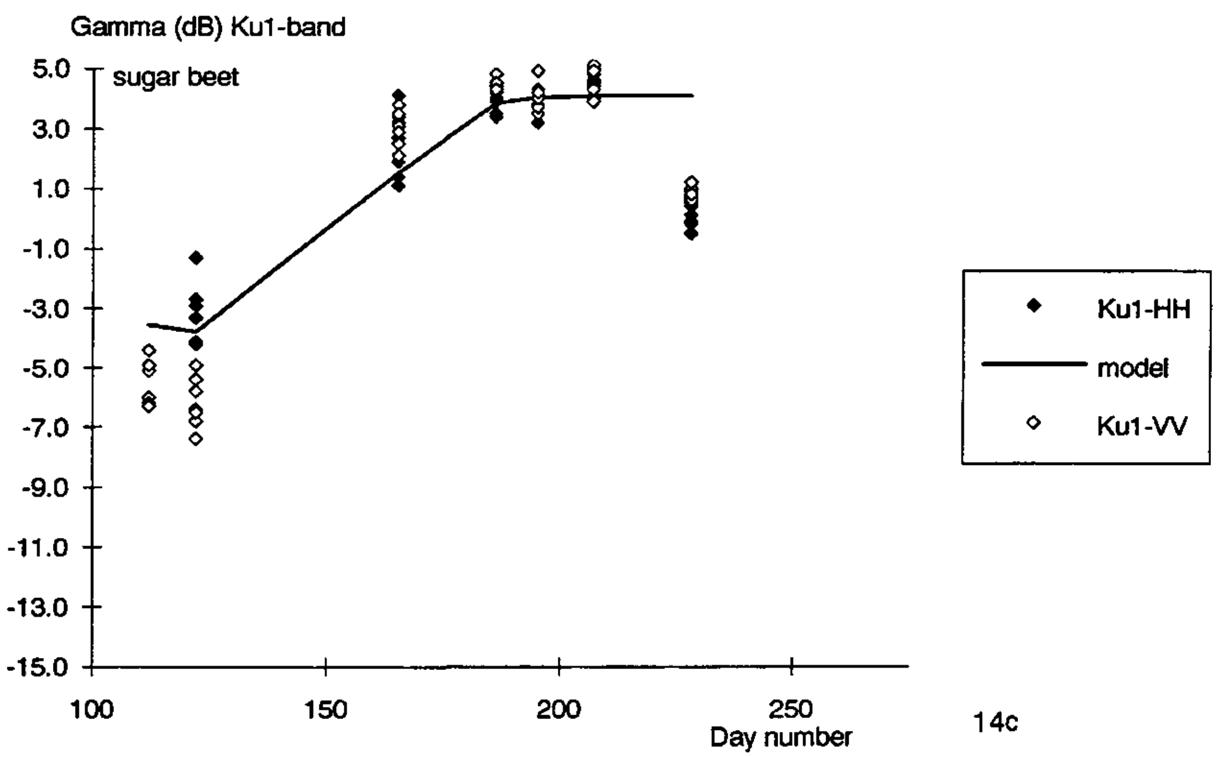
The results of the calibration are depicted in Figure 14 for sugar beet, and Figure 15 for winter wheat.


Gamma (dB) L-band
sugar beet
-5.0
-7.0
-9.0
-11.0
-13.0
-15.0
-17.0
-19.0
-21.0
-23.0
-25.0
100
150
200
250
Day number
L-HH
model
L-VV

14a

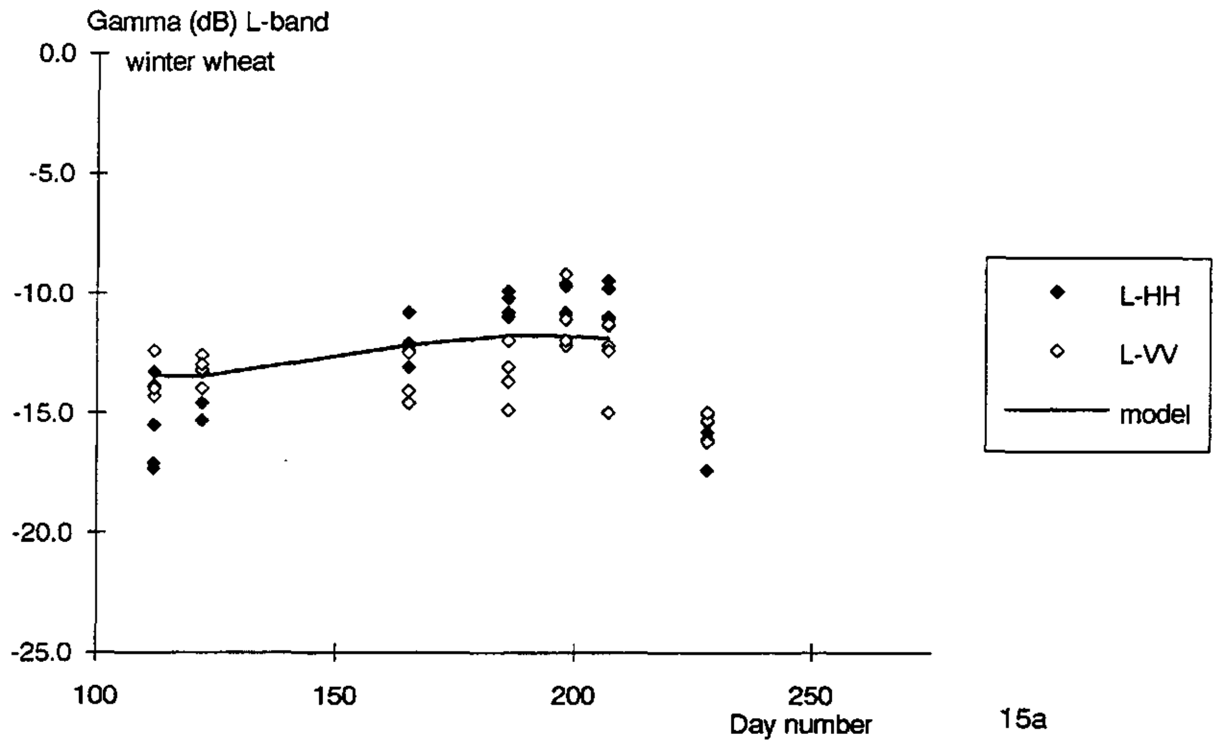

Gamma (dB) C-band
sugar beet
5.0
3.0
1.0
-1.0
-3.0
-5.0
-7.0
-9.0
-11.0
-13.0
-15.0
100
150
200
250
Day number
C-HH
model
C-VV

14b

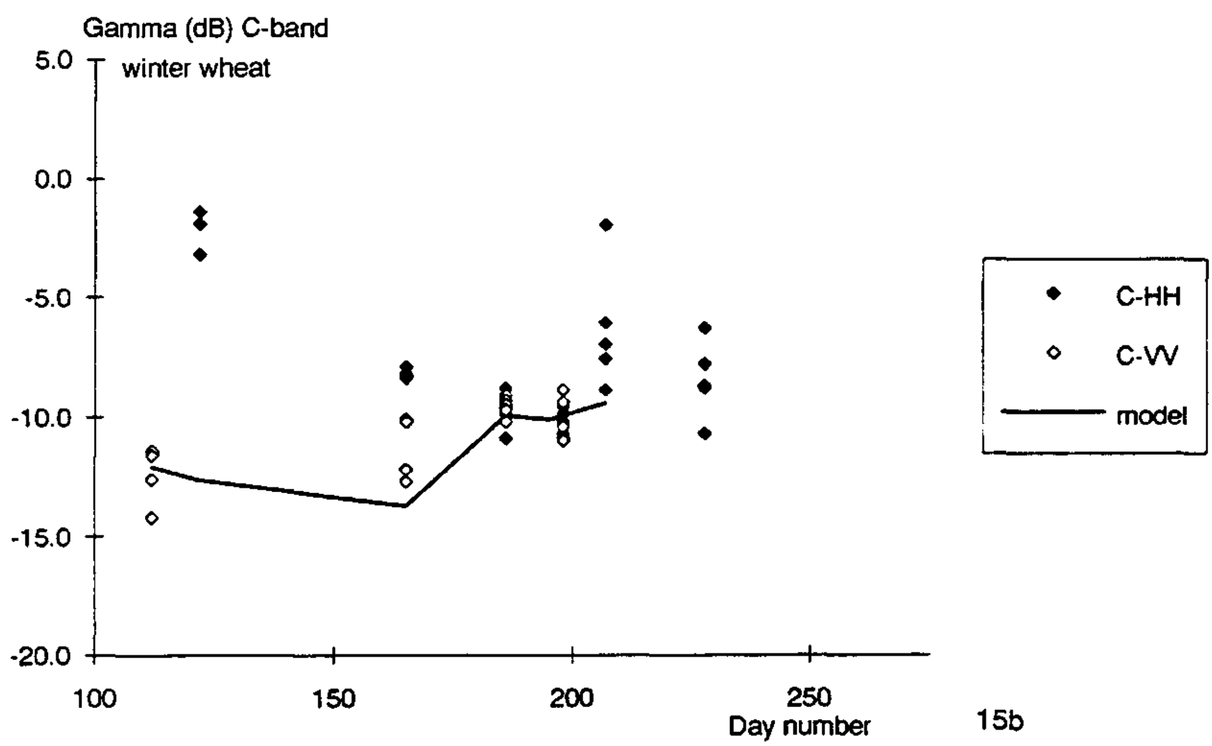


14c

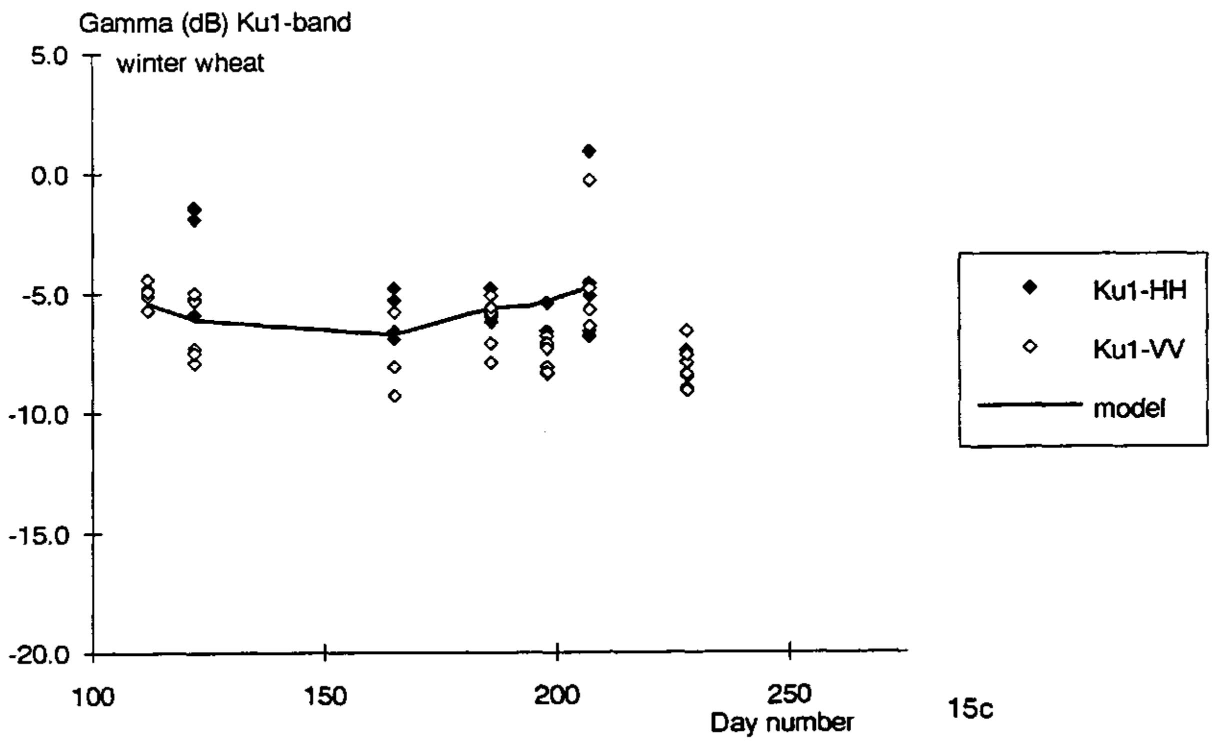
Figure 14. Measured and calculated radar backscatter in the L-band (14a), the C-band (14b) and the Ku1-band (14c) of sugar beet in the Agriscatt campaign 1988. The drawn line is relationship of the calibrated 'Cloud' model, the closed diamonds are the HH polarized measurements, and the open diamonds are the VV polarized measurements. The measurements are from eight fields; seven observations during the growing season.


Gamma (dB) L-band
winter wheat
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
100
150
200
250
Day number
L-HH
L-VV
model

15a


Gamma (dB) C-band
winter wheat
5.0
0.0
-5.0
-10.0
-15.0
-20.0
100
150
200
250
Day number
C-HH
C-VV
model

15b



15c

Figure 15. Measured and calculated radar backscatter in the L-band (15a), the C-band (15b) and the Ku1-band (15c) of winter wheat in the Agriscatt campaign 1988. The drawn line is relationship of the calibrated 'Cloud' model, the closed diamonds are the HH polarized measurements, and the open diamonds are the VV polarized measurements. The measurements are from five fields; seven observations during the growing season.

In the subroutine CLOUDM, the following abbreviations are used:

GAMMAA(I,J)	= X-band radar backscatter at incidence angle denoted by I and at frequency denoted by J; dB
MCCROP	= water content whole canopy; %
PLWCROP	= amount of water in the whole canopy (W); kg/m^2
MS	= volumetric top soil moisture content (M); %
NCA(I)	= incidence angle denoted by I (note: not to be confronted with NC(I) from CLOUDX)
CPLA(I,J)	= 'Cloud' parameter C at incidence angle denoted by I, at frequency denoted by J
GSA(I,J)	= 'Cloud' parameter G at incidence angle denoted by I, at frequency denoted by J
DPLA	= 'Cloud' parameter D at frequency denoted by J
KSA	= 'Cloud' parameter K at frequency denoted by J

I = counter to denote angle of incidence, read from data file:

I :	1	2	3	4	5
Incidence angel:	20°	30°	40°	50°	60°

J = counter to denote frequency, read from data file:

J :	1	2	3	4	5	6
Frequency :	L	S	C	X	Ku1	Ku2

And specifically for winter wheat:

MCVEG	= water content vegetative layer in canopy; %
MCEAR	= water content ear layer in canopy; %
PLWVEG	= amount of water in the vegetative layer of the canopy (W1); kg/m^2
PLWEAR	= amount of water in the ear layer of the canopy (W2); kg/m^2
CVEGA(J)	= 'Cloud' parameter C1, at frequency denoted by J
CEARA(I,J)	= 'Cloud' parameter C2 at incidence angle denoted by I, at frequency denoted by J
DVEGA(J)	= 'Cloud' parameter D1, at frequency denoted by J
DEARA(J)	= 'Cloud' parameter D2, at frequency denoted by J

Note that the simulated output, i.e. the radar backscatter, is given in dB!

5 Running the model

The combined growth and remote sensing model is called 'FLEVO'; SBFLEVO being the version for sugar beet, and WWFLEVO the version for winter wheat. A schematic presentation of the model components is given in Figure 16. The main module is SUCROS, which calls a total of nine subroutines. The complete listings of SBFLEVO and WWFLEVO are given in the appendices I and II respectively.

In the first part of SUCROS, called initialization, model parameters (of SUCROS and of the remote sensing subroutines) are read from the data file FLEVO.IN (note: SBFLEVO.IN or WWFLEVO.IN; the same applies to the other files). Weather data (FLEVOYEAR) are read from the weather file that is specified in the last record of FLEVO.IN.

In the second part of SUCROS, called 'dynamic part', the actual simulation of crop growth takes place. The subroutines ASTRO, TOTAS, ASSIM and GLA are used to calculate diurnal radiation characteristics, daily total gross assimilation and daily increases of leaf area index (LAI). The subroutine LINT performs linear interpolation. The integration of the calculated rate variables and the partitioning of assimilates to the various plant organs is performed in the main module SUCROS. The subroutines CLOUDX and CLOUDM calculate the radar backscatter from the simulated crop, and the subroutine REFLEX calculates the optical reflection and some Vegetation Indices (VI's). The model parameters for these subroutines are also read in the main module from the file FLEVO.IN.

Three output files are produced by the subroutine PRINT: FLEVO.BIO, FLEVO.REF and FLEVO.RAD. FLEVO.BIO contains crop variables; FLEVO.RAD contains simulated radar backscatter and FLEVO.REF contains simulated optical reflectance and Vegetation Indices. All output is given with a certain interval (standard: 5-day) for the whole growing season. While running the program, output is also send to the screen on a daily basis to check the simulation: TIME, TADRW, LAI, COVER, WDVI.

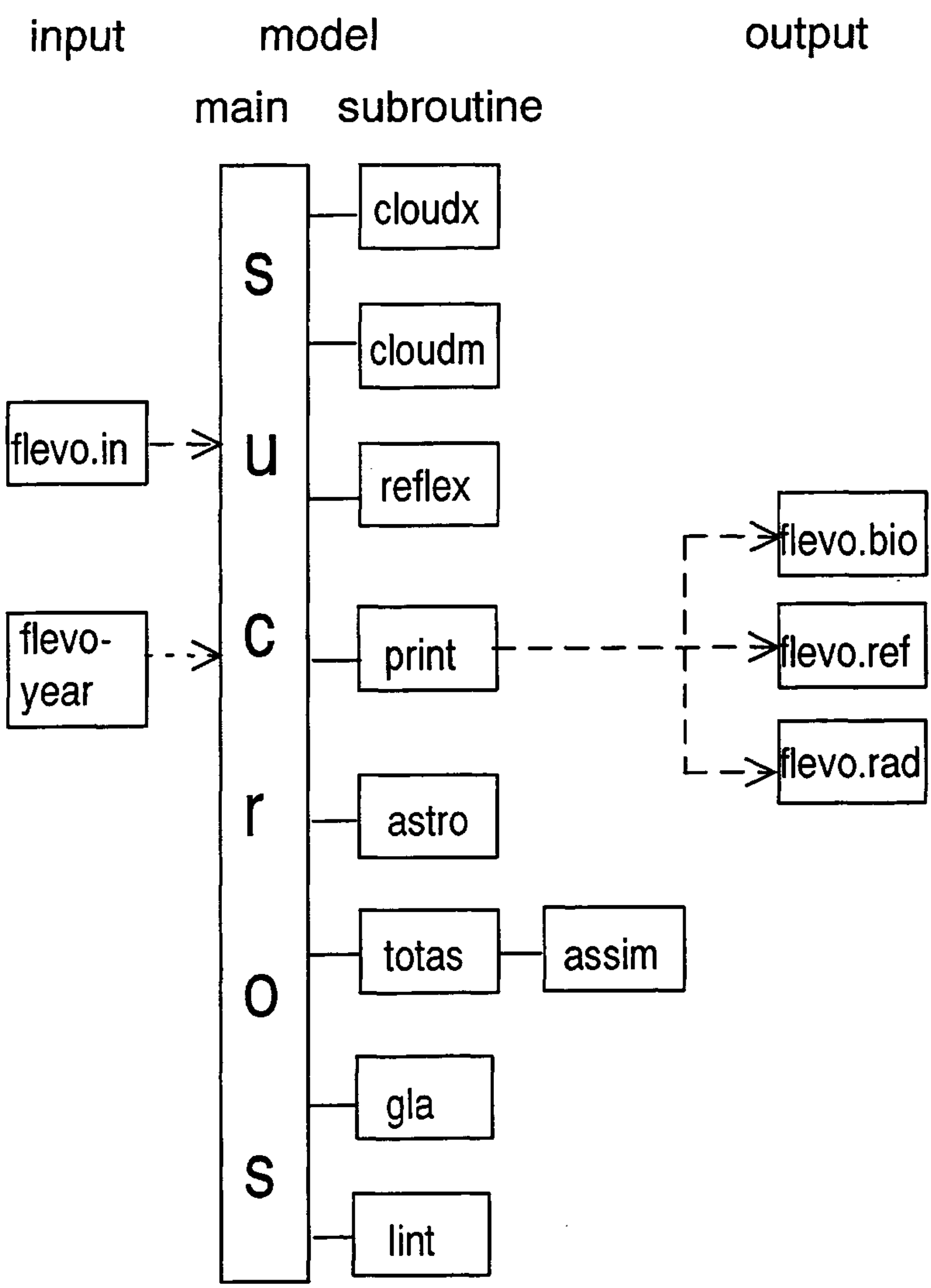


Figure 16. Structure of the model FLEVO: input files FLEVO.IN and FLEVOYEAR; main module SUCROS; subroutines and functions CLOUDX, ..., LINT; output files FLEVO.BIO, FLEVO.REF and FLEVO.RAD.

5.1 Controlling the input

A number of parameter values have to be specified in the data file FLEVO.IN for each simulation. For sugar beet, the date of sowing (DAYSOW) and the date of harvest (FINTIM) has to be given. In Flevoland, these dates are generally between day 80-120 and day 280-305 respectively (though exceptions may occur). Note that the specified day to start the simulation (TIME) should always be lower than the specified date of sowing. For winter wheat, no date of sowing has to be specified since the simulation of crop growth starts at the first calendar day (TIME = 1). The simulation stops when the development of the crop is completed (at development stage 2), or when a specified harvest date (FINTIM) is reached (whichever comes earlier).

The weather data file to be read is specified in the last record of the FLEVO.IN file. Weather data are supplied for six years, from 1987 to 1991: WEER87, WEER88, ... or WEER91. The data from 1987 to 1989 were recorded by the weather station Lelystad in Flevoland, and the data from 1990 to 1991 were recorded by the station Wageningen. There is no great difference between the weather data of these two stations, and the Wageningen data from 1990-1991 can freely be used to simulate crop production in Flevoland. Of course, any user of the model can create own weather files for the year he/she wishes to run the model.

To calculate the radar backscatter of the soil underneath the crop, input for soil moisture has to be supplied in FLEVO.IN. Either actual measurements or hypothetical data can be entered.
An example to illustrate the data structure is as follows:
"6 data IMST, soil moisture content" (*This number refers to the number of data that will be given below*)
"0. 10.0 150. 25. 365. 10.0" (*day number 0, soil moisture content 10%, day number 150, soil moisture content 25%, day number 365, soil moisture content 10%*)
The number of data pairs that can be entered is unlimited, so, in principle, everyday measurements can be entered.

All other parameters that are given in FLEVO.IN are fixed parameters that were derived from literature and from calibration of the model(components) on data collected in Flevoland (see the previous chapters). Deviating parameter values may be chosen for specific studies such as sensitivity analyses. For example, the number of plants NPL may be changed to study the effect of plant density on simulated biomass, reflectance and radar backscatter.

5.2 Controlling the output

As a standard, the following output is written to file by the subroutine PRINT.
For sugar beet:
FLEVO.BIO: TIME, WTUBER, TUBER, TADRW, COVER

For winter wheat:
FLEVO.BIO: TIME, TADRW, WSO, WLV, COVER

And for both sugar beet and winter wheat:
FLEVO.REF: TIME, LAI, RATIO, NDVI, WDVI
FLEVO.RAD: TIME, LHH40, CHH40, Ku1HH40, XVV40

The abbreviations of the output of FLEVO.BIO and FLEVO.REF is explained in Chapters 2 and 3. The output of FLEVO.RAD means:

```
LHH40   = L-band radar backscatter, HH polarization
CHH40   = C-band radar backscatter, HH polarization
Ku1HH40 = Ku1-band radar backscatter, HH polarization,
          (all three bands from DUTSCAT)
XVV40   = X-band radar backscatter, VV polarization,
          (X-band from ground-based ROVE)
All output is given for 40° incidence angle (hence the suffix '40').
```

In principle, the output to these three files can be freely changed to any variable that is given behind brackets in the PRINT-call. One should note that the names of the output columns are already given in the 'initialization' part of the main module SUCROS, and that these should be changed accordingly. The number of columns may also be changed, and in that case, the format of the output file should be changed accordingly.

When output is required that is not specified in the PRINT-call, the required output can be added behind brackets in the PRINT-call.

(Note: When changes are made to the PRINT routine, the FORTRAN model should be compiled and linked anew).

The interval at which output is written during simulation is controlled by the value for PRDEL that is specified in FLEVO.IN. This value can be set to any value between 1 and 365.

6 Model validity

Crop growth
SUCROS simulates potential production; that is the accumulation of dry matter under ample supply of water and nutrients, in an environment that is free from pests and diseases. In most actual field situations, conditions for potential production are rarely met. Flevoland, however, is an area where growing conditions are generally favourable for potential production. Water shortage is rarely a problem, and farmers apply (more than) sufficient fertilizers and pest, disease and weed control measures. On the average, yields in Flevoland reach potential production levels. In the calibration and validation years 1987 and 1988, SUCROS gave fairly reasonable simulations of actual crop growth and development. The results were better for sugar beet than for winter wheat (see Chapter 2, Figures 5 and 6). For winter wheat, the calibration of the model components for the distribution of assimilates to the various plant organs and for the yellowing of the leaves was troublesome. This resulted in relatively less accuracy in the modelling of the LAI (Figures 5b and 6b). Better results were obtained when the calibration was performed for 1987 and 1988 separately but this resulted in different values of the model parameters that govern assimilate distribution and leaf yellowing. [The distribution of assimilates has been recognized as a relatively weak point in SUCROS; Spitters & van Keulen, 1990).

Optical reflectance
The relationships between LAI and canopy reflectance as expressed in the Weighted Difference Vegetation Index, modelled in EXTRAD and in the LAI-WDVI metamodel, were very stable. Even in data sets in other environments, with different cultivars, soil types and growing conditions, the same relationships were applicable (Uenk et al., 1992). The calculation of the WDVI corrects measured reflectance values sufficiently well for 'disturbing' factors such as changing illumination conditions, leaf angle distributions, soil moisture contents and leaf optical properties (see also Bouman, 1991).

For wheat, it should be noted that the empirical linear line segments (Chapter 3.3) gave better descriptions between LAI and WDVI than EXTRAD or the LAI-WDVI metamodel. Probably this is due to the fact that a fixed leaf angle distribution throughout the growing season is assumed in the latter models, while in reality it changes (it changes more than the calculation of WDVI can correct for). Also, the layer of ears (ear area index) is not accounted for in these models.

Radar backscatter
The 'Cloud' model calculates the radar backscatter of the crop from the driving variables canopy water and soil moisture. The main shortcoming of this model is that the effect of canopy structure is not accounted for (it is implicitly included in the model parameters C and D). Recent studies have indicated the important role that canopy structure can have on radar backscatter. Especially for cereals, the azimuthal orientation of ears and stalks, the width and erectness of the flag leaves, and the 'compactness of the canopy were found to affect C- to Ku2-band radar backscatter (Bouman and van Kasteren, 1990b; Bouman and Hoekman, 1992). As a result, the measured variability in radar backscatter of winter wheat fields is relatively large and can not be properly modelled with 'Cloud'. On the other hand, for sugar

beet with its large and broad leaves and with a relatively uniform canopy architecture throughout the growing season, the effect of canopy structure (of a normally developing crop) on radar backscatter is relatively small (Bouman and van Kasteren, 1990a). Thus, the interpretation of simulated radar backscatter with 'Cloud' should be done with caution. The model only explains variation in radar backscatter that can be attributed to variation in canopy water and soil moisture, whereas in reality, much variation in radar backscatter is caused by variation in canopy (and soil surface) structure.

The 'quality' of the simulations of the radar backscatter also depends on the accuracy of the radar data that were used in the calibration of the 'Cloud' model. It should be noted that the ground-based X-band radar data, used to calibrate the subroutine CLOUDX (paragraph 4.1) had an accuracy of about 0.5 dB (Bouman and van Kasteren; 1990a), whereas the airborne DUTSCAT radar data, used to calibrate the subroutine CLOUDM (paragraph 4.2) had an accuracy of about 2 dB (Bouman and Hoekman, 1992 *in press*). Moreover, the quality of the DUTSCAT measurements in 1988 was affected by some technical problems during recording (Bouman et al., 1990b). Especially the X-band data should be labelled 'suspicious' (and hence the X-band simulations with CLOUDM).

7 Simulation results 1991

The models SBFLEVO and WWFLEVO were run to simulate crop growth and remote sensing signals of sugar beet and winter wheat in Flevoland with weather conditions of 1991. These simulations are meant to support, and to help interpret the optical and radar remote sensing data collected with the ERS-1 and with the airborne instruments during the Maceurope-91 campaign.
The simulated yields were compared with actually obtained yields from ten farmers.

7.1 Simulations for sugar beet

First, the simulations were performed for a hypothetical, average sugar beet crop with a sowing date of day number 105 (April 15) and a harvesting date of day number 295 (October 22). The radar backscatter was simulated with a volumetric moisture content of the top soil of 5%, 20% and 35%.

The simulation results are depicted in Figures 17 and 18. In Figure 17a, the simulation of dry canopy biomass and of fresh tuber weight (harvested product) is given; in 17b the simulation of soil cover and of LAI; in 17c the simulation of the optical vegetation indices NDVI and WDVI; and in 17d the simulation of radar backscatter at 40° in the L-, C-, X- and Ku1-band, with a top soil moisture content of 5%. In Figure 17d, one can note that the difference in radar backscatter between bare soil and the fully grown beet canopy is relatively small in the C-band (ERS-1 configuration), whereas this difference is relatively large in the L-band (JERS-configuration). [This relatively small contrast between bare soil and fully grown crops in the C-band was also noticed in radar images collected during the Agriscatt 1987 campaign; Hoekman and Bouman, 1992 *in press*)]. The effect of soil moisture content on the radar backscatter is given in Figure 18. With increasing soil moisture content, the difference in radar backscatter between bare soil and the fully grown beet canopy decreases in all frequency bands. In the C-band (ERS-1 configuration) there is even no difference when the soil moisture content has reached some 35%.

In the framework of the ERS-1 and the Maceurope-91 1991 campaign in Flevoland, ten farmers were interrogated on the actually obtained yields of a number of crops (as well as the dates of sowing and harvesting; Bücker et al., 1992). For sugar beet, the yields are tabulated in Table 1 and the average yield is compared with the simulated yield of the hypothetical, average beet crop. The average yield was underestimated by 14.3 ton/ha, which is an error of some 19%. The average growing season was taken a little too short; the sowing date was set seven days too late and the harvesting date six days too early. Next, SBFLEVO was run again with actual sowing and harvesting dates of all ten farmers. The simulated beet yields are given in Table 2. Now, the underestimation of the average yield is reduced to 6.2 tonne/ha, which is an error of about 8.3%. It should be noted, however, that for practical yield prediction, no information on actual sowing and harvesting dates is generally available (it should be useful if these dates could be derived from remote sensing observations).

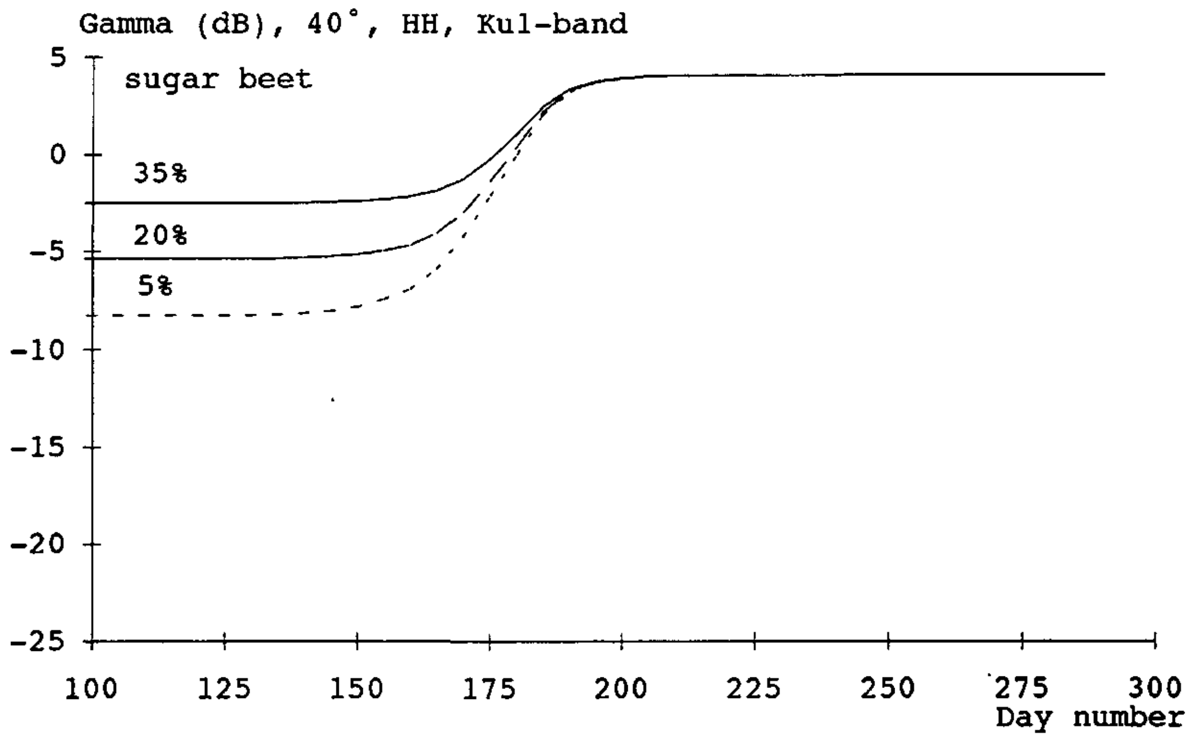


Figure 18c. Simulated Ku1-band radar backscatter in HH polarization, at 40° incidence angle, with 5%, 20% and 35% soil moisture content; sugar beet in Flevoland, 1991 growing season.

7.2 Simulations for winter wheat

For winter wheat, the simulations were performed for a hypothetical, average crop with harvesting at a development stage of 2.0. The radar backscatter was again simulated with a volumetric moisture content of the top soil of 5%, 20% and 35%. The simulation results are depicted in Figures 19 and 20. In Figure 19a, the simulation of dry canopy biomass and of dry grain weight (harvested product) is given; in 19b the simulation of soil cover and of LAI; in 17c the simulation of the optical vegetation indices NDVI and WDVI; in 19d the simulation of radar backscatter at 40° in the X-band; and in 19e the simulation of radar backscatter at 40° in the L-, C-, and Ku1-band (all with a top soil moisture content of 5%). In Figure 19a and 19b, a small horizontal plateau occurs in the curves of biomass, cover and LAI between days 106-111. These days, the respiration of the crop was equal to the gross photosynthesis so that the net photosynthesis, and thus crop growth, was zero. In Figure 19e, it is seen that in the 'high' radar frequency bands C to Ku2, the difference in radar backscatter between bare soil and the fully grown wheat canopy was very small, especially in the C-band (ERS-1). The characteristic decrease in radar backscatter with ear formation found in the ('ground-based') X-band (Figure 19d; Bouman and van Kasteren, 1990b) is not found in the ('airborne') C- and

Ku2-band (Figure 19e). In the L-band (JERS-1), the difference in radar backscatter between bare soil and the fully grown wheat canopy was relatively large.

Figure 20 illustrates the effect of soil moisture on the simulated radar backscatter. Like for sugar beet (see above), the radar backscatter from the bare soil increased with increasing soil moisture content in all frequency bands. The increase in radar backscatter was most dramatic in the L-band (Figure 20a) where the difference in radar backscatter between bare soil and the fully grown wheat canopy disappeared at 35% soil moisture content. The sensitivity of the radar backscatter of a fully grown wheat canopy to soil moisture in the C-band (Figure 20b) is surprising and could be an artefact caused by calibration of CLOUDM on dubious C-band DUTSCAT radar data.

In Table 3, the simulated average yield and harvesting date of winter wheat is compared to the actually obtained yields and harvesting dates of the ten interrogated farmers. The average grain yield is overestimated by 1.5 tonne/ha, which is an error of about 17%. The average actual harvesting date is 12 days later than the simulated harvesting date at development stage 2.0. Since simulations can not continue after development stage 2.0 (which indicates a phenologically ripe crop that does not grow any more), simulations up to the actual harvesting dates were not carried out.

Table 3. Simulated average grain yield and harvesting date, and actually obtained grain yields and harvesting dates of winter wheat of ten farmers in Flevoland in the 1991 growing season.

Farmer	Yield t/ha	Harvesting date
1	11.1	231
	8.7	231, 234
	8.9	234
2	10.5	232
	8.8	233
3	7.8	222
4	8.2	231
5	7.8	227
	8.9	229
6	8.1	234
7	9.0	202
	9.2	203
8	7.5	258
	7.5	258
9	8.6	232
	8.5	236
10	-	-
Average	8.7	231
Simulated	10.2	219

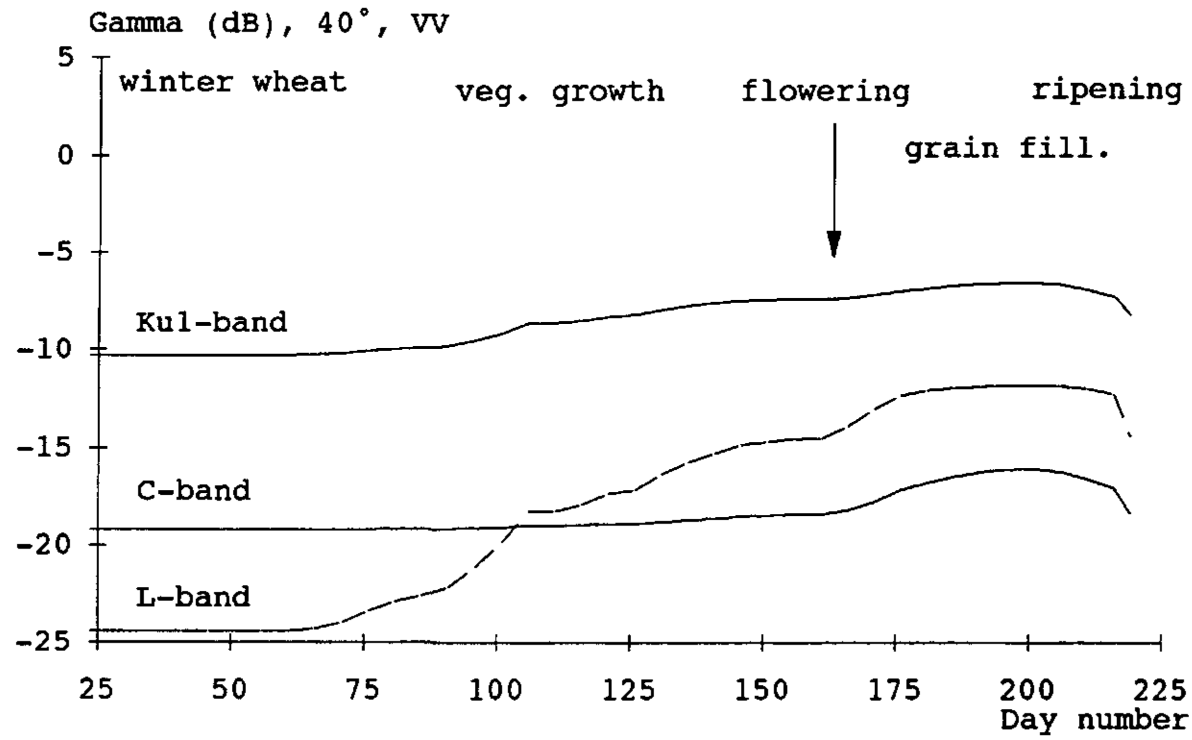


Figure 19e. Simulated L-, C- and Ku1-band radar backscatter in VV polarization, at 40° incidence angle (with CLOUDM) of sugar beet in Flevoland in the 1991 growing season. Soil moisture content is 5%.

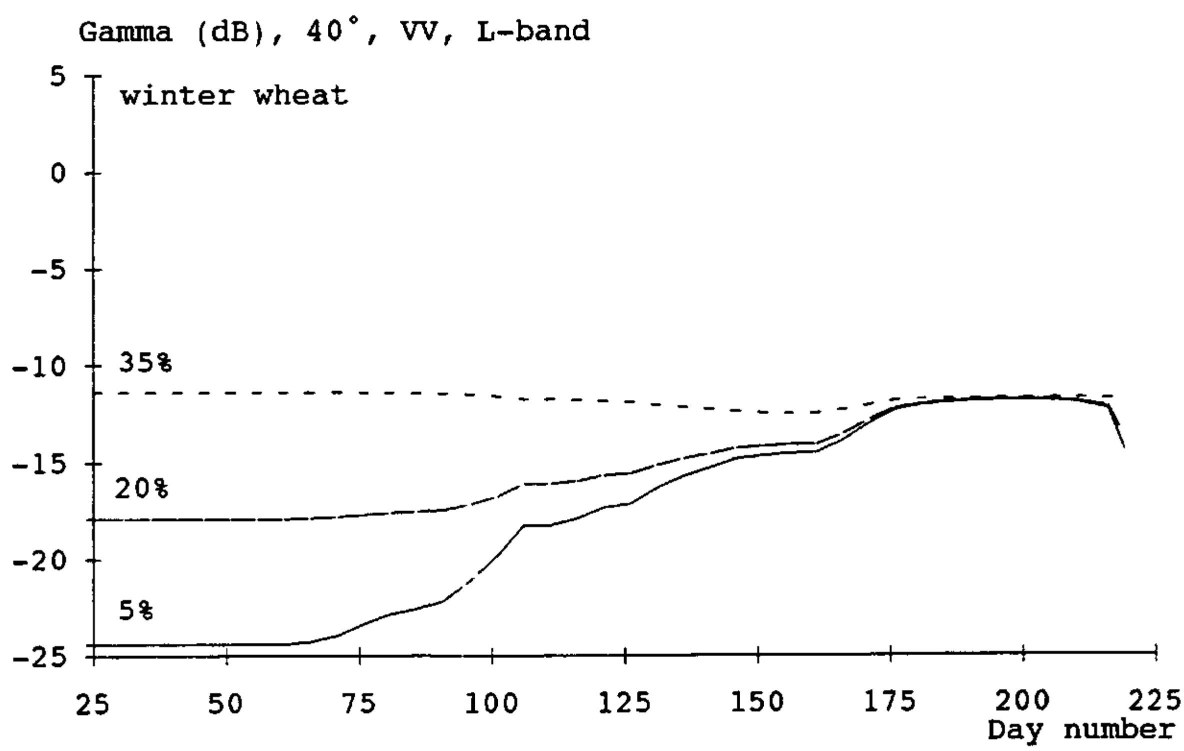


Figure 20a. Simulated L-band radar backscatter in VV polarization, at 40° incidence angle, with 5%, 20% and 35% soil moisture content; winter wheat in Flevoland, 1991 growing season.

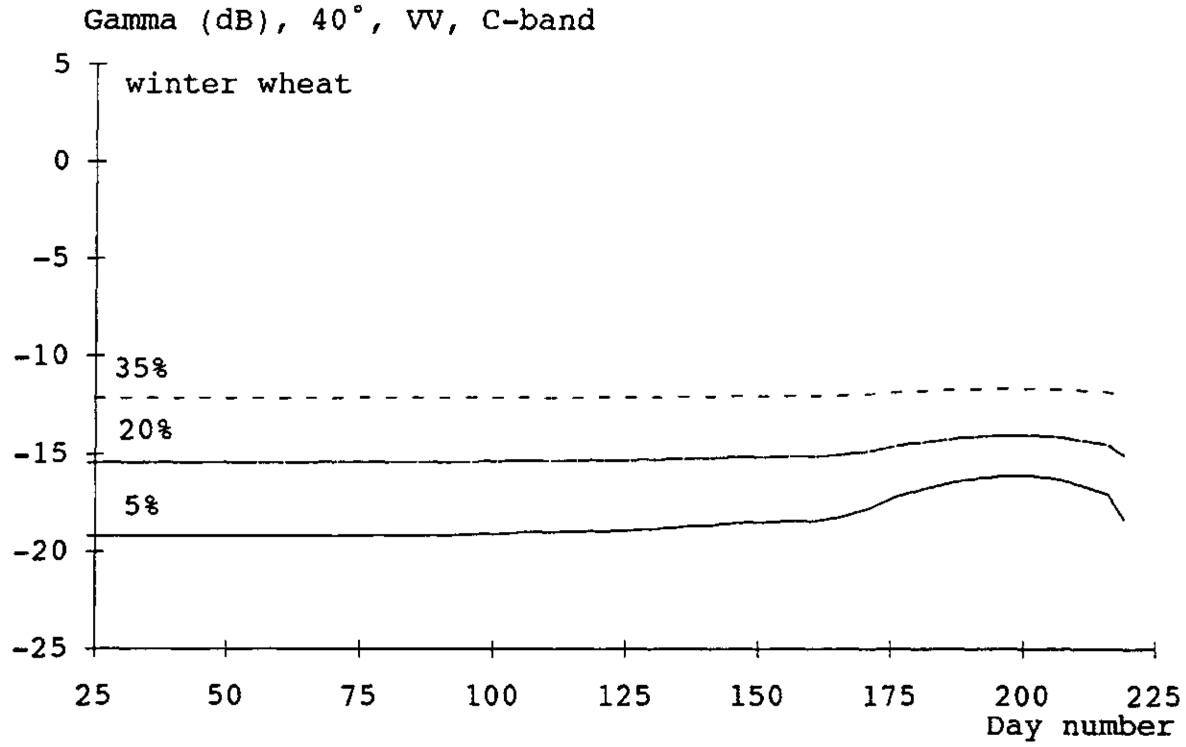


Figure 20b. Simulated C-band radar backscatter in VV polarization, at 40° incidence angle, with 5%, 20% and 35% soil moisture content; winter wheat in Flevoland, 1991 growing season.

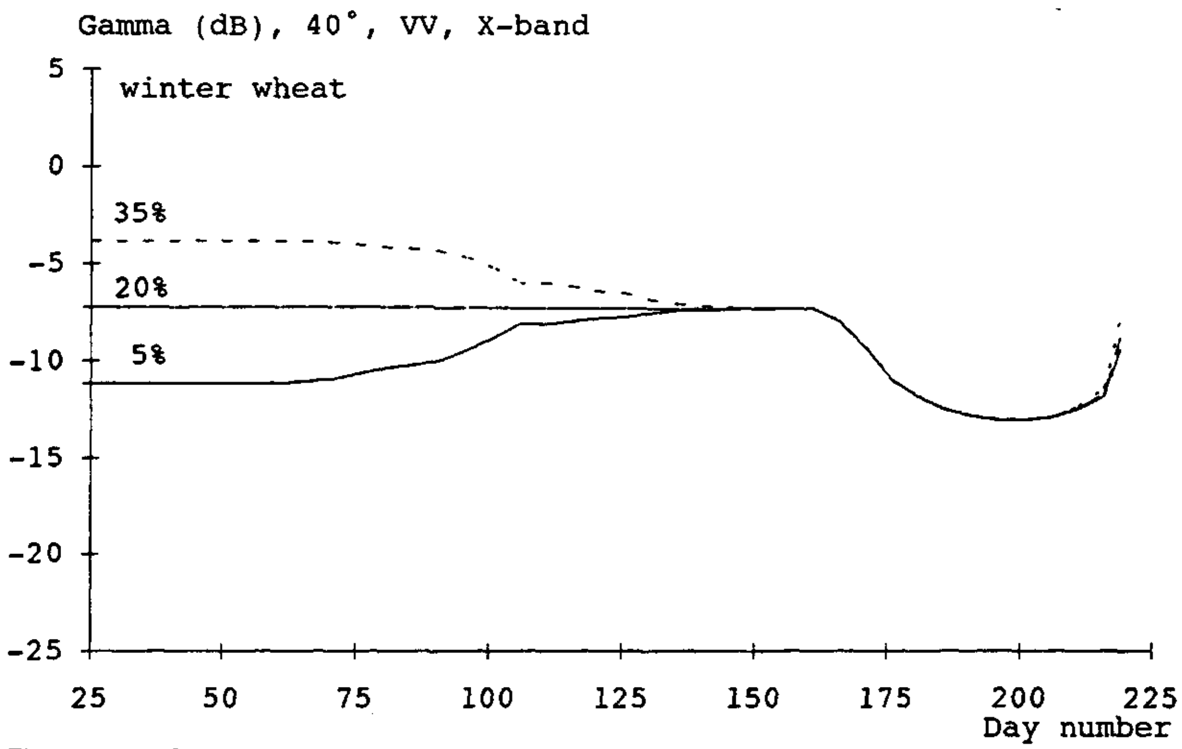


Figure 20c. Simulated X-band radar backscatter in VV polarization, at 40° incidence angle, with 5%, 20% and 35% soil moisture content (CLOUDX); winter wheat in Flevoland, 1991 growing season.

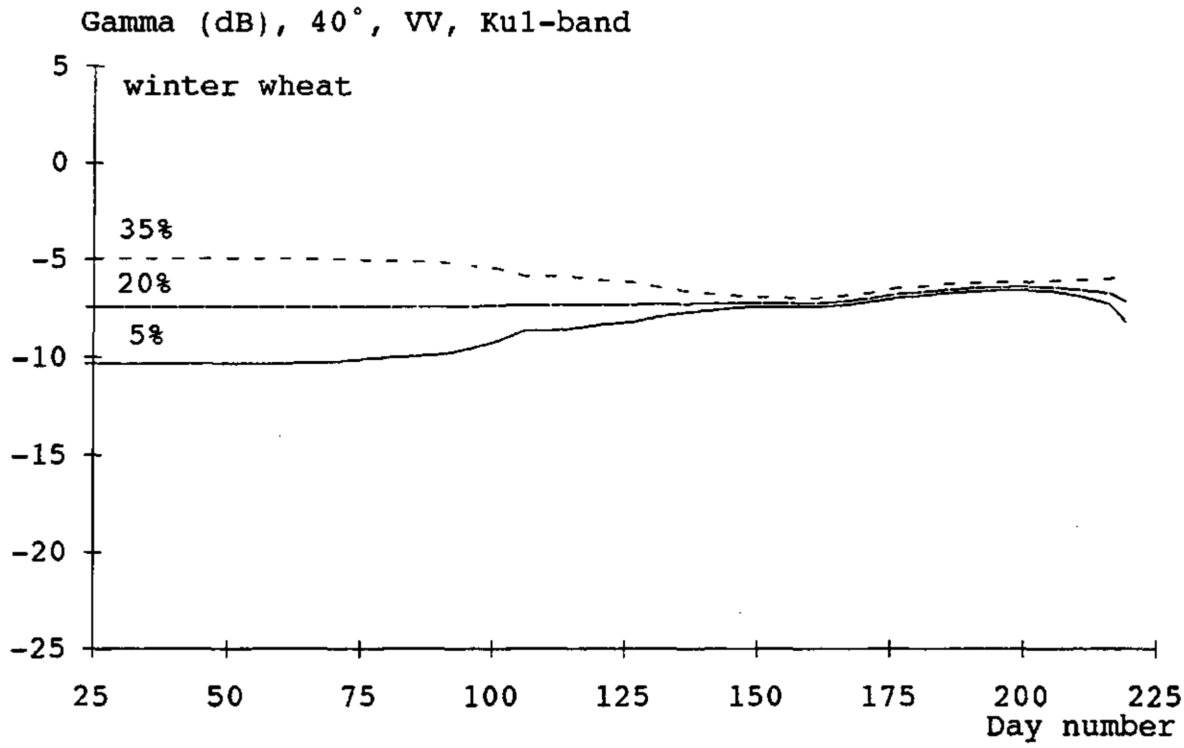


Figure 20d. Simulated Ku1-band radar backscatter in VV polarization, at 40° incidence angle, with 5%, 20% and 35% soil moisture content; winter wheat in Flevoland, 1991 growing season.

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APPENDICES

The appendices I and II contain the listings of the FORTAN programmes SBFLEVO and WWFLEVO together with the listings of the input files:

I.1 SBFLEVO.IN
I.2 SBFLEVO.FOR
II.1 WWFLEVO.IN
II.2 WWFLEVO.FOR

Appendix I.2 gives the complete listing (main module with all subroutines and functions) of the FORTRAN programme for sugar beet. Appendix II.2 only gives the listing of the main module and of the subroutines CLOUDX and CLOUDM for winter wheat. All other subroutines and functions called are the same as those in SBFLEVO for sugar beet (appendix I.2).

APPENDIX I.1 SBFLEVO.IN

APPENDIX I.1 SBFLEVO.IN

Inputfile with crop data and remote sensing-model data (optical and radar) for the SUCROS growth model SBFLEVO for sugar beet in Flevoland.

The text in italic does not make part of the real inputfile, but are comments for clarification.

** General crop data, sugar beet*
52.000 LATitude (The Netherlands)
9.000 NPL, number of plants per m^2
.845 LA0, initial leaf area per plant in cm^2
105.000 TEMERG, tempsum before emergence
.0156 RGRL, relative growth rate per degreeday of leaf area
4.500 LSHAD, LAI above which death of leaf due to shading
2.000 TBASE, base temperature
.0020 SLA, specific leaf area
1.2500 AMX, Amax in μg CO_2 $m^{-2}s^{-1}$
.0125 EFF, light use efficiency in μg J^{-1}(PAR absorbed)
.690 KDIF, extinction coefficient diffuse PAR
.58 KCOVER, extinct. coeff. to calculate soil cover
.200 SCV, scattering coefficient visible light
2.000 Q10
.003 MAINSO, maintenance coefficient of storage organs (d^{-1})
1.290 ASRQSO, assimilate requirement to grow storage organs
.130 RDSTLV, fraction redistributed of dying leaves
0.36 RDSTST, fraction redistributed of dying petioles

** Soil moisture content data for 'Cloud' model for radar backscatter: first number=daynr, second=moist.content(%), third=daynr, fourth = moist. content(%), etc. Number of data is not limited, number is given as first figure (here: 4).*
4 data IMST, soil moisture content
0. 5.0 365. 5.0

** Crop data on temperature effects and assimilate partitioning*
10 data AMDVST, relative effect of temperature sum on Amax
.000 .500 500.000 1.000 700.000 1.000 1700.000 .800
3000.000 .600
16 data AMTMPT, relative effect of temperature on Amax
-10.000 .010 3.000 .010 10.000 .750
15.000 1.000 20.000 1.000 26.000 .750
33.000 .010 45.000 .010
10 data FSHTB, partitioning to shoot growth
.000 .800 400.000 .700 900.000 .520
901.000 .220 3000.000 .220
10 data FLVTB, partitioning of shoot growth to leaves
.000 .650 370.000 .650 665.000 .440
820.000 .290 3000.000 .290
10 data FSTTB, partitioning of shoot growth to petioles

```
    .000    .300  370.000    .300  665.000    .470
   820.000  .610  3000.000    .610
10  data    FCRTB, partitioning of shoot growth to crown
    .000    .050  370.000    .050  665.000    .090
  820.000    .100  3000.000   .100
12  data    FRTTB, partitioning of below ground growth to fibrous roots
   0.000    1.0    400.     1.    500.     0.5
 1000.     0.1   2000.     0.03  3000.     0.03
* further crop data
10  data    RDRT, relative death rate
   0.      0.    600.     0.    1000.     .00022
 1500.     .00050  2500.    .00075
10  data    BDMPT, dry matter percentage of beets
   0.      .135   800.    .135   1150.    .160
 2000.     .242   2500.    .242
```

** RADAR BACKSCATTER*

** Input data for 'Cloud' model for X-band radar backscatter. First the angles of incidence are given; then the G-parameters per angle of incidence; and then the C-parameters per angle of incidence. Finally K, D and the plant water content. Data derived from ground-based X-band, VV polarisation, ROVE measurements 1980 on De Schreef in Flevoland.*

```
8 data INC, incidence angles measured radar backscatter NC
10. 20. 30. 40. 50. 60. 70. 75.
8 data IGS, soil parameter G cloud ROVE-1980, VV
0.525 0.174 0.120 0.095 0.076 0.065 0.055 0.042
8 data ICPL, plant parameter C cloud CPL ROVE-1980, VV
1.060 1.190 1.200 1.150 1.170 1.150 0.980 0.930
0.06 KS
0.46 DPL-1980 (ROVE, VV)
90.83 PLWC
```

** Input data for 'Cloud' model for L-,S-,C-,X-,Ku1- and Ku2-band radar backscatter. Data derived from airborne, HH polarisation, DUTSCAT measurements during Agriscatt 1988 in Flevoland. First the angles of incidence are given:*

```
20. 30. 40. 50. 60. data incidence angles Agriscatt
```

** then, on a line the G-parameters per frequency from L- to Ku2-band, the first line being the parameters for the first angle of incidence (here 20°), the second line for the second angle of incidence, ...*

```
0.00190 0.013024 0.019637 0.125781 0.163298 0.077177
0.00085 0.009141 0.011464 0.067289 0.102148 0.074368
0.00070 0.004448 0.049184 0.034643 0.120707 0.076001
0.00082 0.003735 0.004577 0.021858 0.065574 0.070116
0.00079 0.002933 0.003907 0.025829 0.107194 0.029653
```

** then, on a line the C-parameters per frequency from L- to Ku2-band, the first line being the parameters for the first angle of incidence (here 20°), the second line for the second angle of incidence, ...*

```
.19115 .32000 .58845 1.04065 1.94800 1.37346
.12776 .27578 .50725 .83942 2.66803 1.14837
.11424 .30995 .44199 1.22765 2.57024 1.14212
```

.11386 .34963 .32138 1.13502 2.59050 1.33077
.10328 .36640 .49978 .96138 1.95570 1.20513
** then the K-parameters, per frequency,*
0.100 0.069 0.058 0.048 0.044 0.041
** and finally, the D-parameters per frequency.*
1.1025 0.2314 0.1009 0.2099 1.0000 1.0000

** CANOPY REFLECTANCE*
** Input data for the EXTRAD model to calculate canopy reflectance,*
** data derived from reflectance measurements during Agriscatt 1987*
** and 1988 in Agriscatt campaign.*
0.146 RHOSG green reflection coeff. soil ASCAT
0.166 RHOSR red reflection coefficient soil;
0.199 RHOSIR ir reflection coefficient soil; ASCAT
0.294 SCATG green scattering coeff. leaves ASCAT
0.079 SCATR red scattering coefficient leaves
0.974 SCATIR ir scattering coefficient leaves ASCAT
60. BETA solar height
0.015 0.045 0.074 0.1 0.123 0.143 0.158 0.168 0.174 F leaf angle distribution
** Input data for metamodel WDVI-LA (data also from Agriscatt):*
48.64 WMAX maximum WDVI in metamodel WDVI-LAI
0.485 WEXT extinction coefficient in metamodel WDVI-LAI

** Initialization of crop variables*
0 WLVG
0 WLVD
0 WSTG
0 WSTD
0 WSO
0 WRT
0 WCR
0 LAI
0 TSUM2
0. TSUMEM
0. EMERG
** Timer parameters*
95 DAYSOW
90. TIME
295. FINTIM
5. PRDEL
** Data file that contains the weather data*
'WEER90'

APPENDIX I.2 SBFLEVO.FOR

APPENDIX I.2 SBFLEVO.FOR

```
*-----------------------------------------------------------------
* SBFLEVO.FOR  (Bouman, 1992)
* Fortran version of SUCROS87 (Simple and Universal CROp growth
* Simulator) for sugar beet (Spitters et al., 1987).
* Changed by: J. Goudriaan, February 1988
*
* Parameters for sugar-beet collected by C.J.T. Spitters
* Version 89/04/26 by C.J.T. Spitters
* Dry weights of leaves (green and dead leaf blades), stems
* (petioles+midribs), crowns, storage organs (beets), fibrous
* roots and total recoverable biomass (kgDM/ha) as integrals of
* growth rates. Adapted to FORTRAN by: J. Goudriaan, June 1989
* Sucros87 was calibrated for Flevopolder on Agriscatt 1987
* and 1988 data by Bouman, 1990
*
* Radiation model (EXTRAD) included: Bouman, jan 1990
* Metamodel reflectance (WDVI) included: Bouman, April, 1992
* both models were calibrated on Agriscatt 1987 and 1988 data
*
* Cloud model (X-band) included; Cloud parameters from ROVE
* ground-based 1980 measurements on De Schreef, by Bouman,
* September 1989. Multi-frequency Cloud model included: Bouman,
* May, 1992; model data from van Leeuwen (1991); model calibrated
* on Agriscatt 1988
*
* VERSION WITH ACCOMPANYING WEATHER DATA FILES
*-----------------------------------------------------------------

      PROGRAM SBFLEVO

      IMPLICIT REAL (A-H,J-Z)
      IMPLICIT INTEGER (I)

      REAL AMDVST(50), AMTMPT(50), BDMPT(50)
      REAL DVRVT(50), DVRRT(50), FRTTB(50)
      REAL FSHTB(50), FLVTB(50), FSTTB(50), FCRTB(50)
      REAL RDRT(50), MST(100)
      REAL DTRT(365),TMAXT(365),TMINT(365)
      REAL NC(100),CPL(10),GS(10),ATT(10),SOIL(10),PLANT(10)
      REAL GAMMA(10)
      REAL CPLA(5,6),GSA(5,6),ATTA(5,6),SOILA(5,6),PLANTA(5,6)
      REAL GAMMAA(5,6)
      REAL NCA(5), KSA(6),DPLA(6)
      REAL F(9),BU(9)

      CHARACTER*9 FLEVOYEAR
```

```
      PARAMETER (PI=3.1415926)

      DATA BU/.03015,.08682,.13302,.16318,.17365,
     $        .16318,.13302,.08682,.03015/

************************************************************************
*     INITIALISATION                                                   *
************************************************************************

*-----open datafile crop parameters
      OPEN(20,FILE='SBFLEVO.IN',STATUS='OLD')
      READ(20,*) LAT
      READ(20,*) NPL
      READ(20,*) LA0
      READ(20,*) TEMERG
      READ(20,*) RGRL
      READ(20,*) LSHAD
      READ(20,*) TBASE
      READ(20,*) SLA
      READ(20,*) AMX
      READ(20,*) EFF
      READ(20,*) KDIF
      READ(20,*) KCOVER
      READ(20,*) SCV
      READ(20,*) Q10
      READ(20,*) MAINSO
      READ(20,*) ASRQSO
      READ(20,*) RDSTLV
      READ(20,*) RDSTST
*-----soil moisture data
      READ(20,*) IMST
      READ(20,*) (MST(I),I=1,IMST)
*-----further crop data
      READ(20,*) IAMDVN
      READ(20,*) (AMDVST(I),I=1,IAMDVN)
      READ(20,*) IAMTMN
      READ(20,*) (AMTMPT(I),I=1,IAMTMN)
      READ(20,*) IFSHN
      READ(20,*) (FSHTB(I),I=1,IFSHN)
      READ(20,*) IFLVN
      READ(20,*) (FLVTB(I),I=1,IFLVN)
      READ(20,*) IFSTN
      READ(20,*) (FSTTB(I),I=1,IFSTN)
      READ(20,*) IFCRN
      READ(20,*) (FCRTB(I),I=1,IFCRN)
      READ(20,*) IFRTN
```

```
      READ(20,*) (FRTTB(I),I=1,IFRTN)
      READ(20,*) IRDRN
      READ(20,*) (RDRT(I),I=1,IRDRN)
      READ(20,*) IBDMPN
      READ(20,*) (BDMPT(I),I=1,IBDMPN)
*-----parameters for X-band cloud model (ROVE)
      READ(20,*) INC
      READ(20,*) (NC(I),I=1,INC)
      READ(20,*) IGS
      READ(20,*) (GS(I),I=1,IGS)
      READ(20,*) ICPL
      READ(20,*) (CPL(I),I=1,ICPL)
      READ(20,*) KS
      READ(20,*) DPL
      READ(20,*) MCCROP
*-----parameters for multi-freq. cloud model
*-----Agriscatt-88; 5 inci. angles; 6 frequencies
*-----first: read incidence angles
      READ(20,*) (NCA(I),I=1,5)
*-----bare soil G-values; frequencies in line, inci. angles by row
      READ(20,*) (GSA(1,J),J=1,6)
      READ(20,*) (GSA(2,J),J=1,6)
      READ(20,*) (GSA(3,J),J=1,6)
      READ(20,*) (GSA(4,J),J=1,6)
      READ(20,*) (GSA(5,J),J=1,6)
*-----Crop C-values; frequencies in line, inci. angles by row
      READ(20,*) (CPLA(1,J),J=1,6)
      READ(20,*) (CPLA(2,J),J=1,6)
      READ(20,*) (CPLA(3,J),J=1,6)
      READ(20,*) (CPLA(4,J),J=1,6)
      READ(20,*) (CPLA(5,J),J=1,6)
*-----K-values per frequency; D-values per frequency
      READ(20,*) (KSA(J),J=1,6)
      READ(20,*) (DPLA(J),J=1,6)
*-----parameters for EXTRAD reflection calculations
      READ(20,*)RHOSG
      READ(20,*)RHOSR
      READ(20,*)RHOSIR
      READ(20,*)SCATG
      READ(20,*)SCATR
      READ(20,*)SCATIR
      READ(20,*)BETA
      READ(20,*) (F(I), I=1,9)
*-----parameters for metamodel WDVI-LAI
      READ(20,*) WMAX
      READ(20,*) WEXT
*-----Initialization of crop status; weights in kg/ha
      READ(20,*) WLVG
```

```
      READ(20,*) WLVD
      READ(20,*) WSTG
      READ(20,*) WSTD
      READ(20,*) WSO
      READ(20,*) WRT
      READ(20,*) WCR
      READ(20,*) LAI
      READ(20,*) TSUM2
      READ(20,*) TSUMEM
      READ(20,*) EMERG
      READ(20,*) DAYSOW
      READ(20,*) TIME
      READ(20,*) FINTIM
      READ(20,*) PRDEL
*-----input weather file
      READ(20,*) FLEVOYEAR
      CLOSE (20)

*-----read weather data from file
      OPEN(50,FILE=FLEVOYEAR,STATUS='OLD')
      READ(50,*) IDAYNR
      DO 5 I=1,IDAYNR
      READ(50,*) DTRT(I),TMAXT(I),TMINT(I)
5     CONTINUE
      CLOSE(50)

*-----growth rates are set to 0
      GLV   =0.
      DLV   =0.
      FDLV  =0.
      WLVD  =0.
      GST   =0.
      DST   =0.
      FDST  =0.
      GSO   =0.
      GCR   =0.
      GRT   =0.
      GLAI  =0.
      DTSUM2=0.
      DTSUMM=0.
      DEMERG=0.
      DELT = 1.
      LAI=NPL*LA0*1.E-4
*-----data to use in print subroutine
      PRTIME=TIME

*-----initialisation outputfile
      OPEN (7,FILE='SBFLEVO.BIO',STATUS='UNKNOWN')
```

```
      OPEN (8,FILE='SBFLEVO.REF',STATUS='UNKNOWN')
      OPEN (9,FILE='SBFLEVO.RAD',STATUS='UNKNOWN')
      WRITE(7,'(A22,A10)') 'Sugar beet, Flevoland,',FLEVOYEAR
      WRITE(7,'(A8,5A12)') 'TIME','WTUBER','TUBER','TADRW','COVER'
      WRITE(7,'(A)')
      WRITE(8,'(A22,A10)') 'Sugar beet, Flevoland,',FLEVOYEAR
      WRITE(8,'(A8,5A12)') 'TIME','LAI','IR/G RATIO','NDVI','WDVI'
      WRITE(8,'(A8)')
      WRITE(9,'(A22,A10)') 'Sugar beet, Flevoland,',FLEVOYEAR
      WRITE(9,'(A8,5A12)') 'TIME','LHH40','CHH40','Ku1HH40','XVV40-rove'
      WRITE(9,'(A8)')


*************DYNAMIC PART*************************************

10    CONTINUE

*-----go to end of loop if simulation is complete
      IF(TIME .GT. FINTIM-0.5*DELT) GOTO 1000

      DAY = MOD(TIME,365.)
      IDAY=INT(DAY)

*-----daily temperature ( C): maximum, minimum, average, daytime and
*     effective
      DTR=DTRT(IDAY)
      DTMAX=TMAXT(IDAY)
      DTMIN=TMINT(IDAY)

      DTR=DTR*1.E3
      DAVTMP= 0.5 * (DTMAX+DTMIN)
      DDTMP = DTMAX - 0.25 * (DTMAX-DTMIN)
      DTEFF = MAX(0.,DAVTMP-TBASE)
      TEFF  = Q10**((DAVTMP-25.)/10.)

*-----moisture content of topsoil
      MS=LINT(MST,IMST,DAY)

*-----integration of rate variables (kg/ha/day)
      WLVG  = WLVG  + (GLV-DLV)*DELT
      WLVD  = WLVD  + FDLV*DELT
      WSTG  = WSTG  + (GST-DST)*DELT
      WSTD  = WSTD  + FDST*DELT
      WSO   = WSO   + GSO*DELT
      WCR   = WCR   + GCR*DELT
      WRT   = WRT   + GRT*DELT
      LAI   = LAI   + GLAI*DELT
      TSUM2 = TSUM2 + DTSUM2*DELT
```

```
      TSUMEM= TSUMEM+ DTSUMM*DELT
      EMERG = EMERG + DEMERG*DELT

*-----summation of some state variables (weights in kg/ha)
      WLV   = WLVG + WLVD
      WST   = WSTG + WSTD
      TADRW = WLV + WST
      TUBER = WSO+WCR+WRT
      SUGAR = 0.75*WSO

*-----Beet yield (ton fresh/ha) from dry matter yield and d.m. percentage
*-----WTUBER is total 'underground'+crown; WBEET is only storage organ,
*-----in this SUCROS version, the harvested product is taken to be WTUBER!!
      BDMP  = LINT(BDMPT,IBDMPN,TSUM2)
      WTUBER = TUBER/BDMP * 1.E-3
      WBEET = WSO / BDMP  * 1.E-3

*-----Calculation of soil cover
      COVER = 1-EXP(-KCOVER*LAI)

*-----calculation of X-band radar backscatter (ground-based, ROVE)
      CALL CLOUDX(PI,MCCROP,DPL,KS,NC,GS,CPL,INC,MS,
     $         TADRW,PLWCROP,ATT,SOIL,PLANT,GAMMA)

*-----calculation of L- to Ku2-band radar backscatter (Agriscatt)
      CALL CLOUDM(PI,MCCROP,DPLA,KSA,NCA,GSA,CPLA,MS,
     $         TADRW,PLWCROP,ATTA,SOILA,PLANTA,GAMMAA)

*-----calculation of the optical canopy reflection
      CALL REFLEX(RHOSG,RHOSR,RHOSIR,SCATG,SCATR,SCATIR,BETA,
     $         F,BU,LAI,FRDIF,NADG,NADR,NADIR,NDVI,WDVI,RATIO)

*-----calculation of WDVI via metamodel
*     is WDVIM (to distinguish from WDVI calculated above)
      WDVIM=WMAX*(1-EXP(-WEXT*LAI))

*-----writing the output
      CALL PRINT (TIME,FINTIM,DELT,PRDEL,PRTIME,LAI,TADRW,WSO,
     $        TUBER,WST,WLV,WBEET,WTUBER,PLWCROP,GAMMA,NADG,
     $        NADR,NADIR,RATIO,NDVI,WDVI,WDVIM,GAMMAA,COVER)

       WRITE(*,*) TIME,TADRW,LAI,COVER,WDVI

******CALCULATION OF RATE VARIABLES*********************************

*-----emergence process begins after sowing
      IF(DAY.LT.DAYSOW)GOTO 100
      DEMERG=MAX(0.,DAVTMP-3.)
```

```
      IF(EMERG.LT.TEMERG)GO TO 100

*-----temperatures after emergence
      DTSUM2= MAX(0.,MIN(19.,DAVTMP-2.))
      DTSUMM= DTEFF


*-----relative death rates, due to temperature and shading
*-----(above LAI=LSHAD)
*      RDRV = LINT(RDRT,IRDRN,TSUM2)*DTSUM2
*-----specifically in Flevoland:
      RDRV = 0.
      RDRSH= 0.03*MAX(0.,(LAI-LSHAD)/LSHAD)
      RDR=   MAX(RDRV,RDRSH)

*-----leaf photosynthesis rate at light saturation (kg CO2/ha leaf/h)
      AMDVS = LINT(AMDVST,IAMDVN,TSUM2)
      AMTMP = LINT(AMTMPT,IAMTMN,DDTMP)
*      AMAX  = AMX * AMDVS * AMTMP
*-----specifically in Flevoland:
      AMAX = AMX * AMTMP

*-----subroutine ASTRO computes  day length and daily radiation
*     characteristics from Julian date, latitude and measured daily total
      CALL ASTRO(DAY,LAT,DTR,
     $ SC,SINLD,COSLD,DAYL,DSINB,DSINBE,ATMTR,FRDIF)

*-----subroutine TOTASS computes daily total gross assimilation (DTGA)
      CALL TOTASS(SC,DAYL,SINLD,COSLD,DSINBE,DTR,ATMTR,FRDIF,
     $   SCV,AMAX,EFF,KDIF,LAI,DTGA)

*-----conversion from assimilated CO2 to CH2O
      GPHOT = DTGA * 30./44.

*-----maintenance respiration (kg CH2O/ha/d)
      IF(WLV.GT.0) THEN
         MNDVS = WLVG / WLV
      ELSE
         MNDVS=1.
      ENDIF
      MAINTS = 0.03*WLV + 0.015*WST + 0.015*WRT + MAINSO*WSO
      MAINT  = MIN(GPHOT, MAINTS * TEFF * MNDVS)

      DLV = WLVG * RDR
      DST = WSTG * RDR

* Rate of fall of leaf blades (FDLV) and petioles (FDST) (kgDM/ha/d)
```

```
      FDLV = (1.-RDSTLV) * DLV
      FDST = (1.-RDSTST) * DST

* Redistribution of matter from dying leaves (kg CH2O/ha/d)
      REDIST = RDSTLV * DLV + RDSTST * DST

* Available carbohydrates for growth (kg CH2O/ha/d)
      AVASS = GPHOT - MAINT + REDIST

*-----fraction of dry matter growth occurring in shoots, leaves, stems,
*     storage organs and roots, petioles, crowns, fibrous roots and beets
      FSH = LINT(FSHTB,IFSHN,TSUM2)

      FLV = LINT(FLVTB,IFLVN,TSUM2)
      FST = LINT(FSTTB,IFSTN,TSUM2)
      FCR = 1. - FLV - FST

      FRT = LINT(FRTTB,IFRTN,TSUM2)
      FSO = 1. -FRT

*-----assimilate requirements for dry matter conversion (kgCH2O/kgDM)
      ASRQ = FSH *(1.46*FLV + 1.51*(FST+FCR)) +
     $        (1.-FSH)*(ASRQSO*FSO+1.44*FRT)

* Total growth rate (kgDM/ha/d) and growth rates of
* shoots (leaf blades,petioles,crowns) and below-ground parts (roots,beets)
      GTW = AVASS / ASRQ
      GSH = FSH * GTW
      GLV = FLV * GSH
      GST = FST * GSH
      GCR = FCR * GSH
      GBLW= (1.-FSH) * GTW
      GSO = FSO * GBLW
      GRT = FRT * GBLW

      GLAI = GLA (DTEFF,TSUM2,LAI,RGRL,TSUMEM,SLA,GLV,DLV,LAII,DELT)

100   CONTINUE

      TIME  = TIME  + DELT

      GO TO 10

1000  CONTINUE

      CLOSE(7)
      CLOSE(8)
      CLOSE(9)

      STOP
      END
```

```
* -----------------------------------------------------------------
* Function GLA:
* computes daily increase of leaf area index (ha leaf/ ha ground/ d)
* -----------------------------------------------------------------
      FUNCTION GLA (DTEFF,TSUM2,LAI,RGRL,TSUMEM,SLA,
     $              GLV,DLV,LAII,DELT)
      IMPLICIT REAL (A-Z)
*     during juvenile growth:
      IF ((TSUM2.LT.450.).AND.(LAI.LT.0.75)) THEN
        GLA = LAI * (EXP(RGRL*DTEFF*DELT)-1.)
*       GLA = LAII * RGRL*DTEFF*EXP(RGRL * TSUMEM)
      ELSE
*     during mature plant growth:
        GLA = SLA * (GLV - DLV)
      ENDIF
      RETURN
      END
```

```
*----------------------------------------------------------------------
*  REAL FUNCTION LINT
*  Authors: Daniel van Kraalingen
*  Date    : 28-JAN-1987
*  Purpose: This function is a linear interpolation function.  The
*           function does not extrapolate : in case of X below or
*           above the region defined by TABLE, the first
*           respectively the last Y-value is returned and a message
*           is generated.
*
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
*  name    meaning                                      units  class
*  ----    -------                                      -----  -----
*  LINT   function name, result of the interpolation      =      O
*  TABLE  A one-dimensional array with paired             =      I
*         data: x,y,x,y, etc.
*  ILTAB  The number of elements of the array             -      I
*         TABLE
*  X      The value at which interpolation should         =      I
*         take place
*
*  FATAL ERROR CHECKS (execution terminated, message)
*  condition
*  ---------
*  TABLE(I) < TABLE(I-2) , for I odd
*  ILTAB odd
*
*  No WARNINGS using the control variable IWAR are generated since
*  nobody will check IWAR after each LINT  call ; instead an X-valu
*  below TABLE(1) or above TABLE(ILTAB-1) is reported on screen
*  with a message containing the value of ILTAB and X. Further
*  information on the error is not available within this function.
*
*  No other SUBROUTINES and FUNCTIONS are called
*  No FILE's are used (error message with WRITE(*,...)... )
*----------------------------------------------------------------------
      REAL FUNCTION LINT (TABLE,ILTAB,X)
      IMPLICIT REAL (A-Z)
      INTEGER I, IUP, ILTAB
      DIMENSION TABLE(ILTAB)

*     check on odd ILTAB
      IF (MOD(ILTAB,2).NE.0) THEN
        WRITE (*,'(A,I4/,A)')
     $    ' ERROR in function LINT: ILTAB=',ILTAB,
     $    ' ILTAB must be even !'
        STOP
      END IF
```

```
      IUP = 0
      DO 10 I=3,ILTAB,2
*        check on ascending order of X-values in function
         IF (TABLE(I).LE.TABLE(I-2)) THEN
            WRITE (*,'(A,I4/,A,2F12.4,/,A,I4,A/,A)')
     $         ' X-coordinates not in ascending order at element',I,
     $         ' elements I-2 and I are',TABLE(I-2),TABLE(I),
     $         ' LINT-function contains',ILTAB,' points',
     $         ' Run deleted!'
       PAUSE
       STOP
         END IF
         IF (IUP.EQ.0.AND.TABLE(I).GE.X) IUP = I
10    CONTINUE

      IF (X.LT.TABLE(1)) THEN
         WRITE (*,'(A/A,I4,A/A,G12.4)')
     $         ' Interpolation below defined region!!',
     $         ' LINT-function contains ',ILTAB,' points,',
     $         ' Interpolation at X=',X
         LINT = TABLE(2)
         PAUSE
            GOTO 40
      END IF

      IF (X.GT.TABLE(ILTAB-1)) THEN
         WRITE (*,'(A/A,I4,A/A,G12.4)')
     $         ' Interpolation above defined region!!',
     $         ' LINT-function contains ',ILTAB,' points,',
     $         ' Interpolation at X=',X
         LINT = TABLE(ILTAB)
         PAUSE
            GO TO 40
      END IF

*     normal interpolation
      SLOPE = (TABLE(IUP+1)-TABLE(IUP-1))/(TABLE(IUP)-TABLE(IUP-2))
      LINT = TABLE(IUP-1)+(X-TABLE(IUP-2))*SLOPE

40    RETURN
      END
```

```
*-----------------------------------------------------------------
*  SUBROUTINE ASTRO
*  Authors: Daniel van Kraalingen
*  Date   : 9-Aug-1987
*  Modified by Jan Goudriaan 4 Febr 1988
*  Purpose: This subroutine calculates astronomic daylength and
*           photoperiodic daylength.
*           and diurnal radiation characteristics such as daily
*           integral of sine of solar elevation, solar constant
*           Measured daily total of global radiation is used to find
*           atmospheric transmissivity and fraction diffuse
radiation
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
*  name    meaning                                       units  class
*  ----    -------                                       -----  -----
*  DAY     Day number (Jan 1st = 1)                        -      I
*  LAT     Latitude of the site                         degrees   I
*       Measured daily total global radiation      J m-2 d-1 I
*  SC      Solar constant                              J m-2 s-1 O
*  SINLD   Seasonal offset of sine of solar height         -      O
*  COSLD   Amplitude of sine of solar height               -      O
*  DAYL    Astronomical daylength (base = 0 degrees)       h      O
*  DSINB   Daily total of sine of solar height             s      O
*  DSINBE  Daily total of effective solar height           s      O
*  ATMTR   Atmospheric transmissivity                      -      O
*  FRDIF   Fraction diffuse in global radiation            -      O
*
*  FATAL ERROR CHECKS (execution terminated, message)
*  condition
*
*  LAT > 67, LAT < -67
*
*  SUBROUTINES and FUNCTIONS called : none
*
*  FILE usage : none
*-----------------------------------------------------------------

      SUBROUTINE ASTRO (DAY,LAT,DTR,
     & SC,SINLD,COSLD,DAYL,DSINB,DSINBE,ATMTR,FRDIF)
      IMPLICIT REAL (A-Z)

*-----PI and conversion factor from degrees to radians
      PARAMETER (PI=3.141592654, RAD=0.017453292)

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

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

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

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

*-----daylength (DAYL)

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

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

*-----solar constant (SC) and daily extraterrestrial radiation (ANGOT)

      SC = 1370.*(1.+0.033*COS(2.*PI*DAY/365.))
      DSO = SC*DSINB

*-----diffuse light fraction (FRDIF) from atmospheric transmission (ATMTR)

      ATMTR = DTR/DSO
      IF (ATMTR.GT.0.75) THEN
        FRDIF = 0.23
      ELSE IF (ATMTR.LE.0.75.AND.ATMTR.GT.0.35) THEN
        FRDIF = 1.33-1.46*ATMTR
      ELSE IF (ATMTR.LE.0.35.AND.ATMTR.GT.0.07) THEN
        FRDIF = 1.-2.3*(ATMTR-0.07)**2
      ELSE
        FRDIF=1.
      END IF
      RETURN
      END
```

```
*---------------------------------------------------------------------
*  SUBROUTINE TOTASS
*  Authors: Daniel van Kraalingen
*  Date   : 10-Dec-1987
*  Modified by Jan Goudriaan 5-Febr-1988, to seconds 29-June-89
*  Purpose: This subroutine calculates daily total gross
*           assimilation (DTGA) by performing a Gaussian integration
*           over time. At three different times of the day,
*           radiation is computed and used to determine assimilation
*           whereafter integration takes place.
*
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
*  name    meaning                                       units  class
*  ----    -------                                       -----  -----
*  SC      Solar constant                              J m-2 s-1 I
*  DAYL    Astronomical daylength (base = 0 degrees      h       I
*  SINLD   Seasonal offset of sine of solar height       -       I
*  COSLD   Amplitude of sine of solar height             -       I
*  DSINBE  Daily total of effective solar height         s       I
*  DTR     Daily total of global radiation             J/m2/d    I
*  ATMTR   Atmospheric transmissivity                    -       I
*  FRDIF   Fraction diffuse in global radiation          -       I
*  SCV     Scattering coefficient of leaves for visible
*             radiation (PAR)                            -       I
*  AMAX    Assimilation rate at light saturation       kg CO2/   I
*                                                     ha leaf/h
*  EFF     Initial light use efficiency               kg CO2/J/  I
*                                                     ha/h m2 s
*  KDIF    Extinction coefficient for diffuse light              I
*  LAI     Leaf area index                              ha/ha    I
*  DTGA    Daily total gross assimilation             kg CO2/ha/d O
*
*
*  SUBROUTINES and FUNCTIONS called : ASSIM
*
*  FILE usage : none
*---------------------------------------------------------------------

      SUBROUTINE TOTASS (SC,DAYL,SINLD,COSLD,DSINBE,
     $ DTR,ATMTR,FRDIF,SCV,AMAX,EFF,KDIF,LAI,DTGA)
      IMPLICIT REAL(A-Z)
      REAL XGAUSS(3), WGAUSS(3)
      INTEGER I, IGAUSS

      PARAMETER (PI=3.141592654)

      DATA IGAUSS /3/
      DATA XGAUSS /0.1127, 0.5000, 0.8873/
```

```
      DATA WGAUSS /0.2778, 0.4444, 0.2778/


*-----assimilation set to zero and three different times of the day (HOUR)

      DTGA = 0.
      DO 10 I=1,IGAUSS
       HOUR = 12.0+DAYL*0.5*XGAUSS(I)

*-------at the specified HOUR, radiation is computed and used to compute
*       assimilation

*-----sine of solar elevation

      SINB  = AMAX1(0.,SINLD+COSLD*COS(2.*PI*(HOUR+12.)/24.))

*-----diffuse PAR (PARDIF) and direct PAR (PARDIR)

      PAR   = 0.5*DTR*SINB*(1.+0.4*SINB)/DSINBE
      PARDIF =  MIN (PAR,SINB*FRDIF*ATMTR*0.5*SC)
      PARDIR = PAR-PARDIF
       CALL ASSIM (SCV,AMAX,EFF,KDIF,LAI,SINB,PARDIR,PARDIF,FGROS)

*-------integration of assimilation rate to a daily total (DTGA)

       DTGA = DTGA+FGROS*WGAUSS(I)
10    CONTINUE

*-------to kg ha-1 d-1:
      DTGA = DTGA*DAYL*36.

      RETURN
      END
```

```
*-------------------------------------------------------------------
*  SUBROUTINE ASSIM
*  Authors: Daniel van Kraalingen
*  Date   : 10-Dec-1987
*  Modified by Jan Goudriaan 5-Febr-1988
*  Purpose: This subroutine performs a Gaussian integration over
*           depth of canopy by selecting three different LAI's and
*           computing assimilation at these LAI levels. The
*           integrated variable is FGROS.
*
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
*  name    meaning                                      units  class
*  ----    -------                                      -----  -----
*  SCV     Scattering coefficient of leaves for visible
*             radiation (PAR)                             -       I
*  AMAX    Assimilation rate at light saturation      kg CO2/    I
*                                                    ha leaf/h
*  EFF     Initial light use efficiency              kg CO2/J/   I
*                                                    ha/h m2 s
*  KDIF    Extinction coefficient for diffuse light               I
*  LAI     Leaf area index                              ha/ha     I
*  SINB    Sine of solar height                           -       I
*  PARDIR  Instantaneous flux of direct radiation (PAR) W/m2     I
*  PARDIF  Instantaneous flux of diffuse radiation(PAR) W/m2     I
*  FGROS   Instantaneous assimilation rate of         kg CO2/    O
*          whole canopy                              ha soil/h
*
*  SUBROUTINES and FUNCTIONS called : none
*
*  FILE usage : none
*-------------------------------------------------------------------
      SUBROUTINE ASSIM (SCV,AMAX,EFF,KDIF,LAI,SINB,PARDIR,
     $PARDIF,FGROS)
      IMPLICIT REAL(A-Z)
      REAL XGAUSS(3), WGAUSS(3)
      INTEGER I1, I2, IGAUSS

*-----Gauss weights for three point Gauss
      DATA IGAUSS /3/
      DATA XGAUSS /0.1127, 0.5000, 0.8873/
      DATA WGAUSS /0.2778, 0.4444, 0.2778/

*-----reflection of horizontal and spherical leaf angle distribution
      SQV=SQRT(1.-SCV)
      REFH = (1.-SQV)/(1.+SQV)
C     REFS = REFH*2./(1.+1.6*SINB)
      REFS=REFH
*-----extinction coefficient for direct radiation and total direct flux
```

```
      CLUSTF=KDIF/(0.8*SQV)
      KDIRBL = (0.5/SINB)*CLUSTF
      KDIRT=KDIRBL*SQV

*-----selection of depth of canopy, canopy assimilation is set to zero

      FGROS = 0.
      DO 10 I1=1,IGAUSS
        LAIC = LAI*XGAUSS(I1)

*--------absorbed fluxes per unit leaf area: diffuse flux, total direct
*        flux, direct component of direct flux.

        VISDF = (1.-REFS)*PARDIF*KDIF*EXP(-KDIF*LAIC)
        VIST  = (1.-REFS)*PARDIR*KDIRT*EXP(-KDIRT*LAIC)
        VISD  = (1.-SCV)*PARDIR*KDIRBL*EXP(-KDIRBL*LAIC)

*--------absorbed flux (J/M2 leaf/s) for shaded leaves and assimilation of
*        shaded leaves

        VISSHD = VISDF+VIST-VISD
        FGRSH  = AMAX*(1.-EXP(-VISSHD*EFF/AMAX))

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

        VISPP = (1.-SCV)*PARDIR/SINB
        FGRSUN = 0.
        DO 20 I2=1,IGAUSS
          VISSUN = VISSHD+VISPP*XGAUSS(I2)
          FGRS = AMAX*(1.-EXP(-VISSUN*EFF/AMAX))
          FGRSUN = FGRSUN+FGRS*WGAUSS(I2)
20      CONTINUE

*--------fraction sunlit leaf area (FSLLA) and local assimilation rate (FGL)

        FSLLA = CLUSTF*EXP(-KDIRBL*LAIC)
        FGL =FSLLA*FGRSUN+(1.-FSLLA)*FGRSH

*--------integration of local assimilation rate to canopy assimilation (FGROS)

        FGROS = FGROS+FGL*WGAUSS(I1)
10    CONTINUE
      FGROS = FGROS*LAI

      RETURN
      END
```

```
*----------------------------------------------------------------
* SUBROUTINE CLOUDX
* Calculates X-band radar backscatter from 'Cloud' model
* one-layer version for sugar beet.
*
* FORMAL PARAMETERS:
* name:       meaning:
* TADRW       above-ground dry biomass                kg/ha       I
* MS          topsoil moisture content                %(vol.)     I
* MCCROP      plant water content                     %
* GAMMA(I)    radar backscatter crop at I degrees
*             incidence angle                         dB          O
*
* LOCAL PARAMETERS
* PLWCROP     plant water of canopy                   kg/m2       O
* INC(I)      I/10 incidence angle                    degree
* CPL(I)      Cloud parameter C at I/10 incidence     -
* GS(I)       Cloud parameter G at I/10 incidence     -
* DPL         Attenuation factor D (plant)            -
* KS          Moisture coefficient K (soil)           -
*------------------------------------------------------------------
      SUBROUTINE CLOUDX(PI,MCCROP,DPL,KS,NC,GS,CPL,INC,MS,
     $       TADRW,PLWCROP,ATT,SOIL,PLANT,GAMMA)

      IMPLICIT REAL (A-H,J-Z)
      IMPLICIT INTEGER (I)

      REAL NC(100),CPL(10),GS(10),ATT(10),SOIL(10),PLANT(10)
      REAL GAMMA(10)

      RADC=PI/180.

* calculation of plant water in kg/m2
      PLWCROP = 0.0001*TADRW*MCCROP/(100.-MCCROP)

* calculation of radar backscatter
      DO 10 I=1,INC
       ATT(I)=DPL*PLWCROP/COS(RADC*NC(I))
       SOIL(I)=GS(I)*EXP(KS*MS-ATT(I))
       PLANT(I)=CPL(I)*(1.-EXP(-ATT(I)))
       GAMMA(I)=10*ALOG10(PLANT(I)+SOIL(I))
10     CONTINUE
      RETURN
      END
```

```
*----------------------------------------------------------------------
* SUBROUTINE CLOUDM
* Calculates L- to Ku2-band radar backscatter from 'Cloud' model
* one-layer version for sugar beet.
*
* FORMAL PARAMETERS:
* name:        meaning:
* TADRW        above-ground dry biomass                kg/ha      I
* MS           topsoil moisture content                %(vol.)    I
* MCCROP       plant water content                     %
* GAMMA(I,J) radar backscatter crop at I degrees
*              incidence angle, and at frequency J     dB         O
*              J=1 = L-band
*                2 = S-band
*                3 = C-band
*                4 = X-band
*                5 = Ku1-band
*                6 = Ku2-band
* LOCAL PARAMETERS
* Note that J stands for frequency!
* PLWCROP      plant water of canopy                   kg/m2      O
* NCA(I)         I/10 incidence angle                    degree
* CPLA(I,J)       Cloud parameter C at I/10 incidence    -
* GSA(I,J)        Cloud parameter G at I/10 incidence    -
* DPLA(J)          Attenuation factor D (plant)          -
* KSA(J)           Moisture coefficient K (soil)         -
*----------------------------------------------------------------------
      SUBROUTINE CLOUDM(PI,MCCROP,DPLA,KSA,NCA,GSA,CPLA,MS,
     $         TADRW,PLWCROP,ATTA,SOILA,PLANTA,GAMMAA)

      IMPLICIT REAL (A-H,K-Z)
      IMPLICIT INTEGER (I)
      IMPLICIT INTEGER (J)

      REAL CPLA(5,6),GSA(5,6),ATTA(5,6),SOILA(5,6),PLANTA(5,6)
      REAL GAMMAA(5,6)

*-----NB: 5 incidence angles and 6 frequencies in Agriscatt

      REAL NCA(5)
      REAL KSA(6),DPLA(6)

      RADC=PI/180.

* calculation of plant water in kg/m2
      PLWCROP = 0.0001*TADRW*MCCROP/(100.-MCCROP)

* calculation of radar backscatter
```

```
      SOILA(I,J)=GSA(I,J)*EXP(KSA(J)*MS-ATTA(I,J))
      PLANTA(I,J)=CPLA(I,J)*(1.-EXP(-ATTA(I,J)))
      GAMMAA(I,J)=10*ALOG10(PLANTA(I,J)+SOILA(I,J))
5     CONTINUE
10    CONTINUE
      RETURN
      END
```

```
*******************************************************************
* Radiation programme EXTRAD by Jan Goudriaan (1977)              *
* Version adapted by Bouman 1990, for calculations of reflectance *
* Calculation of nadir reflectance in G, R and IR                 *
* and calculation of reflectance ratio's  IR/GR, WDVI and NDVI    *
*                                                                 *
* FORMAL PARAMETERS:                                              *
* name:        meaning:                                           *
* RHOSG        green hemispherical reflectance coeff. soil        *
* RHOSR        red hemispherical reflectance coeff. soil          *
* RHOSIR       infrared hemispherical reflectance coeff. soil     *
* SCATG        green scattering coeff. leaves                     *
* SCATR        red scattering coeff. leaves                       *
* SCATIR       infrared scattering coeff. leaves                  *
* BETA         solar elevation angle                              *
* F            leaf angle distribution                            *
* FRDIF        fraction diffuse sky  irradiance                   *
* LAI          leaf area index                                    *
*                                                                 *
* LOCAL PARAMETERS:                                               *
* name:        meaning:                                           *
* NADG         nadir green canopy reflectance                     *
* NADR         nadir red canopy reflectance                       *
* NADIR        nadir infrared canopy reflectance                  *
* RATIO        infrared/green reflectance ratio                   *
* WDVI         weighted difference vegetation index               *
* NDVI         normalized difference vegetation index             *
*******************************************************************

SUBROUTINE REFLEX(RHOSG,RHOSR,RHOSIR,SCATG,SCATR,SCATIR,BETA,
  $        F,BU,LAI,FRDIF,NADG,NADR,NADIR,NDVI,WDVI,RATIO)

   IMPLICIT REAL(A-Z)
   INTEGER I,J,K,IS,ITER,ITERM,N,N1
   REAL BL(9),MI(9),MT(9),OAV(9),SM(9),F(9),BU(9)
   REAL PHID(9,101),PHIU(9,101)
   REAL RN(101),TPHIU(1010),TPHID(101)
   PARAMETER (PI=3.1415926)


*******************************************************************
*-----initialisation; calculations for leaf angle distribution

   FRDIR=1.-FRDIF
   LS=0.1
   IS=1+ INT(BETA*0.1)
   RAD=PI/180.
   SBL=0.
```

```
      DO 20 K=1,9
      SINB=SIN(RAD*(10.*(FLOAT(K)-0.5)))
      COSB=COS(RAD*(10.*(FLOAT(K)-0.5)))
      OAV(K)=0.
      DO 25 I=1,9
        SINL=SIN(RAD*(10.*(FLOAT(I)-0.5)))
          COSL=COS(RAD*(10.*(FLOAT(I)-0.5)))
          IF(K.GE.I)THEN
            O=SINB*COSL
          ELSE
            O=2.*(SINB*COSL*ASIN(SINB*COSL/(SINL*COSB))+
     $          SQRT(SINL*SINL-SINB*SINB))/PI
        ENDIF
*-----OAV(K) is the leaf projection into direction K:
      OAV(K)=OAV(K)+O*F(I)
25    CONTINUE
*-----Fraction intercepted MI and transmitted MT:
      MI(K)=OAV(K)*LS/SINB
      MT(K)=1.-MI(K)
*-----SBL is needed for normalization of the view factors BL(K):
      SBL=SBL+BU(K)*MI(K)
20    CONTINUE


*-----initialsiation according to leaf layers
      N=INT(LAI/LS  +0.5)
      N1=N+1

**************************************************************************
*-----loop for calculating red and IR parts of the profile

      SCAT=SCATG
      RHOS=RHOSG

10    CONTINUE

*-----initialization of radiation profile:
      DO 30 K=1,9
      DO 40 J=1,N1
      PHIU(K,J)=0.
      PHID(K,J)=0.
40    CONTINUE
      BL(K)=BU(K)*MI(K)/SBL
* diffuse radiation is distributed according to BU(K):
      PHID(K,1)=100.*BU(K)*FRDIF
30    CONTINUE
* the direct incoming component is added:
      PHID(IS,1)=PHID(IS,1)+100.*FRDIR
```

```
*************************************************************************
*----main routine for the profile calculation

*-----number of iterations depends on scattering coefficient:
    ITERM=1
    IF(SCAT.GT.0.1)ITERM=2
    IF(SCAT.GT.0.5)ITERM=5
    IF(SCAT.GT.0.9)ITERM=10
    IF(SCAT.GT.0.99)ITERM=20
    IF(SCAT*RHOS.GT.0.99)ITERM=50

    DO 2000 ITER=1,ITERM

*-----first a calculation from top to bottom:
    DO 220 J=2,N1
    INTER=0.
      DO 205 K=1,9
205      INTER=INTER + MI(K)*(PHID(K,J-1)+PHIU(K,J))
      DO 215 K=1,9
215     PHID(K,J)=PHID(K,J-1)*MT(K) +0.5*SCAT*INTER*BL(K)
220  CONTINUE

* reflected radiation at the soil surface:
    INTER=0.
    DO 225 K=1,9
225  INTER=INTER + PHID(K,N1)
    DO 230 K=1,9
230  PHIU(K,N1)=RHOS*INTER*BU(K)

* now the calculation from bottom to top:
    DO 250 J=N,1,-1
    INTER=0.
      DO 235 K=1,9
235     INTER=INTER +MI(K)*(PHID(K,J)+PHIU(K,J+1))
      DO 250 K=1,9
250     PHIU(K,J)=PHIU(K,J+1)*MT(K)+0.5*SCAT*INTER*BL(K)


2000  CONTINUE

*************************************************************************
*-----calculating the nadir reflection and reflectance, writing output

    DO 2500 LAIC=0,LAI,0.5
    J=1+INT(LAIC/LS)
    TPHIU(J)=0.
    TPHID(J)=0.
```

```
      DO 2150 K=1,9
      TPHIU(J)=TPHIU(J)+PHIU(K,J)
      TPHID(J)=TPHID(J)+PHID(K,J)
2150  CONTINUE
2500  CONTINUE

*-----calculation of reflectance values for the green, red and IR part
      IF (SCAT .EQ. SCATG .AND. RHOS .EQ. RHOSG) THEN
       RHOMG=100*TPHIU(1)/TPHID(1)
       NADG=PHIU(9,1)/BU(9)
       SCAT=SCATR
       RHOS=RHOSR
       GOTO 10
      END IF

      IF (SCAT .EQ. SCATR .AND. RHOS .EQ. RHOSR) THEN
       RHOMR=100*TPHIU(1)/TPHID(1)
       NADR=PHIU(9,1)/BU(9)
       SCAT=SCATIR
       RHOS=RHOSIR
       GOTO 10
      ELSE
       RHOMIR=100*TPHIU(1)/TPHID(1)
       NADIR=PHIU(9,1)/BU(9)
      ENDIF

*-----calculation of some reflectance ratio's
*-----1)NDVI (Tucker)
      NDVI=(NADIR-NADG)/(NADIR+NADG)

*-----2) IR/GREEN ratio
      RATIO=NADIR/NADG

*-----3)WDVI (Clevers)
      WDVI=NADIR-(RHOSIR/RHOSG)*NADG
*********************************************************************


      RETURN
      END
```

```
*********************************************************************
*      SUBROUTINE PRINT                                             *
*********************************************************************

      SUBROUTINE PRINT (TIME,FINTIM,DELT,PRDEL,PRTIME,LAI,TADRW,WSO,
     $        TUBER,WST,WLV,WBEET,WTUBER,PLWCROP,GAMMA,NADG,
     $        NADR,NADIR,RATIO,NDVI,WDVI,WDVIM,GAMMAA,COVER)

      IMPLICIT REAL(A-Z)
      REAL GAMMA(8)
      REAL GAMMAA(5,6)
      INTEGER I

      HDELT=0.5*DELT
      DELFIN=FINTIM-DELT

      IF(ABS(TIME-PRTIME) .LT. HDELT .OR.
     $  TIME .GT. DELFIN ) THEN
       WRITE(7,'(5G12.5)') TIME,WTUBER,TUBER,TADRW,COVER
       WRITE(8,'(5G12.5)') TIME,LAI,RATIO,NDVI,WDVI
       WRITE(9,'(5G12.5)') TIME,GAMMAA(3,1),GAMMAA(3,3),
     $   GAMMAA(3,5),GAMMA(4)
       PRTIME=PRTIME+PRDEL
      END IF
      RETURN
      END
```

APPENDIX II.1 WWFLEVO.IN

APPENDIX II.1 WWFLEVO.IN

Inputfile with crop data and remote sensing-model data (optical and radar) for the SUCROS growth model WWFLEVO for winter wheat in Flevoland

The text in italic does not make part of the real inputfile, but are comments for clarification.

** General crop data, winter wheat*
52.000 LATitude
210.000 NPL, number of plants per m^2
6.500 LA0, initial leaf area per plant in cm^2
156.000 TEMERG, tempsum needed to 'restart' crop growth after winter
.0070 RGRL, relative growth rate per degreeday of leaf area
0.000 TBASE, base temperature
.0020 SLA, specific leaf area
40.0 AMX, kg CO_2 $ha^{-1}h^{-1}$
.45 EFF, initial light use efficiency kg CO_2 $ha^{-1}h^{-1}$
.600 KDIF, extinction coefficient diffuse PAR
.64 KCOVER, extinct. coeff. to calculate soil cover
.200 SCV, scattering coefficient visible light
2.000 Q10
.010 MAINSO, maintenance coefficient of storage organs (d_{-1})
1.410 ASRQSO, assimilate requirement to grow storage organs
6.3E-5 EAR

** Soil moisture content for 'Cloud' model for radar backscatter: first number = daynr, second = moist.content(%), third = daynr, fourth = moist.content(%), etc. Number of data is not limited, number is given as first figure (here: 4)*
4 data IMST, soil moisture content
0. 5.0 364. 5.0

** Crop data on temp. effects and assimilate partitioning*
8 data AMDVST, relative effect of DVS on Amax
0.0 1.0 1.0 1.0 2.0 1.0 2.5 0.0
14 data AMTMPT, relative effect of temperature on Amax
-30.0 0.0 0.0 0.01 8.0 0.01 10.0 0.4 15.0 0.9 25.0 1.0 35.0 0.0
28 data FSHTB, partitioning to shoot growth
0.00 0.50 0.10 0.50 0.20 0.60 0.35 0.78 0.40 0.83 0.50 0.87
0.60 0.90 0.70 0.93 0.80 0.95 0.90 0.97 1.00 0.98 1.10 0.99
1.20 1.00 2.50 1.00
14 data FLVTB, partitioning of shoot growth to leaves
0.00 0.66 0.10 0.66 0.25 0.66 0.50 0.63 0.70 0.29 0.95 0.00
2.50 0.00
16 data FSTTB, partitioning of shoot growth to stems
0.00 0.34 0.10 0.34 0.25 0.34 0.50 0.37 0.70 0.71 0.95 1.00
1.07 0.00 2.50 0.00
6 data IDVRVN, development rate pre-anthesis
-30.0 0.0 0.0 0.0 30.0 0.0280

6 data IDVRRN, development rate post-anthesis
-10.0 0.0 0.0 0.0 30.0 0.0330

** Death reates of leaves*
8 data IRDRN, relative death rate of leaves as f of temp.
0.0 0.03 10.0 0.03 15.0 0.04 30.0 0.09
16 DATA IRDRDN, relative death rate of leaves as f of DVS
0.00 0.00 0.59 0.00 0.60 0.00 1.04 0.00 1.05 0.50
1.54 0.50 1.55 1.00 2.50 1.00

** RADAR BACKSCATTER*
** Input data for 'Cloud' model for X-band radar backscatter. Data derived from ground-based X-band, VV polarisatio, ROVE measurements 1979 on Droevendaal at Wageningen (cv. Okapi).*
** First the angles of incidence are given; then the G-parameters per angle of incidence; and then the C2-parameter (ear-layer) per angle of incidence:*
8 data INC, incidence angles measured radar backscatter NC
10. 20. 30. 40. 50. 60. 70. 75.
8 data IGS, soil parameter G cloud GS 1979
0.344 0.326 0.088 0.057 0.019 0.010 0.012 0.009
8 data ICEAR, ear parameter C cloud CPL 1979
0.101 0.048 0.039 0.040 0.054 0.079 0.130 0.172
** Moisture content as function of development stage (first number=stage, second number is moisture content, etc); first the data for the vegetative matter, then the data for the ear-layer:*
14 data IMCVN, data of moisture content vegetative matter
0.00 83.0 0.80 83.0 1.15 74.0 1.70 74.0 1.95 61.0 2.00 49.0 2.50 49.0
12 data IMCEN, data moisture content ears
0.00 69.0 1.25 69.0 1.70 58.0 1.95 40.0 2.00 15.0 2.50 15.0
** Then the last 'Cloud' parameters: K, D1 (vegetative matter), D2 (ear layer) and C1 (vegetative matter):*
0.06 KS
1.1530 DVEG, cloud parameter D for vegetative matter
2.0565 DEAR, cloud parameter D for ears
0.1850 CVEG, cloud parameter C for vegetative matter

** Input data for 'Cloud' model for the L-,S-,C-,X,Ku1, and Ku2-band radar backscatter. Data derived from airborne, VV polarisation, DUTSCAT measurements during Agriscatt 1988 in Flevoland.*
** First, the angles of incidence are given:*
20. 30. 40. 50. 60.
** the, on a line the G-parameters per frequency from L- to Ku2-band; the first line being the parameters for the first angle of incidence (here 20°), the second line for the second angle of incidence (here 30°), etc.:*
.0061 .0255 .0200 .0400 .1100 .0800
.0047 .0150 .0190 .0250 .0700 .0850
.0022 .0080 .0090 .0104 .0750 .0980
.0012 .0067 .0110 .0005 .0900 .0900
.0016 .0090 .0110 .0400 .0600 .0600

** then, on a line the C2-parameters (ear-layer) per frequency from L- to Ku2-band; the first line being the parameters for the first angle of incidence (here 20°), the second line for the second angle of incidence (here 30°), etc.:*
.0556 .4861 .2249 .1230 .3919 .2661
.0698 .2771 .2086 .1331 .4379 .2975
.0676 .2203 .1302 .1191 .4188 .2954
.0868 .1996 .1547 .1001 .4843 .3103
.1150 .3009 .2795 .2298 .3302 .3623
** then, the C1-parameters (vegetative matter) per frequency:*
.0486 .1566 .1727 .2099 .1904 .1813
** then, the D2-parameters (ear-layer) per frequency:*
2.0789 1.9799 .0717 .0009 .1491 .4810
** then, the D1-parameters (vegetative matter) per frequency:*
.2678 .0047 .0033 .5568 .5568 .5847
** then, the K-parameters per frequency:*
0.100 0.069 0.058 0.048 0.044 0.041

** CANOPY REFLECTANCE*
**Input data for the EXTRAD model to calculate canopy reflectance. Data derived from reflectance measurements during Agriscatt 1987 and 1988.*
0.134 RHOSG green reflection coeff. soil
0.145 RHOSR red reflection coefficient soil;
0.174 RHOSIR ir reflection coefficient soil;
0.341 SCATG green scattering coeff. leaves
0.123 SCATR red scattering coefficient leaves
0.960 SCATIR ir scattering coefficient leaves
60. BETA solar height
0.015 0.045 0.074 0.1 0.123 0.143 0.158 0.168 0.174 F leaf angle distribution
** Input for metamodel WDVI-LAI (data from various data sets)*
47.0 WMAX maximum WDVI
0.40 WEXT extinction coeef. in exponential WDVI-LAI relation

** Timer parameters:*
1. TIME
271. FINTIM
1.0 DELT
5.0 PRDEL
** Data file that contains the weather data*
'WEER88'

APPENDIX II.2 WWFLEVO.FOR

APPENDIX II.2 WWFLEVO.FOR

```
*----------------------------------------------------------------
* WWFLEVO.FOR BOUMAN (Bouman, 1992)
* Fortran version of SUCROS87 (Simple and Universal CROp growth
* Simulator) for spring wheat (Spitters et al., 1987). Changed by:
* Jan Goudriaan, February 1988.
* Adapted to winter wheat based on Rabbinge et al., simulation
* monographs 32, 1989. (Bouman, July 1989)
*
* Main references to the crop characteristics of wheat:
* van Keulen & Seligman (1987): AMTMPT,FSHTB,FLVTB,FSTTB,DVRVT,DVRRT
* Spitters & Kramer (1986): LA0,RGRL,SLA,FLVTB,FSTTB,EAR,DVRVT
* Groot (1987): FLVTB,FSTTB; van Keulen & de Milliano (1984): RDRT
* Calibrated for Flevoland: Bouman, June 1992
*
* Radiation model (EXTRAD) included: Bouman, Jan 1990
* model calibrated on Agriscatt 1987 and 1988 data
* Metamodel reflectance (WDV) included: Bouman, April, 1992
* Empirical relation LAI-WDVI included: Bouman, May, 1992
* Metamodel and empirical model calibrated on large number of
* experiments inside and outside Flevoland
*
* Cloud model (X-band; two-layer) included; Cloud parameters from
* ROVE ground-based 1979 measurements (cv Okapi; Hoekman et al.,
* 1982) on Droevendaal, Wageningen: Bouman, september 1989.
* Multi-frequency, two-layer Cloud model included: Bouman, June
* 1992; model parameters by van Leeuwen (1991); model calibrated on
* Agriscatt 1988 data
*
* VERSION WITH ACCOMPANYING WEATHER DATA FILES
*----------------------------------------------------------------

      PROGRAM WWFLEVO
      IMPLICIT REAL(A-H,J-Z)
      IMPLICIT INTEGER(I)
      REAL INTGRL

      REAL AMDVST(25), AMTMPT(25), DVRVT(25), RDRDST(25)
      REAL DVRRT(25), FSHTB(50), FLVTB(25), FSTTB(25)
      REAL DTRT(365),TMAXT(365),TMINT(365)
      REAL RDRT(25), MCVEGT(25), MCEART(25), MST(100)
      REAL SOIL(8),VEG(8),EARS(8),GAMMA(8),NC(8),GS(8)
      REAL CEAR(8)
      REAL GSA(5,6),CEARA(5,6),AVEGA(5,6),AEARA(5,6),ASOILA(5,6)
      REAL SOILA(5,6),VEGA(5,6),EARSA(5,6),GAMMAA(5,6)
      REAL NCA(6)
      REAL KSA(6),DVEGA(6),DEARA(6),CVEGA(6)
```

```
      REAL F(9),BU(9)

      CHARACTER*9 FLEVOYEAR

      PARAMETER (PI=3.1415926)

      DATA BU/.03015,.08682,.13302,.16318,.17365,
     $        .16318,.13302,.08682,.03015/

*****************************************************************
*    INITIALISATION                                             *
*****************************************************************

*-----open datafile crop parameters
      OPEN(20,FILE='WWFLEVO.IN',STATUS='OLD')
*-----species and field parameters
      READ(20,*) LAT
      READ(20,*) NPL
      READ(20,*) LA0
      READ(20,*) TEMERG
      READ(20,*) RGRL
      READ(20,*) TBASE
      READ(20,*) SLA
      READ(20,*) AMX
      READ(20,*) EFF
      READ(20,*) KDIF
      READ(20,*) KCOVER
      READ(20,*) SCV
      READ(20,*) Q10
      READ(20,*) MAINSO
      READ(20,*) ASRQSO
      READ(20,*) EAR
*-----soil moisture data
      READ(20,*) IMSTN
      READ(20,*) (MST(I),I=1,IMSTN)
*-----further crop data:
*-----effects of DVS and daytime temp. on AMX
      READ(20,*) IAMDVN
      READ(20,*) (AMDVST(I),I=1,IAMDVN)
      READ(20,*) IAMTMN
      READ(20,*) (AMTMPT(I),I=1,IAMTMN)
*-----dry matter distribution factors
      READ(20,*) IFSHN
      READ(20,*) (FSHTB(I),I=1,IFSHN)
      READ(20,*) IFLVN
      READ(20,*) (FLVTB(I),I=1,IFLVN)
      READ(20,*) IFSTN
      READ(20,*) (FSTTB(I),I=1,IFSTN)
```

```
*-----development and death rates
      READ(20,*) IDVRVN
      READ(20,*) (DVRVT(I),I=1,IDVRVN)
      READ(20,*) IDVRRN
      READ(20,*) (DVRRT(I),I=1,IDVRRN)
      READ(20,*) IRDRN
      READ(20,*) (RDRT(I),I=1,IRDRN)
      READ(20,*) IRDRDN
      READ(20,*) (RDRDST(I),I=1,IRDRDN)
*-----parameters for X-band cloud model (ROVE)
      READ(20,*) INC
      READ(20,*) (NC(I),I=1,INC)
      READ(20,*) IGS
      READ(20,*) (GS(I),I=1,IGS)
      READ(20,*) ICEAR
      READ(20,*) (CEAR(I),I=1,ICEAR)
      READ(20,*) IMCVN
      READ(20,*) (MCVEGT(I),I=1,IMCVN)
      READ(20,*) IMCEN
      READ(20,*) (MCEART(I),I=1,IMCEN)
      READ(20,*) KS
      READ(20,*) DVEG
      READ(20,*) DEAR
      READ(20,*) CVEG
*-----parameters for multi-frequency cloud model
*-----Agriscatt-88; 5 incidence anfles and 6 frequencies
      READ(20,*) (NCA(I),I=1,5)
*-----bare soil values; frequencies in line, i.a. by row
      READ(20,*) (GSA(1,J),J=1,6)
      READ(20,*) (GSA(2,J),J=1,6)
      READ(20,*) (GSA(3,J),J=1,6)
      READ(20,*) (GSA(4,J),J=1,6)
      READ(20,*) (GSA(5,J),J=1,6)
*-----Crop C-values (ear layer); freq. in line, i.a. by row
      READ(20,*) (CEARA(1,J),J=1,6)
      READ(20,*) (CEARA(2,J),J=1,6)
      READ(20,*) (CEARA(3,J),J=1,6)
      READ(20,*) (CEARA(4,J),J=1,6)
      READ(20,*) (CEARA(5,J),J=1,6)
*-----Crop C-values (vegetative layer), per frequency
      READ(20,*) (CVEGA(J),J=1,6)
*-----Crop D-values (ear layer), per frequency
      READ(20,*) (DEARA(J),J=1,6)
*-----Crop D-values (vegetative layer), per frequency
      READ(20,*) (DVEGA(J),J=1,6)
*-----Soil K-values, per frequency
      READ(20,*) (KSA(J),J=1,6)
*-----parameters for EXTRAD reflection calculations
```

```
      READ(20,*)RHOSG
      READ(20,*)RHOSR
      READ(20,*)RHOSIR
      READ(20,*)SCATG
      READ(20,*)SCATR
      READ(20,*)SCATIR
      READ(20,*)BETA
      READ(20,*) (F(I), I=1,9)
*-----parameters for metamodel WDVI-LAI
      READ(20,*) WMAX
      READ(20,*) WEXT
*-----timer parameters
      READ(20,*) TIME
      READ(20,*) FINTIM
      READ(20,*) DELT
      READ(20,*) PRDEL
*-----input weather file
      READ(20,*) FLEVOYEAR
*-----closing file
      CLOSE (20)

*-----read weather data from file
      OPEN(50,FILE=FLEVOYEAR,STATUS='OLD')
      READ(50,*) IDAYNR
      DO 5 I=1,IDAYNR
       READ(50,*) DTRT(I),TMAXT(I),TMINT(I)
5      CONTINUE
      CLOSE(50)

*-----initial amounts of rate and state variables
      WLVG=0.
      GLV=0.
      WLVD =0.
      DLV =0.
      WST =0.
      GST =0.
      WSO =0.
      GSO =0.
      WRT =0.
      GST =0.
      EAI =0.
      GEAI =0.
      LAIH =0.0
      GLAI =0.
      DVS =0.
      DVR =0.
      RDR =0.
      TSUMEM =0.
```

```
      DTEFF =0.

*-----initial variables to use in print-subroutine
      PRTIME = TIME
      LAII=NPL*LA0*1.E-4

*-----initialisation outputfile

      OPEN (7,FILE='WWFLEVO.BIO',STATUS='UNKNOWN')
      OPEN (8,FILE='WWFLEVO.REF',STATUS='UNKNOWN')
      OPEN (9,FILE='WWFLEVO.RAD',STATUS='UNKNOWN')
      WRITE(7,'(A25,A10)') 'Winter wheat, Flevoland',FLEVOYEAR
      WRITE(7,'(A8,5A12)') 'TIME','TADRW','WSO','WLV','COVER'
      WRITE(7,'(A)')
      WRITE(8,'(A25,A10)') 'Winter wheat, Flevoland,',FLEVOYEAR
      WRITE(8,'(A8,5A12)') 'TIME','LAIH','IR/G RATIO','NDVI','WDVI'
      WRITE(8,'(A8)')
      WRITE(9,'(A25,A10)') 'Winter wheat, Flevoland,',FLEVOYEAR
      WRITE(9,'(A8,5A12)') 'TIME','LVV40','CVV40','KU1VV40','XVV-rove'
      WRITE(9,'(A8)')

**********************************************************************
*     DYNAMIC PART                                                   *
**********************************************************************

*-----simulation loop
10    CONTINUE

*-----go to end of loop if development is complete
      IF (TIME .GT. FINTIM .OR. DVS .GT. 2.) GOTO 20

*-----simulation run specifications
      DAY = MOD(TIME,365.)
      IDAY=INT(DAY)

*-----setting daily temperatures and irradiation
      DTR=DTRT(IDAY)
      DTMAX=TMAXT(IDAY)
      DTMIN=TMINT(IDAY)

      DTR=DTR*1.E3
      DAVTMP= 0.5 * (DTMAX+DTMIN)
      DDTMP = DTMAX - 0.25 * (DTMAX-DTMIN)
      DTEFF = MAX(0.,DAVTMP-TBASE)

*-----integration of state variables:
      WLVG  = INTGRL(WLVG,GLV-DLV,DELT)
      WLVD  = INTGRL(WLVD,DLV,DELT)
```

```
      WLV   = WLVG + WLVD
      WST   = INTGRL(WST,GST,DELT)
      WSO   = INTGRL(WSO,GSO,DELT)
      WRT   = INTGRL(WRT,GRT,DELT)
      TADRW = WLV + WST + WSO
      EAI   = INTGRL(EAI,GEAI,DELT)
      LAIH = INTGRL(LAIH,GLAI,DELT)
      LAI = LAIH +  0.5 * EAI
      DVS = INTGRL(DVS,DVR,DELT)
      TSUMEM = INTGRL(TSUMEM,DTEFF,DELT)

*-----Calculation of soil cover
      COVER = 1-EXP(-KCOVER*LAIH)

*---- moisture contents vegetation
      MCVEG = LINT(MCVEGT,IMCVN,DVS)
      MCEAR = LINT(MCEART,IMCEN,DVS)

*-----moisture content topsoil
      MS=LINT(MST,IMSTN,DAY)

*-----calculation of X-band radar backscatter (ground-based, ROVE)
      CALL CLOUDX(MCVEG,MCEAR,WLV,WST,WSO,MS,PLWEAR,
     $        PLWVEG,GS,CEAR,INC,NC,DVEG,DEAR,CVEG,
     $        KS,SOIL,VEG,EARS,GAMMA,)

*-----calculation of L- to Ku2-band radar backscatter (Agriscatt)
      CALL CLOUDM(MCVEG,MCEAR,WLV,WST,WSO,MS,PLWEAR,
     $   PLWVEG,GSA,CEARA,NCA,DVEGA,DEARA,CVEGA,KSA,SOILA,
     $   VEGA,EARSA,GAMMAA)

*-----calculation of the optical canopy reflection
*-----1) via EXTRAD model
      CALL REFLEX(TIME,RHOSG,RHOSR,RHOSIR,SCATG,SCATR,SCATIR,BETA,
     $        F,BU,LAI,FRDIF,NADG,NADR,NADIR,NDVI,WDVI,RATIO)
*-----2) calculation of WDVI via metamodel
      WDVIM=WMAX*(1-EXP(-WEXT*LAIH))
*-----3) calculation of WDVI via linear line segments
      IF (LAI .GT. 4.06) THEN
        WDVIE=2.6453*(LAIH+10.44)
      ELSE
        IF (LAI .GT. 0.6) THEN
          WDVIE=7.4627*(LAIH+1.03)
        ELSE
          WDVIE=20*LAIH
        ENDIF
      ENDIF
```

```
*-----relative death rate of leaves and development rate
      IF(DVS.LT.1.) THEN
         RDR = 0.
         DVR = LINT(DVRVT,IDVRVN,DAVTMP)
       ELSE
         RDR = LINT(RDRT,IRDRN,DAVTMP)*LINT(RDRDST,IRDRDN,DVS)
         DVR = LINT(DVRRT,IDVRRN,DAVTMP)
      ENDIF

*-----output during simulation
      CALL PRINT (TIME,FINTIM,DELT,PRDEL,PRTIME,DVS,TADRW,LAI,
     $      WSO,WLV,WLVG,WST,MCVEG,MCEAR,PLWVEG,PLWEAR,GAMMA,
     $      NADG,NADR,NADIR,RATIO,NDVI,WDVI,LAIH,GAMMAA,COVER)

      WRITE(*,*) TIME,TADRW,LAI,COVER,WDVI


******CALCULATION OF RATE VARIABLES***********************************

*-----skip calculation of rates if time is smaller than Temerg
      IF (TSUMEM .LT. TEMERG) GOTO 15

*-----leaf photosynthesis rate at light saturation (kg CO2/ha leaf/h)
      AMDVS = LINT(AMDVST,IAMDVN,DVS)
      AMTMP = LINT(AMTMPT,IAMTMN,DDTMP)
      AMAX  = AMX * AMDVS * AMTMP

*-----subroutine ASTRO computes  day length and daily radiation
*     characteristics from Julian date, latitude and measured daily total
      CALL ASTRO(DAY,LAT,DTR,
     $ SC,SINLD,COSLD,DAYL,DAYLP,DSINB,DSINBE,ATMTR,FRDIF)

*-----subroutine TOTASS computes daily total gross assimilation (DTGA)
      CALL TOTASS(SC,DAYL,SINLD,COSLD,DSINBE,DTR,ATMTR,FRDIF,
     $  SCV,AMAX,EFF,KDIF,LAI,DTGA)

*-----conversion from assimilated CO2 to CH2O
      GPHOT = DTGA * 30./44.

*-----maintenance respiration (kg CH2O/ha/d)
      IF(WLV.GT.0) THEN
         MNDVS = WLVG / WLV
      ELSE
         MNDVS=1.
      ENDIF

      TEFF   = Q10**((DAVTMP-25.)/10.)
      MAINTS = 0.03*WLV + 0.015*WST + 0.01*WRT + MAINSO*WSO
```

```
      MAINT  = MIN(GPHOT, MAINTS * TEFF * MNDVS)

*-----fraction of dry matter growth occurring in shoots, leaves, stems,
*     storage organs and roots
      FSH = LINT(FSHTB,IFSHN,DVS)
      FLV = LINT(FLVTB,IFLVN,DVS)
      FST = LINT(FSTTB,IFSTN,DVS)
      FSO = 1. - FLV - FST
      FRT = 1. - FSH

*-----assimilate requirements for dry matter conversion (kgCH2O/kgDM)
      ASRQ = FSH *(1.46*FLV + 1.51*FST + ASRQSO*FSO) + 1.44*FRT


*-----final rates
      GTW = (GPHOT - MAINT) / ASRQ
      GSH = FSH * GTW
      GLV = FLV * GSH
      GST = FST * GSH
      GSO = FSO * GSH
      GRT = FRT * GTW
      DLV = WLVG * RDR
      GLAI = GLA (DTEFF,DVS,LAII,LAI,RGRL,DELT,SLA,GLV,DLV)
      GEAI = EAR * TADRW
      IF(DVS.LT.0.8) GEAI=0.
      IF(EAI.GT.0) GEAI=0.
      IF(DVS.GT.1.3) GEAI=GEAI-RDR*EAI

15    CONTINUE

      TIME = TIME + DELT

      GOTO 10
***********************************************************************
*     END OF DYNAMIC PART                                              *
***********************************************************************
20    CONTINUE

*-----closing file

      CLOSE (7)
      CLOSE (8)
      CLOSE (9)

      STOP
      END
```

```
*------------------------------------------------------------------*
* SUBROUTINE CLOUDX                                                *
* Calculates X-band radar backscatter of the crop using the 'Cloud'*
* model two-layer version for winter wheat                         *
*                                                                  *
* FORMAL PARAMETERS:                                               *
* name:       meaning:                                             *
* WLV         biomass leaves                      kg/ha       I    *
* WST         biomass stems                       kg/ha       I    *
* WSO         biomass ears                        kg/ha       I    *
* MS          topsoil moisture content            %(vol.)     I    *
* MCVEG       moisture content vegetative matter  %(weight)   I    *
* MCEAR       moisture content ears               %(weight)   I    *
* GAMMA(I)    radar backscatter crop at I degrees                  *
*             incidence angle                     dB          O    *
*                                                                  *
* LOCAL PARAMETERS                                                 *
* PLWVEG      plant water of vegetative matter    kg/m2            *
* PLWEAR      plant water of ear-layer            kg/m2            *
* INC(I)      I/10 incidence angle                degree           *
* GS(I)       Backscatter dry soil                -                *
* CVEG        Maximum backscatter leaves+stems    -                *
* CEAR(I)     Maximum backscatter ears            -                *
* DVEG        Attenuation factor leaves+stems     -                *
* DEAR        Attenuation factor ears             -                *
* KS          Moisture coefficient K (soil)       -                *
*------------------------------------------------------------------*

      SUBROUTINE CLOUDX(MCVEG,MCEAR,WLV,WST,WSO,MS,PLWEAR,
     $    PLWVEG,GS,CEAR,INC,NC,DVEG,DEAR,CVEG,KS,SOIL,
     $    VEG,EARS,GAMMA)

      IMPLICIT REAL (A-Z)
      REAL GS(8),CEAR(8),AVEG(8),AEAR(8),ASOIL(8)
      REAL SOIL(8),VEG(8),EARS(8),GAMMA(8),NC(8)
      INTEGER I,INC
      PARAMETER PI=3.1415926

      RADC=PI/180.

* calculation of plant water in kg/m2 for ears and vegetative matter
      PLWVEG = 0.0001*(WLV+WST)*MCVEG/(100.-MCVEG)
      PLWEAR = 0.0001*WSO*MCEAR/(100.-MCEAR)

* calculation of radar backscatter
      DO 10 I=1,INC
       AVEG(I) =DVEG*PLWVEG/COS(RADC*NC(I))
```

```
      AEAR(I) =DEAR*PLWEAR/COS(RADC*NC(I))
      ASOIL(I)=(DEAR*PLWEAR+DVEG*PLWVEG)/COS(RADC*NC(I))
      SOIL(I)=GS(I)*EXP(KS*MS)*EXP(-ASOIL(I))
      VEG(I)=CVEG*(1.-EXP(-AVEG(I)))*EXP(-AEAR(I))
      EARS(I)=CEAR(I)*(1.-EXP(-AEAR(I)))
      GAMMA(I)=10*ALOG10(SOIL(I)+VEG(I)+EARS(I))
10    CONTINUE
     RETURN
     END
```

```
*-----------------------------------------------------------------*
* SUBROUTINE CLOUDM                                               *
* Calculates L- to Ku2-band radar backscatter of the crop using the*
* 'Cloud' model; two-layer version for winter wheat               *
* FORMAL PARAMETERS:                                              *
* name:       meaning:                                            *
* WLV         biomass leaves                 kg/ha        I       *
* WST         biomass stems                  kg/ha        I       *
* WSO         biomass ears                   kg/ha        I       *
* MS          topsoil moisture content       %(vol.)      I       *
* MCVEG       moisture content vegetative matter  %(weight)  I    *
* MCEAR       moisture content ears          %(weight)    I       *
* GAMMAA(I,J) radar backscatter crop at I degrees                 *
*             incidence angle, and at frequency J  dB      O      *
*             J = 1 = L-band                                      *
*                 2 = S-band                                      *
*                 2 = C-band                                      *
*                 2 = X-band                                      *
*                 2 = Ku1-band                                    *
*                 2 = Ku2-band                                    *
*                                                                 *
* LOCAL PARAMETERS                                                *
* PLWVEG      plant water of vegetative matter    kg/m2           *
* PLWEAR      plant water of ear-layer            kg/m2           *
* NCA(I)      I/10 incidence angle                degree          *
* GSA(I,J)    Backscatter dry soil                -               *
* CVEGA(J)    Maximum backscatter leaves+stems    -               *
* CEARA(I,J)  Maximum backscatter ears            -               *
* DVEGA(J)    Attenuation factor leaves+stems     -               *
* DEARA(J)    Attenuation factor ears             -               *
* KSA(J)      Moisture coefficient K (soil)       -               *
*-----------------------------------------------------------------*

      SUBROUTINE CLOUDM(MCVEG,MCEAR,WLV,WST,WSO,MS,PLWEAR,
     $ PLWVEG,GSA,CEARA,NCA,DVEGA,DEARA,CVEGA,KSA,SOILA,
     $ VEGA,EARSA,GAMMAA)

      IMPLICIT REAL (A-H,K-Z)
      IMPLICIT INTEGER(I)
      IMPLICIT INTEGER(J)

      REAL GSA(5,6),CEARA(5,6),AVEGA(5,6),AEARA(5,6),ASOILA(5,6)
      REAL SOILA(5,6),VEGA(5,6),EARSA(5,6),GAMMAA(5,6)
      REAL NCA(6)
      REAL KSA(6),DVEGA(6),DEARA(6),CVEGA(6)

      PARAMETER PI=3.1415926
```

```
      RADC=PI/180.

* calculation of plant water in kg/m2 for ears and vegetative matter
      PLWVEG = 0.0001*(WLV+WST)*MCVEG/(100.-MCVEG)
      PLWEAR = 0.0001*WSO*MCEAR/(100.-MCEAR)

* calculation of radar backscatter
      DO 10 J=1,6
       DO 5 I=1,5
        AVEGA(I,J) =DVEGA(J)*PLWVEG/COS(RADC*NCA(I))
        AEARA(I,J) =DEARA(J)*PLWEAR/COS(RADC*NCA(I))
        ASOILA(I,J)=(DEARA(J)*PLWEAR+DVEGA(J)*PLWVEG)/COS(RADC*NCA(I))
        SOILA(I,J)=GSA(I,J)*EXP(KSA(J)*MS)*EXP(-ASOILA(I,J))
        VEGA(I,J)=CVEGA(J)*(1.-EXP(-AVEGA(I,J)))*EXP(-AEARA(I,J))
        EARSA(I,J)=CEARA(I,J)*(1.-EXP(-AEARA(I,J)))
        GAMMAA(I,J)=10*ALOG10(SOILA(I,J)+VEGA(I,J)+EARSA(I,J))
5      CONTINUE
10     CONTINUE
      RETURN
      END
```