A user friendly menu and batch facility for the crop simulation model WOFOST v4.3

(Supplement to WOFOST v4.1 User's Guide)

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INTERNATIONAL SOIL REFERENCE AND INFORMATION CENTRE

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1 INTRODUCTION

History

Crop growth models have been developed for analyzing the growth and production of crops under a wide range of climate and soil conditions. The crop growth simulation model WOFOST described in this paper was developed the Centre for World Food Studies (WOFOST), and will be further referred to as the WOFOST crop model. The WOFOST model is an elaboration of more basic crop growth models that have been developed at the Department of Theoretical Production Ecology and the Centre for Agrobiological Research (CABO), both in Wageningen. WOFOST is programmed in Fortran 66. The scientific background is described by H. van Keulen and J. Wolf (1986). For details on the program, reference is made to the documentation of version 4.1 of WOFOST (van Diepen et al., 1988). This Technical Paper can be considered as a supplement to that documentation.

Land evaluation and WOFOST

The National Soil Reference Collection (NASREC) project of ISRIC aims at the establishment of national or regional soil reference collections. Reference soils are those soils that are representative for major ecological regions and which are used for training, extension, and research purposes. For each reference soil a comprehensive and verified data set of soil and other environmental factors such as climate, landscape, hydrology, vegetation, and land-use is available. This data set is used for a number of applications, and special attention is given to its use for land evaluation purposes.

The FAO framework for land evaluation (1976) is currently being used for the qualitative assessment of the soil and land qualities. The WOFOST model enables a quantitative analysis of the production possibilities of land for a wide range of soil/land and climate characteristics. However, it should be stressed that WOFOST uses only a limited number of Land Qualities to simulate the crop production. For example, the model can be used to study quantitatively the interaction between radiation, rainfall (distribution), soil waterholding capacity, and soil fertility on the crop production. Not included in the model are e.g. plant diseases, competition with weeds,management practices, aluminium toxicity, etc. The use of WOFOST results is therefore seen as complementary to existing qualitative/subjective land evaluation procedures. The model has been introduced to a number of national soil/land oriented institutions in countries receiving support from the NASREC project[1]. Currently the model is tested with local soil and climate data.

Adaptations

Several changes to WOFOST versions 4.1 and 4.2 have been made to make the model more accessible for users in the countries receiving support from the NASREC project. The following adaptations have been made:

- An easy input of climate and soil data. Inputs are not dependent any more on fixed positions as required by Fortran.
- Daily rainfall data of several stations can be read from a single file.
- The crop species, climate, and soil types that are available can be read from the appropriate data files.
- Availability of a batch operation facility, allowing a large number of simulations to be run from a batch file, instead of the time-consuming interactive use.
- Various output options have been made available. Besides the standard WOFOST 4.1 output, the user may select also a summarized or a more comprehensive output form.

[1]Costa Rica, Cuba, Peru, Venezuela, Nigeria and Zimbabwe.

- Besides the english version, a translation in spanish was made and tested in a number of Latin American countries.

Further details are given in this paper.

These adaptations and a user-friendly shell around the WOFOST program enable the user to analyze more easily the influence on crop production of a large number of climate, soil and hydrology factors such as: rainfall distribution, groundwater depth, effective soil depth, soil fertility, waterholding capacity.

Additional explanatory text and examples on the use of the WOFOST model were included to give the beginning users of the WOFOST model the first necessary background information. It is recommended to have the above mentioned documentation at hand for further study. Most examples apply to simulations of maize production at Sikasso (Mali) with the date of crop emergence set at day 150 (beginning of June).

2 WOFOST CROP MODEL

The WOFOST crop model is briefly described in this chapter. For more details reference is made to the WOFOST documentation mentioned in the introduction. For soil nutrients aspects, the reader is referred to Jansen et al. (1990).
The WOFOST model recognizes three levels of calculation: the potential, water limited, and nutrient limited crop production.

2.1 Potential production

In the WOFOST model, crop growth is simulated on a daily basis. Each day the deterministic process rates are calculated and subsequently the crop development status is updated. The potential dry matter production of a crop is determined by the climate (radiation, temperature) and the present status of the crop as characterized by development stage, leaf area, etc. This production is partitioned to four plant parts: leaves, stems, roots, and storage organs. The partitioning is a function of the development stage of the crop –see figure 1– and determines the daily weight increases of the different plant parts. Other crop productivity factors, such as the availability of water and nutrients, are considered to be optional. The influence of these factors can be studied in subsequent simulation runs.
The simulation of crop growth is terminated when the crop reaches maturity.

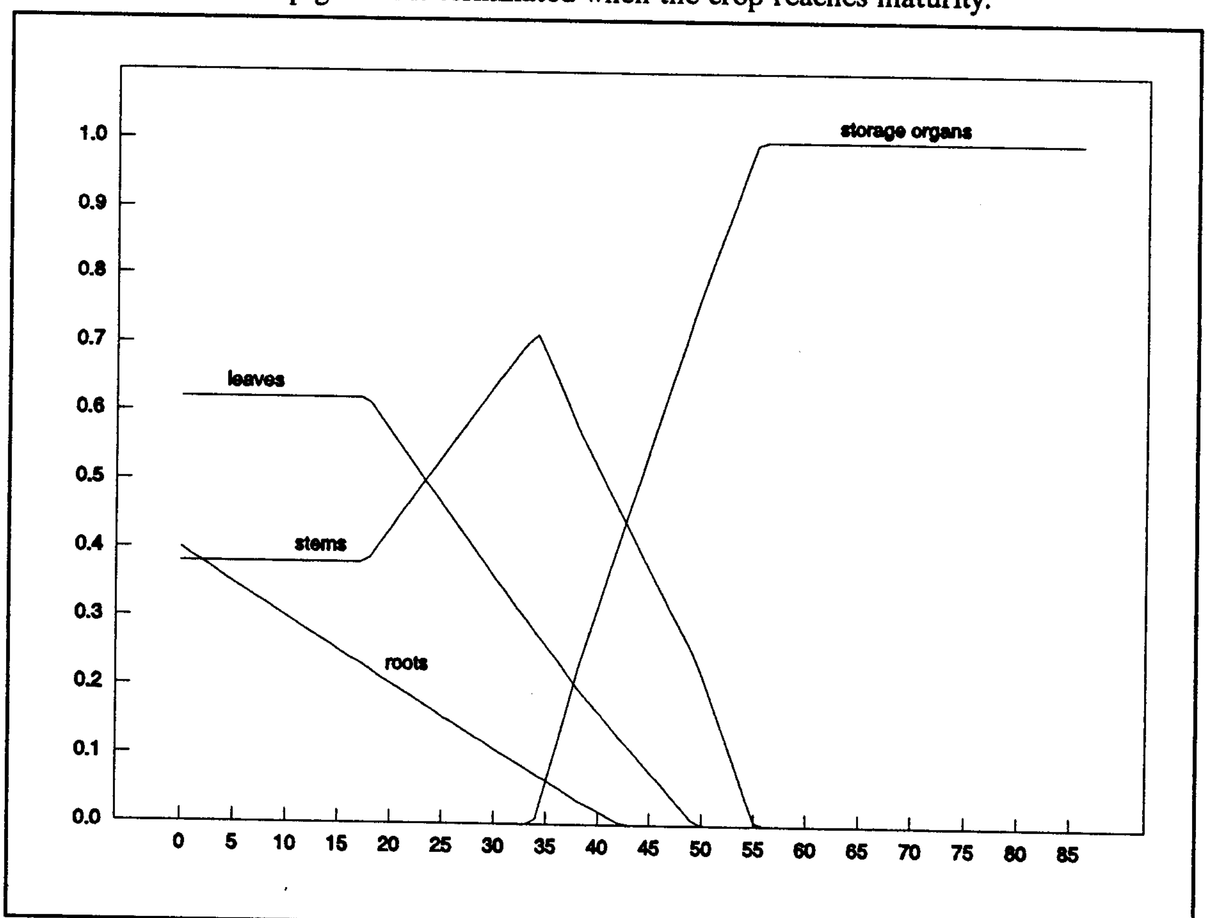

Figure 1 Partitioning factors during crop growth. Number of days from emergence till maturation at x-axis, fractions of dry matter at y-axis.

Note that the partitioning factor for roots is a fraction of the total dry matter. For stems, storage organs, and leaves the factors are fractions of the total above-ground dry matter, and the sum of these 3 factors are therefore 1.

altitude correction
In the original version of the WOFOST model the potential production is calculated for sealevel only, but results can be corrected for altitude. Both the assimilation and the evaporation rates are influenced by altitude. The assumptions of the altitude correction are given in annex 1.

In the current version of WOFOST only a correction of the assimilation rate is incorporated. An adjustment of the evaporation rate should be investigated.

2.2 Water limited production

The water limited production is determined by the availability of rainfall or irrigation water. It includes the factors necesary for the potential crop production. The water limited production can be calculated without or with groundwater influence. WOFOST uses a daily waterbalance bookkeeping procedure to estimate the moisture available for crop growth. The simulation of crop growth is terminated when the crop reaches maturity, or when severe drought or severe waterlogging (non-rice crops) occur.

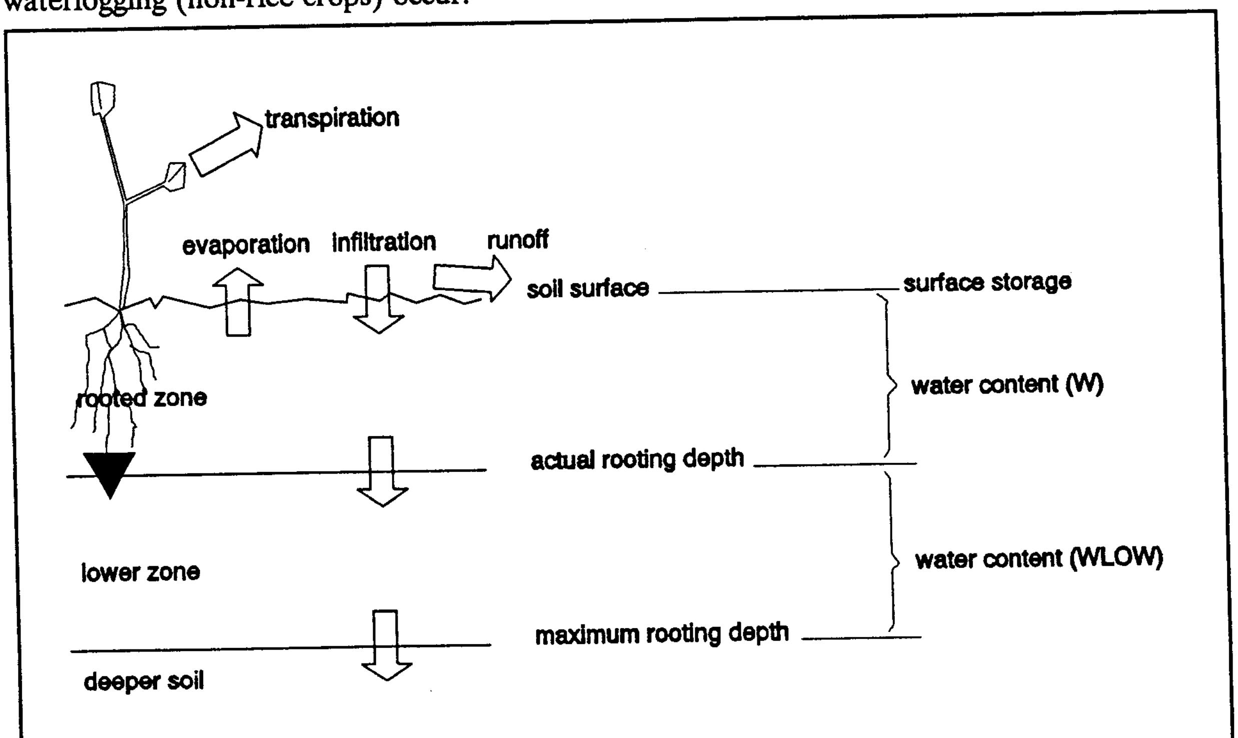

Figure 2 Soil water system without groundwater influence.

No groundwater
The soil-water system without ground water influence is schematically visualized in figure 2. Three soil layers are distinguished: the rooted zone, the lower zone, and the soil below maximum rooting depth. The actual rooting depth is a variable, nil at the start and increasing during the growing period. By root growth, water in the lower zone becomes available for crop growth. The water fluxes that are used in the bookkeeping procedure are precipitation, (crop) transpiration, (soil) evaporation, runoff, surface storage, and downward flow. Downward flow

from the two upper layers occurs when soil moisture content is above field capacity, but it this is determined by the hydraulic conductivity (e.g. it can be limited by a low hydraulic conductivity).

With groundwater influence
The soil-water system with groundwater is schematically visualized in figure 3. Likewise three layers are distinguished: the rooted zone, the zone between rooting depth and groundwater level, and the zone below groundwater level to a reference depth of 16000 cm.
In a situation where groundwater enters the rooted zone (or when roots enter the groundwater), the system is subdivided in a different way: 1) the rooted zone is subdivided into a saturated and a non-saturated layer, 2) there is one saturated zone between rooting depth and the reference depth.
Compared with a freely drained situation, additional fluxes of moisture occur in soils with groundwater, these are capillary rise and percolation.

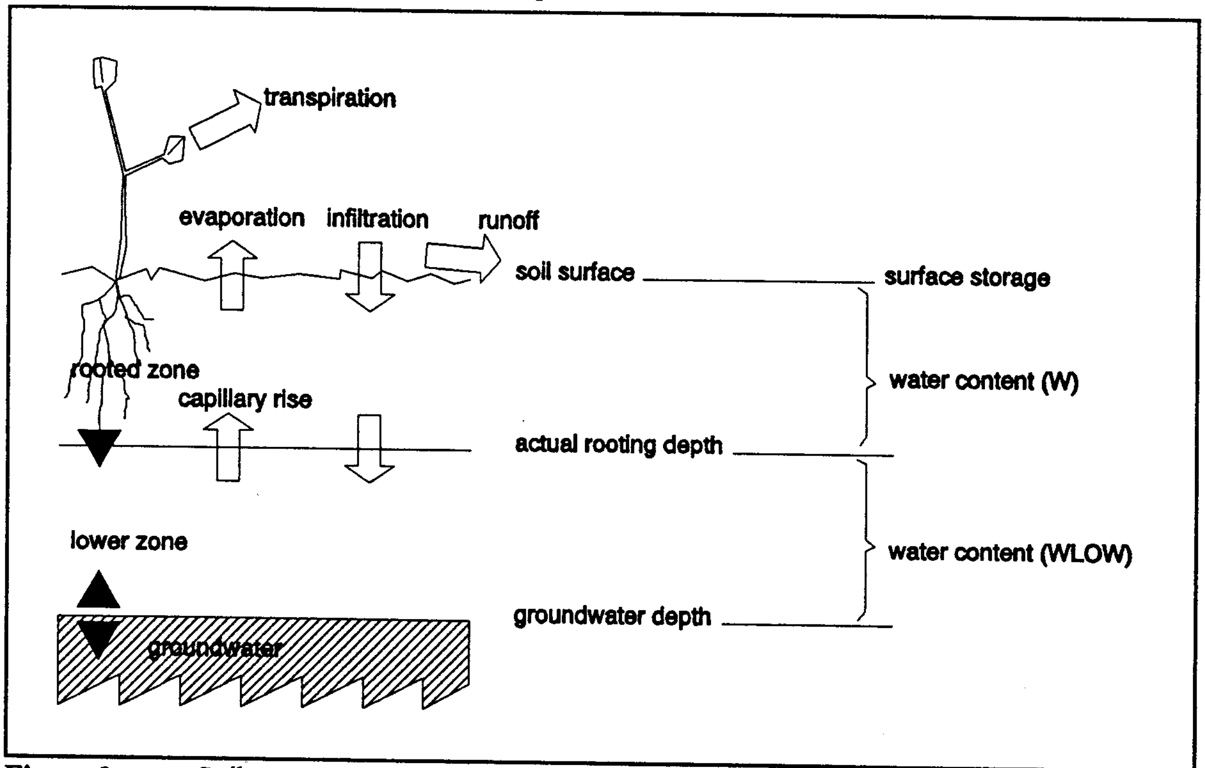

Figure 3 Soil water system with ground water influence.

2.3 Nutrient limited production

The fertilizer requirements for attaining the potential and the average water limited production levels are calculated in the nutrient part of the WOFOST model. In addition, the actual soil nutrient limited yields are calculated using the method of the QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) system (Janssen et al., 1990).
This method only accounts for the three macro nutrients, N, P, and K. The basic principles of QUEFTS are first to calculate the actual uptake for a given potential supply of nutrients, and secondly to calculate the yield for the actual N, P, and K uptake.
Crop data used are the minimum and maximum nutrient concentrations in vegetative parts and storage organs. During the crop growth simulation, the dry weights of vegetative parts and

storage organs produced in a potential production situation are calculated. For both datasets, the yield-nutrient uptake relationships can be calculated, for use in the QUEFTS system.

For information on the formulas used in the nutrient calculations, reference is made to Janssen et al. (1990).

Potential supply and actual uptake
The potential supplies of the three macro nutrients N, P, and K in the soil, should be determined or estimated first. From the potential nutrient supply, the actual nutrient uptake is calculated in dependence of the supply of one other macronutrient. This results in two estimates for the actual uptake for the two other macro nutrients, of which the lower estimate is considered the more realistic. Figure 4 represents such a relation between potential supply and actual uptake of nitrogen in dependence of the phosphorus supply. In this figure, three situations can be recognized:

A The potential supply of nitrogen is very small compared to that of phosphorus, and hence, the uptake of nitrogen by the crop will be equal to the soil supply.

C The potential supply of nitrogen is very large compared to that of phosphorus; in that case the total soil supply of phosphorus is taken up by the crop and an increased supply of nitrogen does not lead to a higher nitrogen uptake: nitrogen is maximally accumulated in the crop (maximum N concentration) and phosphorus maximally diluted (minimum P concentration).

B For a situation in between A and C, the ratio d(uptake)/d(supply) decreases from 1 to 0, and this decrease is assumed to be linear. That results in a parabolic relation between uptake and supply.

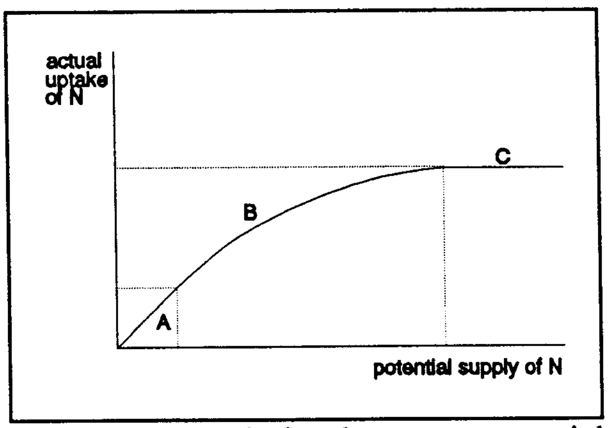

Figure 4 Relation between potential supply and actual uptake of nitrogen as affected by a second nutrient.

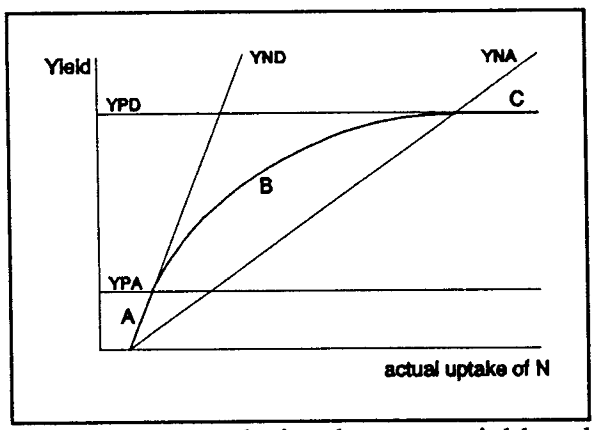

Figure 5 Relation between yield and actual uptake of a nutrient as affected by the yield range of one other nutrient.

Actual nutrient uptake and yield
For each pair of nutrients a yield estimate can be made in dependence of the nutrient uptake. Such a relation between actual nutrient uptake and yield is represented in figure 5. In this case, the uptake of phosphorus is set constant and that of nitrogen varies.

In the figure, again three situations can be distinguished:

A very low uptake of nitrogen, so yield is limited by nitrogen, i.e. YND (Yield when Nitrogen is Diluted and minimum N concentration);

C very high uptake of nitrogen, so yield is limited by phosphorus, i.e. YPD (Yield when Phosphorus is Diluted and minimum P concentration);

B parabolic relation.

For each pair of nutrients two yield estimates are calculated, for example that for the actual N uptake in dependence of the yield range for the P uptake, that for the actual P uptake in dependence of the yield range for the N uptake, etc. The final yield estimate is calculated as the average of the yield estimates for the six nutrient pairs. In the procedure, an estimate based on two nutrients may not exceed the upper limit of the yield range of the third nutrient, i.e. its concentration cannot be lower than its minimum. In addition, also the potential and the water-limited yields serve as an upper limit.

Nitrogen fixation by crops
Nitrogen fixation by crops, e.g. by Rhizobium nodules etc., which will become available for crop growth, is included in the WOFOST model. The nitrogen fixation is accounted for by the parameter NFIX. It indicates the proportion of the total nitrogen supply that is supplied by biological fixation and is given as a constant. However, in reality, NFIX may decrease in dependence of the amount of readily available nitrogen.

Table .. N-fixation in crops

Crop	N-fix

3 DATA REQUIREMENTS

3.1 General

The WOFOST model uses two types of data:

- Basic data; these are permanent stored in files with site specific data on climate and soil, and basic crop parameters.
- Boundary conditions; these are data which are requested by the WOFOST model during the start procedure. Besides selections from the basic climate, soil, and crop files, the boundary conditions include answers on twenty questions such as the emergence date of the crop, rootable soil depth, presence of groundwater, etc.

In this chapter the required basic data will be discussed. In chapter 5 "How to use WOFOST" attention will be given to the boundary conditions or control variables. The basic datafiles contain already data of a number of selected meteo stations, soil types and crops.
The basic data files can be easily edited or expanded with new data of other sites. Some adaptations were made to facilitate the editing procedure. Please note that *for editing the data files, your text editor must support files with a maximum line length of more than 1024.* In the basic data file, comment text is allowed in-between the data sets. Each comment line must start with an asterisk (*).
In general, values in data files must be separated by at least 1 space; unlike what is usual in FORTRAN data files, values need not start at fixed positions on a line.
Care should be taken when updating data files. Mistakes do not always lead to error messages or results that are obviously incorrect. For this reason, it is recommended to compare from time to time the results of an earlier studied identical dataset.

3.2 Climate

The following basic climate data are required to run the WOFOST model:

General station data
-name meteorological station
-latitude (°)
-elevation (m)
-empirical constants A, B
-MARKOV constants

Average monthly data of
-minimum temperature (°C)
-maximum temperature (°C)
-radiation ($MJ.m^{-2}.d^{-1}$) (if not available, these data can also be derived from hours of clear sunshine per day)
-vapour pressure (mbar) } (either vapour pressure or relative humidity data is needed)
-relative humidity (%)
-windspeed ($m.s^{-1}$)
-rainfall (mm)
-number of rainy days (d).

These data are stored in the file CLIM.DAT. At present, data of 40 meteo stations are already available from the CLIM.DAT file. These stations are listed in Annex 2. An example set of data of meteorological station Sikasso (Mali) is given in figure 6. Missing values are represented by -1. For this station, data of relative humidity are not needed as data on vapour pressure are available.

```
Sikasso - Mali
   11.4  375.   0.25  0.45  1.0
   13.5   34.1 18.084   10.1    -1  2.3      1.      1.
   18.0   36.7 19.237   11.0    -1  2.5      3.      1.
   21.7   37.6 19.354   15.0    -1  2.7     15.      2.
   24.3   37.0 18.935   20.8    -1  2.8     45.      4.
   23.8   36.0 19.227   25.2    -1  2.6    106.      8.
   22.3   33.6 18.814   25.7    -1  2.3    152.     11.
   21.3   31.3 17.554   25.8    -1  2.5    253.     16.
   21.0   30.2 16.362   26.3    -1  2.2    326.     17.
   20.8   31.5 17.011   26.3    -1  1.9    217.     14.
   21.1   34.0 19.281   25.3    -1  1.9     84.      6.
   17.8   34.6 18.573   23.2    -1  1.9     19.      2.
   14.5   33.5 17.107   12.5    -1  2.0      4.      1.
```

Figure 6 Example set of climate data.

Figure 6 reads as follows:

- line 1: climate name (up to 30 characters; additional characters are ignored)
- line 2: latitude, elevation, empirical constants A and B for Angstrom formula, and a MARKOV constant.
- lines 3-14: 8 columns with average monthly data for: minimum temperature, maximum temperature, radiation, vapour pressure, relative humidity, wind speed, rainfall, and number of rainy days.

Daily rainfall records are separately stored in the file RAIN.DAT. The format is given in figure 7. The daily rainfall records for each year with 365 days of data are presented on *one* line. In this figure, all first and last days of the year have zero rainfall. Take care that the meteorological station name in the rain data file (RAIN.DAT) has to be identical to the one in the climate file (CLIM.DAT).

```
Chittagong (306) - Bangladesh
0
Niamey Aero - Niger
3
1950 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 [..] 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1951 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 [..] 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1952 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 [..] 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
```

Figure 7 Daily rainfall data

The rain data file has the format:

- line 1: name of meteorological station (up to 30 characters; must be identical to climate name used in CLIM.DAT!)
- line 2: number of years for which data are available and given in this file
- lines 3 etc. each line contains 365 rainfall data

If daily rainfall data are not available, WOFOST uses monthly rainfall data to generate a daily rainfall pattern. This pattern is determined by the average monthly rainfall, the number of rainy days, and the value of the MARKOV constant. This constant determines the degree of clustering of rainy days and should be in the range between 0 and 1. If it is 1, clustering of rainy days is absent which means that the chance of a rainy day after a rainy day is equal to that after a dry day. In general, the MARKOV constant for tropical climates is set at 1, and that for temperate climates at 0.75 (Geng et al., 1986).
Rainfall generation uses a pseudo-random number generator. This means that for each series of water limited crop growth simulations, the same series of rainfall pattern is generated. The generator is reset to its initial state after a potential production calculation.

If the average number of rainy days is missing, it is automatically calculated from the amount of rainfall divided by 15. Some more information on the rainfall generator is given in Annex 3.

3.3 Soils

The following basic soil data are required to run WOFOST:

- soil name (may include acronym)
- saturated conductivity of the topsoil ($cm.d^{-1}$)
- saturated conductivity of the subsoil ($cm.d^{-1}$)
- volumetric moisture content as a function of pF ($cm^3.cm^{-3}$)
- log(conductivity) as a function of pF ($log(cm.d^{-1})$) (only used for the situation with groundwater, in order to calculate the capillary rise).

In the SOIL.DAT file these basic data are given for twelve soils from the Netherlands, characterized only by the textural class. The soils comprise medium to coarse sand, fine sand, loamy fine sand, very loamy fine sand, fine sandy loam, silt, light loam, loam, heavy loam, clay loam, clay, and heavy clay.

The data of soils of the Netherlands can not be applied indiscriminately to soils in different regions. Soil data from other sites can be easily appended by using the text editor mentioned before. Generally pF data are available. However, reliable saturated hydraulic conductivity data of top- and subsoil are not so easily available. If not available, these data can be adapted from soils with a similar pF curve. The pF curves of soils available at present in the SOIL.DAT file are given in Annex 4.

At present, the soil data file contains only physical data. The soil supply of nutrients has to be entered separately when nutrient calculations are required. This supply should be determined for a standard crop with a growth duration of 120 days. In the WOFOST model, the actual soil supply is corrected for the actual growth duration.

Figure 8 contains an example set of soil data. Each set of soil data consists of five lines. Before or after each set of data, comment lines are allowed (each line starting with an asterisk.

```
Clay Loam
 0.30    3.00     0.73
-1.000  0.448    1.000  0.408    1.300  0.401    1.491  0.396  [..]  4.204  0.143    6.000  0.046
 0.000  1.785    1.000 -0.137    1.300 -0.553    1.491 -0.796  [..]  4.000 -4.770    4.204 -5.319
 0 0 0 0
```

Figure 8 Example set of soil data.

The soil data file contains:

line 1: soil name (up to 30 characters);
line 2: saturated conductivity of top soil, sorptivity (not used), and saturated conductivity of the sub soil;
line 3: table with maximally 15 pairs of pF-values and volumetric soil moisture contents;
line 4: table with maximally 15 pairs of pF-values and the 10-logarithm of the hydraulic conductivity;
line 5: chemical characteristics pH(H_2O), organic carbon (g/kg), P-Olsen (mg/kg), and exchangeable K (mmol/kg).

3.4 Crops

A large number of basic crop data are required to run the WOFOST model, and these are crop and variety specific. They can only be obtained from time-consuming field experiments and are therefore often not easily obtainable. For the following crops the basic data are available in the CROP.DAT file.

1. Barley	2. Cassava
3. Chickpea	4. Cotton
5. Cowpea	6. Field bean
7. Groundnut	8. Maize
9. Millet,bulrush	10. Mungbean
11. Pigeonpea	12. Potato (late cv.)
13. Rapeseed	14. Rice HYV-IR8
15. Sorghum	16. Soybean
17. Sugarbeet	18. Sugarcane
19. Sunflower	20. Sweet potato
21. Tobacco	22. Wheat,spring

It should be advised not to change the major part of the crop data. The contents of the crop data file is given in annex 7.

If required, parameters that might be adapted, are (van Diepen et al., 1988):
- life span of leaves (SPAN), if the simulated amount of leaves is too low or too high compared to reality;
- fractions partitioned to roots (FRTB), leaves (FLTB), stems (FSTB), and storage organs (FOTB) if the simulated distribution does not correspond with the actual distribution;
- initial total dry weight (TDWI) if the actual sowing or planting density results in a different initial weight;
- the development rates (DVRC1 and DVRC2) if the simulated growth periods between emergence and flowering and between flowering and maturation do not correspond with the actual growth periods. This adjustment may also find place by entering values (for VARP1/2) from screen.

4 SIMULATION RESULTS

Results of the WOFOST crop model are presented in tables for each of the three production situations (i.e. the potential, water-limited, and nutrient-limited production situations). This chapter gives default output; other output options will be explained in chapter 5.

4.1 Potential production

WOFOST will first give the results of the potential production calculations. An example of the default output for the meteo station Sikasso in Mali and the crop maize is given in figure 9.

POTENTIAL CROP PRODUCTION

Sikasso - Mali   Maize   Start day 150

DAY	ID	WLV	WST	WSO	LAI	DVS	RD	T	GASS	MRES	DMI	TAGP
150	0	7.	5.	0.	.03	.00	10.	.01	8.5	.5	5.7	12
160	10	96.	59.	0.	.31	.28	22.	.06	93.0	5.7	62.1	155
170	20	816.	512.	0.	2.24	.54	34.	.30	449.4	44.4	287.3	1328
180	30	2129.	1997.	0.	5.19	.80	46.	.41	613.4	120.6	346.2	4126
188	38	2783.	3644.	110.	6.31	1.00	56.	.42	622.5	170.5	317.7	6593
190	40	2866.	3988.	263.	6.39	1.05	58.	.42	620.7	179.8	310.6	7206
200	50	2941.	5131.	1822.	6.28	1.26	62.	.40	605.1	212.7	279.9	10159
210	60	2815.	5313.	4285.	5.94	1.47	62.	.38	575.5	234.7	245.4	12805
220	70	2736.	4520.	6586.	5.73	1.68	62.	.36	532.7	238.3	211.9	15106
230	80	2261.	3694.	8363.	4.52	1.89	62.	.33	353.4	225.3	92.2	16883
236	86	1577.	3272.	8549.	2.93	2.01	62.	.28	46.9	46.9	.0	17069

SUMMARY :

DAYS		TWRT	TWLV	TWST	TWSO	TAGP	GASST	MREST	HIDX	TRC	WUSE
38	86	1221.	3207.	5313.	8549.	17069.	38174.	12478.	.50	157.	26.9

Figure 9 Output for potential crop production.

Each line represents the state of growth at an interval of 10 days for the following variables:

DAY	day number (value 1 = 1st January, 365 = 31st December)
ID	number of days of simulated crop growth since emergence
WLV	dry weight of living leaves (kg.ha^{-1})
WST	dry weight of living stems (kg.ha^{-1})
WSO	dry weight of storage organs (kg.ha^{-1})
LAI	leaf area index (value < 1 = not closed canopy, 1 = completely closed single leaf canopy, > 1 = multiple layers of leafs)
DVS	development stage of crop (value 1 indicates flowering, 2 indicates maturation)
RD	rooting depth (cm)
T	actual transpiration rate (cm.d^{-1})
GASS	actual gross assimilation rate of the canopy (kg CH_2O.ha^{-1}.d^{-1})
MRES	maintenance respiration rate (kg.ha^{-1}.d^{-1})
DMI	rate of dry matter increase of the crop (kg.ha^{-1}.d^{-1})
TAGP	total above-ground dry weight of dead and living plant materials (kg.ha^{-1})

The lower three lines of the output in figure 10 represents the summary output. These variables are:

DAYS	number of days after emergence that anthesis was reached and growth was terminated, either by maturation or by failure.
TWRT	total dry weight of roots

TWLV	total dry weight of leaves
TWST	total dry weight of stems
TWSO	total dry weight of storage organs
TAGP	total dry weight of above-ground plant organs (leaves, stems, and storage organs)
GASST	total gross assimilation
MREST	total maintenance respiration
HIDX	harvest index (TWSO/TAGP)
TRC	transpiration coefficient; weight of water used per total amount of above-ground dry weight produced (10^5•WUSE/TAGP)
WUSE	water use, total transpiration during crop growth (cm)

4.2 Water-limited production

After the potential production calculation, WOFOST will continue with the water-limited production calculations. An example of output for the water-limited production situation is given in figure 10. In addition to the variables that have already been explained, this output table contains some additional variables:

RAIN	cumulative daily rainfall (cm)
EVAP	actual evaporation rate from soil and surface water ($cm.d^{-1}$)
SM	soil moisture content ($cm^3.cm^{-3}$)
SS	surface storage (cm)
W+WLOW	total amount of water in rootable zone (root zone and lower part of rootable zone)
ZT	groundwater depth (cm)

```
WATER LIMITED CROP PRODUCTION, Year    1                              Start day 150
==============================                                    monthly raindata
Sikasso - Mali                       Maize                           fixed fraction
Clay Loam (B10 + O11)                   RDMso=120.   no groundwater      NOTinf= .00
  SM0= .448 SMFC= .357 SMW= .143      RDM= 62.         WAV=  2.0           SSmax=  .0

DAY  ID   WLV    WST    WSO    LAI   RD    RAIN    T  EVAP    SM     SS W+WLOW
150   0     7.     5.     0.   .03  10.     .0   .01  .39   .343    .0  10.8
160  10    69.    43.     0.   .22  22.    5.6   .05  .21   .223    .0  10.8
170  20   219.   150.     0.   .62  34.   15.3   .04  .32   .382    .0  17.7
180  30   364.   351.     0.   .91  46.   22.5   .08  .26   .372    .0  21.3
188  38   549.   872.    52.  1.21  56.   25.0   .19  .20   .341    .0  21.0
190  40   565.   971.    91.  1.22  58.   29.9   .00  .25   .411    .0  25.1
200  50   445.  1015.   172.   .89  62.   33.2   .08  .24   .368    .0  22.7
210  60   358.  1061.   437.   .68  62.   54.4   .00  .28   .400    .0  24.6
220  70   270.   903.   447.   .48  62.   62.9   .00  .33   .438    .0  27.0
230  80   199.   738.   447.   .34  62.   83.9   .00  .34   .427    .0  26.3
236  86   169.   654.   447.   .28  62.   88.7   .00  .36   .444    .0  27.4

SUMMARY :
DAYS       TWRT     TWLV    TWST     TWSO     TAGP    GASST    MREST  HIDX TRC  WUSE
 38  86     314.     713.   1061.     447.    2222.    4468.     910.  .20 133.  3.0
```

Figure 10 Output for water limited production.

The header above the output contains some control and soil moisture content parameters as derived from the basic soil data:

SM0	moisture content at saturation ($cm^3.cm^{-3}$)
SMFC	moisture content at field capacity ($cm^3.cm^{-3}$)
SMW	moisture content at wilting point ($cm^3.cm^{-3}$)

RDM	maximum rooting depth attained (determined by rootable soil depth and maximum rooting depth of the crop) (cm)
WAV	initial amount of available moisture in root zone (cm)
SSMAX	maximum surface storage capacity

The output for production in a water limited situation with groundwater influence will display the groundwater depth (ZT) in the last column, instead of the total amount of water in the rootable zone (W+WLOW).

Two water balances are presented in figure 11. The units are expressed in cm. The first balance applies to the whole system, the second only to the root zone. The term irrigation will always be zero because irrigation is not possible in the current program. However, irrigation can be simulated by replacement of rainfall data by irrigation quantities in the RAIN.DAT file.

```
                 WATER BALANCE WHOLE SYSTEM
          irrigation    .0     evap. water surface    .0
            rainfall  88.7      evap. soil surface  23.8
final minus initial:                 transpiration   3.0
     -surface storage   .0          surface runoff  32.0
   -water in rootzone 23.9        lost to deep soil 13.4  checksum:  .0
 -water in lower zone -7.4

                   WATER BALANCE ROOT ZONE
initial water content  3.4     final water content  27.4
         infiltration 56.7      evap. soil surface  23.8
  added by root growth 11.3          transpiration   3.0
                                       percolation  17.3  checksum:  .0
```

Figure 11 Output of water balances of the whole system and of the root zone.

4.3 Nutrient limited production

Nutrient limited production calculations are made of the potential production situation, of the average result of previous water-limited production simulations, and of the soil fertility situation as given in the SOIL.DAT file. The required nutrients for these three production situations are given together with a summary of other essential production data. An example of a summary output table is given in figure 12. The required quantities of N, P, and K fertilizer to attain the potential, the water-limited production levels, and the nutrient limited crop production levels are given. The amounts of fertilizer are expressed in kg N, P, and K per ha. Because of differences in the length of growing period, the required NPK fertilizers differ from the input amounts as the latter are based upon a growing season of 120 days.

SUMMARY CROP PRODUCTION AND NUTRIENT REQUIREMENTS Nbas= 22. Pbas= 7. Kbas= 22.
Nrec= .50 Prec= .10 Krec= .50

	Potential Crop production	Nutrient limited Crop production	Water limited Crop production
Leaves	3207.	555.	713.
Stems	5313.	919.	1061.
Storage organ	8549.	1130.	447.
Ratio SO/straw	1.00	.77	.25
Harvest index	.50	.43	.20
Fertilizer N	365.2	-	.0
Fertilizer P	463.6	-	.0
Fertilizer K	236.7	-	3.2

Figure 12 Potential, water-limited, and nutrient-limited crop production and their nutrient requirements.

5 HOW TO RUN WOFOST?

In this chapter attention is given to the installation, start, output and batch procedures. The potential water limited and/or nutrient limited production situations are chosen via the start command and this determines the control variables that should be entered, either interactively or with a batch file.

5.1 Installation and file management

The WOFOST crop model consists of the following files:

- WOFOST. EXE	Execute file
- WOFOST. FMT	Format file
- WOFOST. INI	Initial settings file
- CROP.DAT	|
- SOIL.DAT	| basic data files
- CLIM.DAT	|
- RAIN.DAT	|

- A number of "batch" and "output" files, which are to be made and named by the user.

All these files can be put in the subdirectory \WOFOST. However, when different basic data files are required, it is possible to store these in different subdirectories.

For example, it is possible to maintain different directories for other language versions of WOFOST, or to store different sets of climate and soil data in other sub-directories. WOFOST can be started from its own directory or from another. If the WOFOST model is started, it searches first for the WOFOST.FMT file in the current directory, and if not found, in the WOFOST sub-directory (DOS versions ≥ 3).

```
C:\WOFOST\wofost.exe
          wofost.fmt
          wofost.ini
          crop.dat
          clim.dat
          soil.dat
          rain.dat
C:\MALI\clim.dat
        rain.dat
C:\PERU\clim.dat
        rain.dat
        soil.dat
```

Figure 13 Example directory structure and data files.

An example of the directory structure is given in figure 13. In this example, the WOFOST directory contains the WOFOST files and an example data set. Subdirectories MALI and PERU contain the climate and soil data for Mali and Peru respectively. If no soil data are available for Mali, the soil data from the WOFOST sub-directory is used as default.
The order in which the data files are searched for is:

a) search current directory, and when not found,
b) search the directory that contains the WOFOST executable program.

If a data file cannot be found, the program is aborted.

5.2 Start and output options

WOFOST is started by a command line like:

```
[sub-directory]WOFOST [options] [output-file]
```

Various start and output have been made available in the form of command lines given below. The options are built into WOFOST in the form of a shell. The programming for this shell was largely done in Microsoft FORTRAN, and partly in Microsoft C (see ANNEX 6). When required, further modifications to this shell can be made in the appropriate files.

The following line options are given in figure 14:

/a	Correction facility for higher altitudes (see paragraph 2.1)
/b<file name>	Batch mode; WOFOST will be run with the input of boundary conditions to be read from a batch file (see paragraph 5.2). Without such a batch file, WOFOST will interactively request the user to enter the boundary conditions necessary for each simulation.
/h	Display **help** text; displays this list of options
/i*xx*	Set **interval** for output to *xx* days; if set to zero, no interval output is generated; the default *xx* value is 10 days.
/n	Enable **nutrient**-limited calculations; after the water-limited production calculations, nutrient requirements are calculated for the average water-limited yields.
/p	Turns **pause** off between different output sections; output defaults to the console (screen) with pauses between the output sections.
/q	**Quicker** simulation (not implemented at present)
/s	Disables **summary** output after each block of simulation intervals
/t*xx*	Run **water** limited production calculations *xx* times; when you forget this option, you can enter the desired number of runs after the first simulation at the prompt 'More runs with generated rain? 0 is stop. [1]: '.
/w{0|1|2|3}	Controls display of **water balances**; 0 = no water balances, 1 = water balance for whole system, 2 = water balance for root zone, 3 = both water balances (see figure 12)
/1	Calculates potential crop production only (production situation 1)

Figure 14

Some examples of command lines:

wofost /i0/s/w0	- no output will be given
wofost /i0/w0	- summary output only (attractive when running many production situations in batch mode)
wofost /1	- potential crop production (with default output)
wofost	- potential and water limited crop production (with default output)
wofost /n	- potential, water limited, and nutrient-limited crop production (with default output)
wofost /n/i0/w0/bBATCH.IN BATCH.OUT	
	- WOFOST runs from a batch file with the name BATCH.IN for the potential, water limited, and nutrient limited productions; summary output data are written to an output file with the name BATCH.OUT
	note: 1. the naming of BATCH.IN and BATCH.OUT are free 2. one space is needed between BATCH.IN and BATCH.OUT.

In the examples above, the 0 represents a zero and not the capital O letter.
The number of input parameters required by WOFOST, are determined by the production level situations as chosen by the command options. A flow chart of the boundary conditions input is shown in figure 15.
Except for the batch mode command, for all other command the WOFOST programme will run in an interactive way. In the latter sitution the user will specify the boundary conditions by typing the answers of questions displayed on screen. The first required input is the selection of crop, climate, and soil conditions. Correction factors can be given for the crop development rates before and after anthesis (not shown in figure 15).

5.3 Batch processing

Generally, the interactive use of WOFOST is only used in the learning stage, e.g. to familiarize oneself with the programme, to understand the relative large number of variables which can be studied etc. There after one will appreciate soon the batch facility as it enables considerable time saving.

A batch file can be made with a text editor as mentioned in chapter 3. In a batch file, each line contains all the required boundary conditions or control variables for a simulation run which are requested by WOFOST when interactively used. It depends on the production situation selected whether all variables are used. Note that the desired production situation itself (potential, water limited, or nutrient limited) is **not** selected in the batch file. Figure 15 gives an example of a batch file.

```
*Batch series to check the effect of variables a and b for climate 29
*crp clm                      sol year rep ssi ssmax grw dd wav rdmsol notinf start maxdur nfert nrec
* .. pfert prec kfert krec
8 clim=(id=29, a=0.18, b=0.55) 10 0 2 0 0 0 0 2 120 0.0 150 365 30 0.5 10 0.1 30 0.5
8 clim=(id=29, a=0.25, b=0.45) 10 0 2 0 0 0 0 2 120 0.0 150 365 30 0.5 10 0.1 30 0.5
8 clim=(id=29, a=0.29, b=0.42) 10 0 2 0 0 0 0 2 120 0.0 150 365 30 0.5 10 0.1 30 0.5
```

Figure 16 Example batch file for wofost.

The batch file contains the following variables:

CROP	Crop species number as given in the basic data file CROP.DAT.
CLIM	Climate station number as specified in the CLIM.DAT file.
SOIL	Soil type number as given in the SOIL.DAT file.

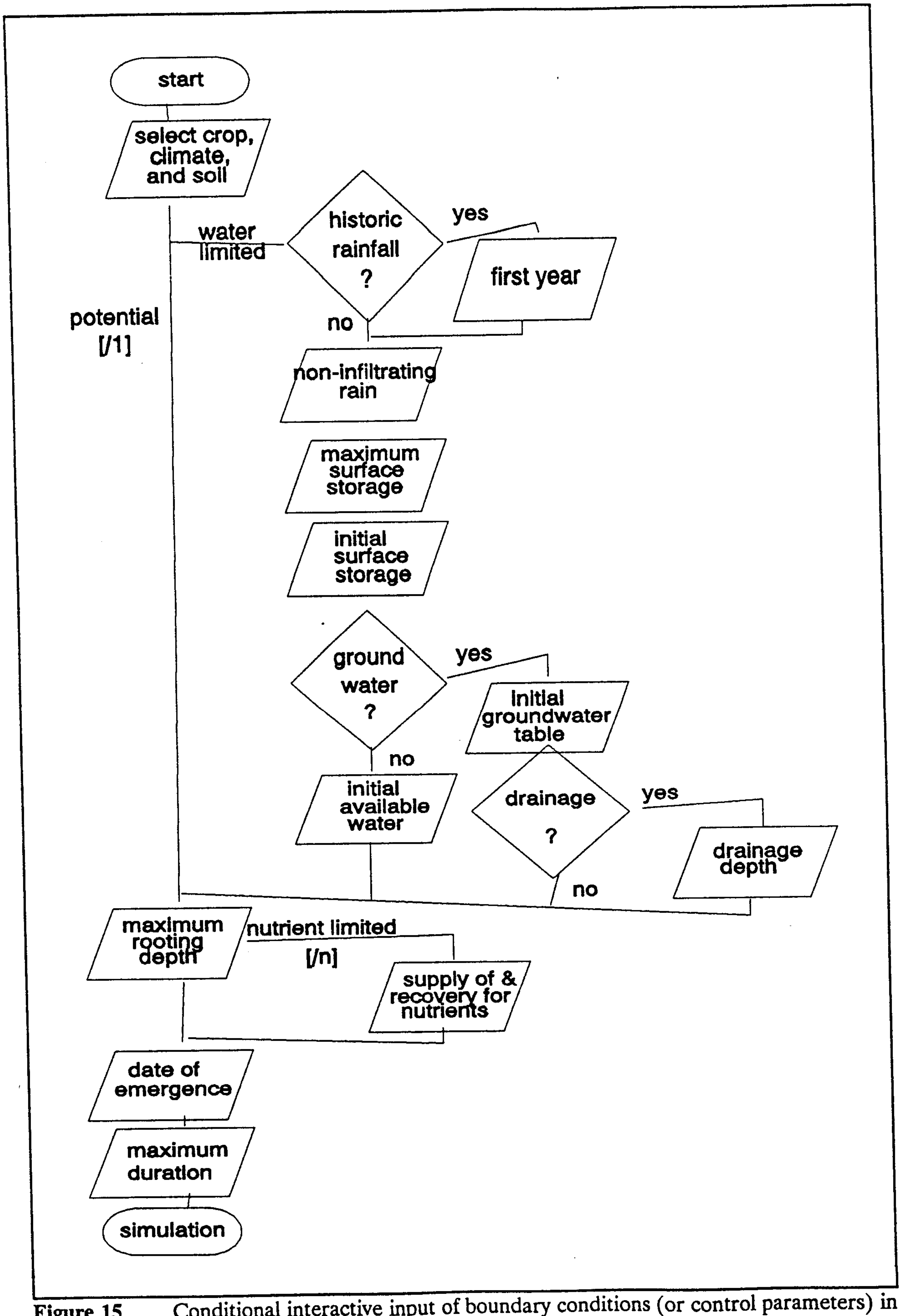

Figure 15 Conditional interactive input of boundary conditions (or control parameters) in WOFOST for the potential, water and nutrient limited production situations.

YEAR	Values 1,2,3, etc. indicates the first year of historic daily rainfall data as given in the RAIN.DAT file; or 0 for generated rainfall from monthly data in the CLIM.DAT file.
REP	Number of runs/years that water limited production is calculated (when using the rainfall generator).
SSI	Initial surface storage; the initial surface storage is only required for wet rice cultivation.
SSMAX	Maximum surface storage.
GRW	Groundwater depth, or 0 in absence of groundwater.
DD	Drainage depth, or 0 in absence of drainage.
WAV	Initial amount of available water (cm); it is used to calculate the initial soil moisture content in the root and the lower zones.
RDMSOL	Maximum rootable soil depth.
NOTINF	Fraction of non-infiltrating rain; it can be used to vary the average amount of surface runoff; note that the fraction of non-infiltrating rain is not made dependent on the amount of rainfall.
START	Start of simulation, i.e. emergence of crop (e.g. 1 = 1 Jan, 121 = 1 May etc.).
MAXDUR	Maximum duration of crop growth; it is used to limit the total period of crop growth; e.g. fodder maize cultivated in the Netherlands is always harvested before maturation because of low temperatures.
NFERT	Amount of nitrogen applied.
NREC	Recovery fraction for nitrogen applied.
PFERT	Amount of phosphorus applied.
PREC	Recovery fraction for phosphorus applied.
KFERT	Amount of potassium applied.
KREC	Recovery fraction for potassium applied.

The variables that can be set for crop, climate, and soil type are all variables referring to the basic data files. Therefore, e.g. monthly temperatures can not be specified here.

The water limited production calculation depends on the presence of ground water and drainage depth. If ground water is absent, the value of the groundwater parameter GRW (see figure 14) is set to 0. If drainage is absent, DD is set to 0.
The type of rainfall data to be used is determined by the value in the YEAR column. A zero '0' activates the use of monthly data and the rainfall generator. Another value (1,2,3, etc.) indicates the first year of historic rainfall that will be used in the simulation.
When running in batch mode, no pauses are included in output to the screen, and the corresponding line in the batch file is given above the output of each simulation. In order to get only summary output from batch runs, use the command line options */i0/w0.*

5.4 Initial settings

WOFOST.INI contains the initial settings for the program. These settings are read at the startup of the program. The variables which are initialized by this file are presented here with their default values at the right margin.

MHFC	matric head at field capacity, cm (pF 2.3)	200
MHPWP	matric head at permanent wilting point, cm (pF 4.2)	16000
IDOUT	number of days in output interval	10

IVARP	controls request for VARP1 and VARP2; when IVARP equals 0, these are not requested	0
IFUNRN	controls whether or not the infiltrating fraction of rainfall depends on the amount of rainfall; 0 means not dependent (i.e. fixed fraction)	0
IDSTAR	default start date for crop growth	1
IDEND	maximum duration of crop growth	365
CRPFIL	name of crop data file	CROP.DAT
CLMFIL	name of climate data file	CLIM.DAT
SOLFIL	name of soil data file	SOIL.DAT
RAIFIL	name of daily rainfall data file	RAIN.DAT

5.5 Recommended testing procedure

For initial testing and calibration the following procedure is recommended:

1. Install the WOFOST as explained before
2. Calculate the potential, water and nutrient limited production situations for a combination of known climate, soil and crop conditions.
   Keep these output results for future error testing of the programme.
3. Adapt or expand local data the climate and soil basic data files (CLIM.DAT, SOIL.DAT and RAIN.DAT if daily rainfall are available).
4. Execute a number of sensitivity tests, i.e. run the programme for studying the influence on crop production of e.g. germination date, effective soil depth, fraction of not-infiltrating rain.
   Study the influence of the rainfall generator by running e.g. 20 or more (year) repetitions.
5. Compare above mentioned output with available data of field production situations, e.g.
   - Adapt the growing period of the crop (VARP1 and VARP2, see below)
   - Make correlation studies of WOFOST output and historic field crop production data.

6 DISCUSSION AND POSSIBLE ADAPTATIONS

Some preliminary comments and possible future adaptations to the current model are given here.

It is strongly recommended to use WOFOST first at a research level before using it in a routine way. Updating of basic data files (CLIM.DAT and SOIL.DAT) and subsequent testing for a number of local conditions with historic crop production data are first activities to be executed.

The results of the water limited production are strongly influenced by the selected soil type (from the SOIL.DAT file). When Dutch soils are selected for tropical regions with high rainfall values, the crop growth will be stagnated by saturation of the soil. Because generally, saturated hydraulic conductivity values of Dutch loam and clay soils are (very) low in comparison to e.g. well drained tropical red clay soils (Ferralsols/Uxisols, Acrisols/Ultisols, etc.). Those clay soils have generally a very high porosity and a very high permeability.

In the WOFOST model, nitrogen fixation is taken into account for a crop as a fixed fraction of the required nitrogen that is supplied by the crop itself. In practice however, the amount of nitrogen fixed is reduced when the mineral nitrogen supply increases.

Initial moisture content is of great importance for the outcome of the simulation. Initial moisture content in root zone gives a lower moisture content for a deep-rooting crop!
Initial available water (WAV) means the amount of water present above wilting point. It is used to fill up the initial root zone to field capacity (saturation when rice). Note that WAV is required only in absence of groundwater (see figure 15).
Figures 17 and 18 show the influence of initial available moisture on maize yield, when the MARKOV constant is 1 or 0.75.

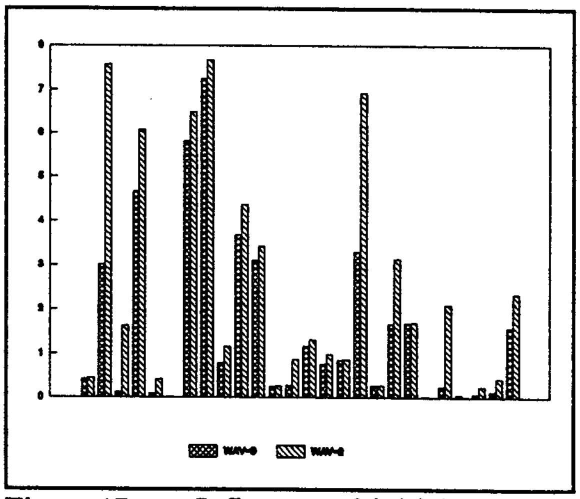

Figure 17 Influence of initial moisture content on maize yield (tons/ha), markov = 1.

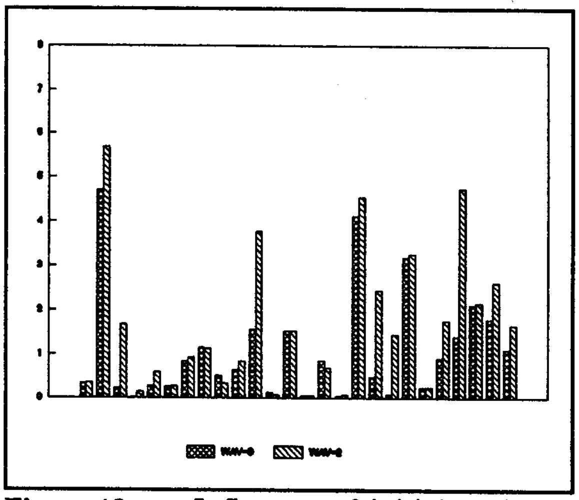

Figure 18 Influence of initial available moisture when markov is 0.75.

Simulation without a crop, before the crop is actually planted, may serve as a means to estimate the initial moisture state. Another aspect is the distinction between sowing date and date of emergence. Seed will only emerge when moisture content is favourable.

A conditional start may be desirable with the planting day being delayed if calendar date, temperature, or soil moisture status do not fall within acceptable boundaries. In practice, delayed rains will result in a delayed planting date.

WOFOST uses "afgen" tables for linear interpolation. This gives an error in peaks and depths in the data (see January, April, figure 19). Thus the average of an "afgen" interpolated table does not results in the actual average, but less.

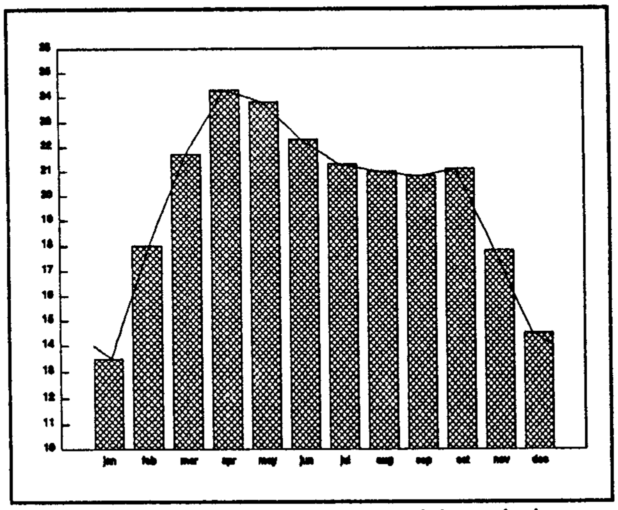

Figure 19 Average monthly minimum temperatures and interpolated daily minimum temperature for Sikasso (Mali).

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