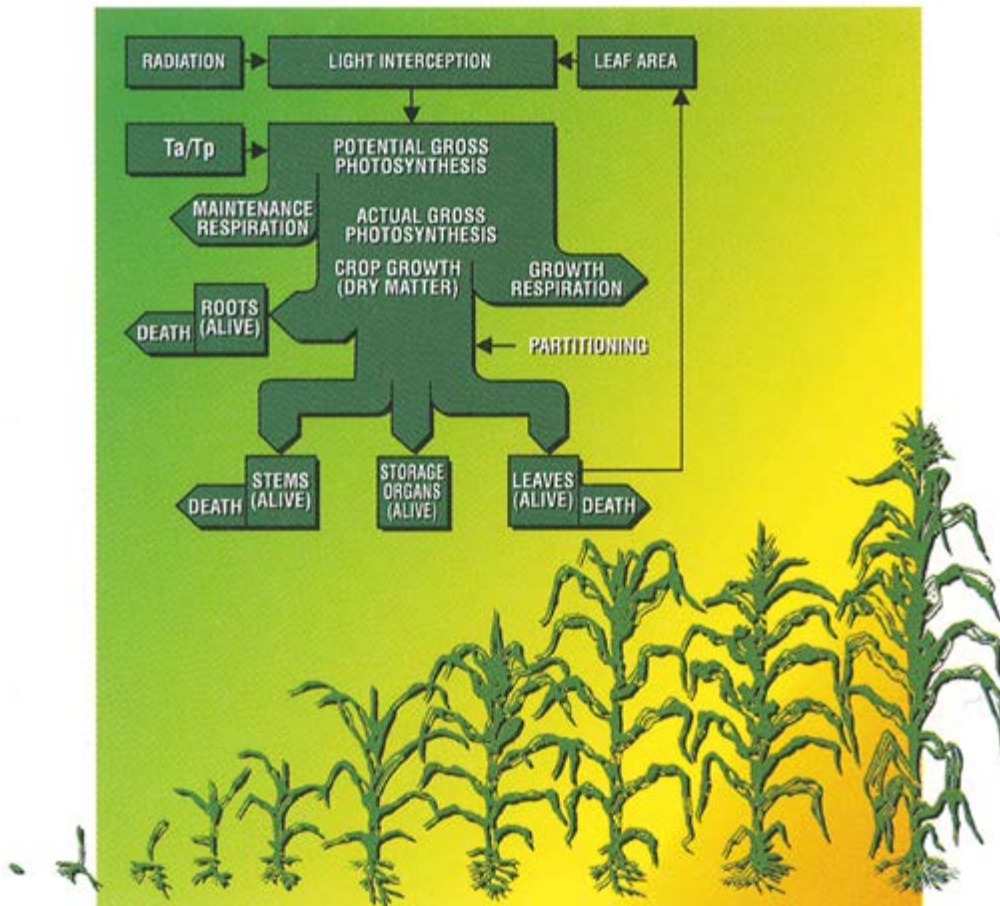


WOFOST Control Centre 2.1 and WOFOST 7.1.7



<http://www.wageningenur.nl/wofost>

WOFOST Control Centre 2.1 and WOFOST 7.1.7

User's guide for the WOFOST Control Centre 2.1 and WOFOST 7.1.7 crop growth simulation model

Editors of updated version:

**H.L. Boogaard
A.J.W. De Wit
J.A. te Roller
C.A. Van Diepen**

Original authors:

**H.L. Boogaard
C.A. Van Diepen
R.P. Rötter
J.M.C.A. Cabrera
H.H. Van Laar**

**Alterra, Wageningen University & Research Centre,
Wageningen, 2014**

ABSTRACT

H.L. Boogaard, A.J.W. De Wit, J.A. te Roller, C.A. Van Diepen, 2014. *WOFOST CONTROL CENTRE 2.1; User's guide for the WOFOST CONTROL CENTRE 2.1 and the crop growth simulation model WOFOST 7.1.7.* Wageningen (Netherlands), Alterra, Wageningen University & Research Centre.

WOFOST version 7.1.7 is a computer model that simulates the growth and production of annual field crops. All the run options are operational through a graphical user interface named WOFOST Control Centre version 2.1 (WCC). WCC facilitates selecting the production level, and input data sets on crop, soil, weather, crop calendar, hydrological field conditions, soil fertility parameters and the output options. The files with crop, soil and weather data are explained, as well as the run files and the output files. A general overview is given of the development and the applications of the model. Its underlying concepts are discussed briefly.

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Foreword

By the end of the 1960's computers had evolved sufficiently to allow synthesis of detailed knowledge in different disciplines, and languages were developed that facilitated the use of computers for description of natural phenomena that contrary to the computer, were parallel and continuous. One of the first scientist to recognize the potential of this tool for agricultural sciences was C.T. (Cees) de Wit, professor of Theoretical Production Ecology and founder of the Department of that name in Wageningen Agricultural University. His efforts in developing the ELementary CROp growth Simulator (ELCROS), in collaboration with colleagues of the Institute for Biological and Chemical Research on Field Crops and Herbage (IBS) were mainly aimed at unraveling the 'mysteries' of the growing crop and provide a consistent quantitative basis for their theories on the functioning of the plant and its component parts.

This 'Eden' of basic, curiosity-driven research, however, followed in the footsteps of its biblical predecessor, in that it appeared only a temporary refuge, from which the scientists were expelled into the client-driven world of applied research. One of the first projects in which crop growth simulation was an integral part of the research methodology applied, was that initiated by the Centre for World Food Studies (SOW, by its Dutch acronym). This comprised an interdisciplinary group of scientists from the Department of Development Economics of Amsterdam's Free University and from Wageningen the Department of Theoretical Production Ecology and the Center for Agrobiological Research (CABO, currently AB-DLO) of the Department of Agricultural Research (DLO). The aim of the Centre, funded by the Ministries of Development Cooperation and Agriculture in the wake of the Club of Rome report, aimed at exploring the potentials and constraints for increased food security in developing countries, by integrating advanced knowledge from the (agro-)technical and the (socio-)economic disciplines, using a modelling approach. For the agro-technical side the model WORld FOod STudies (WOFOST) was developed along the 'Wageningen lines', parallel to other models such as SUCROS, to simulate crop production potentials as dictated by environmental conditions (soils, climate), crop genetic properties and crop management (irrigation, fertilizer application, pest and disease control).

Since those early days WOFOST has gone a long and winding road, often being used (or applied) for purposes it was not intended for, and, befitting a dynamic model, going through a continuous (and sometimes parallel) series of corrections, modifications, adaptations, extensions and... improvements. Along this tortuous road, milestones have been erected at (ir)regular intervals, consisting of successive User Manuals, in attempts by the developers/custodians to, on the one hand, 'freeze' the situation at a certain moment and take (documented) stock of the turbulent developments and on the other hand make the model accessible to potential 'clients'.

The current report is yet another of those milestones, documenting version 7.1.7 of WOFOST (which by no means would even suggest that it was preceded by no more than six other operational versions), which again provides an array of new and advanced features in model structure, input and output handling and user-oriented menu interface. Many individuals and organisations have contributed to the transition from the previous (documented) version, as witnessed by the many reports on the application and use of the model in the last years. In the past decade, the 'Wageningen family' of models has been further developed and extended in joint projects with the International Rice Research Institute (IRRI) in the Philippines, resulting in the ORYZA branch, based on the same principles. The current version of WOFOST has strongly profited also from these developments.

This seems an appropriate moment to release this joint baby of Wageningen Agricultural University and the Research Department of the Ministry of Agriculture, to whose further development many others have contributed, at a point in time where the courtship between the two has become serious on their way to the happy marriage in the Wageningen University and Research Center (WUR). We are convinced that this version of WOFOST again will find many clients and will continue to play its role in the development of agricultural production systems that provide sufficient and healthy food for all people in a sustainable environment.

Herman van Keulen

DLO Research Institute for Agrobiological Sciences (AB-DLO)

Martin Kropff

The C.T. de Wit Graduate School for Production Ecology

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This technical document is the user manual for WOFOST version 7.1.7 and the user interface WOFOST Control Centre (WCC) 2.1. Of course there would not have been a user manual without the development of WOFOST. Many people have directly or indirectly contributed to the development of WOFOST. We would like to acknowledge here specifically the contributors to the main stream development.

WOFOST 4.1 was the most fully documented version, in 1988 by C.A. Van Diepen, C. Rappoldt, J. Wolf and H. Van Keulen. Conceptual model development since that time leading to version 6 has been carried by the same group with collaboration of D.W.G Van Kraalingen and G.H.J. de Koning. Software development was carried out by Van Kraalingen, Rappoldt and Van Diepen. Model formulation and documentation has benefited from the work of the late C.J.T. Spitters, J. Goudriaan, M.J. Kropff, and H.H. Van Laar of the Department of Theoretical Production Ecology of the Wageningen Agricultural University (WAU-TPE), and the establishment of crop parameters from the work of H.D.J. Van Heemst, E.R. Boons-Prins, W. Stol, G.H.J. de Koning, F.W.T. Penning de Vries (AB-DLO).

WOFOST version 6.0 was developed for the Joint Research Centre (JRC) of the European Commission at Ispra, Italy (MARS project: Monitoring Agriculture with Remote Sensing). The user manual of WOFOST version 6.0 was prepared by R.J. Hijmans, I.M. Guiking-Lens and C.A. van Diepen. The system description of WOFOST version 6.0 was made by I. Supit, A.A. Hooijer and C.A. van Diepen. We acknowledge the support of P. Vossen (JRC).

Incentives for further improvement of WOFOST came from the Sysnet project (which stands for the collaborative Systems Research Network to develop Systems Methodology for Ecoregional Land Use Planning in Support of Sustainable Resource Management in Tropical Asia) of the International Rice Research Institute (IRRI) and the NWO funded project to estimate Regional Production Potential in the Russian Federation (RPPR). We thank NWO for its financial support.

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C.A. Van Diepen, WOFOST development coordinator, SC-DLO

R.P. Rötter, SysNet Project Coordinator, IRRI

Summary

This guide explains how to use the WOFOST 7.1.7 crop growth simulation model and its graphical user interface WOFOST Control Centre 2.1 (WCC). WOFOST estimates the growth of an annual crop, given a set of specific soil and weather conditions. The simulation of crop growth is based on eco-physiological processes. The major processes are phenological development, CO₂-assimilation, transpiration, respiration, partitioning of assimilates to the various organs, and dry matter formation. Potential production and two levels of limited production (water-limited and nutrient-limited) can be calculated. Production-reducing factors (like weed and pests) are not taken into account.

WOFOST is a member of the family of models developed in Wageningen by the school of C.T. De Wit. All these Wageningen models follow the hierarchical distinction between potential and limited production, and share similar crop growth sub models, with light interception and CO₂ assimilation as growth driving processes, and crop phenological development as growth controlling process.

WOFOST originated in the framework of interdisciplinary studies on world food security and on the potential world food production by the Center for World Food Studies (CWFS) in cooperation with the Wageningen Agricultural University and the DLO-Center for Agrobiological Research and Soil Fertility. The development of WOFOST has been connected to the need for its application in various studies carried out by DLO Winand Staring Centre (SC-DLO). SC-DLO developed WOFOST version 6.0 to simulate the production of annual field crops all over Europe for the Commission of the European Communities. It was incorporated in a Crop Growth Monitoring System (CGMS) to provide objective data for regional crop state monitoring and yield forecasting at regional and national scales. In CGMS WOFOST is fully linked to a geographical information system and to a relational data base management system.

The version 7.1.7 of WOFOST is normally used with the graphical user interface WCC version 2.1. The WCC offers a user friendly way to operate WOFOST version 7.1.7. Chapter 3 of this technical document describes the various functions and features in the WCC and serves as a reference. Each different cluster of input and output data (a tab) in WCC is presented, discussed and visualized with examples. The data on crops, crop calendar, soil, and site can be modified through the tabs or through a special rerun table format. The output can be displayed in the classical table format or as graphs as function of time (days) or can be exported to a spreadsheet.

In principle, WOFOST can simulate the growth of any annual crop growing at any location. To facilitate this, the specific crop, soil and weather parameters have been put in separate data files (crop, soil and weather files). This makes it relatively easy to add a new file to the WCC with e.g. the parameters of a specific

crop you work with, or data from a nearby weather station. In case of adding new files this technical document explains the obligated format of the crop, soil and weather files. It is also possible to run the WOFOST without the WCC. In this case you edit and view the input and output files of WOFOST. The format of all these files is fully described.

Finally, this technical document provides information on the installation of WCC and the source code of WOFOST

1 Introduction

1.1 Scope of this user's manual

This guide is an introduction to WOFOST Control Centre 2.1 and WOFOST version 7.1.7. To facilitate dealing with a large number of options the current version of WOFOST is accompanied with a graphical user interface named WOFOST Control Centre (WCC) version 2.1 managing the various input and run options. This manual will guide you through all options available in the WCC. The different data files used in WOFOST: the input files, the run files and the output files are discussed as well.

To be able to use WOFOST in a meaningful way, a general knowledge of plant growth and development and of the environmental factors by which these are influenced is a prerequisite. Ideally, you have a background in crop ecology (e.g. Loomis and Connor, 1992) and land evaluation (e.g. FAO, 1976; Driessen and Konijn, 1992), and, you are familiar with the system-analytical approach to agricultural production (e.g. Penning de Vries et al., 1989; Van Keulen and Wolf, 1986; Leffelaar, 1993). In this guide, WOFOST is treated as a 'black-box'. You will be explained how to provide input to WOFOST and how to have it calculate the type of output you desire. The guide does not discuss all concepts on which the model is based, nor its algorithms. However, an overview of the theoretical background is provided in Chapter 5. For a detailed program description, you are referred to Supit et al. (1994).

1.2 Conditions of use and distribution

The copyright holder of WOFOST Control Centre 2.1 and WOFOST 7.1.7 is Alterra, Wageningen University & Research Centre. The software can be ordered at the contact addresses (see below) and is also available at the internet (<http://www.wageningenur.nl/wofost>).

The source code of the WOFOST 7.1.7 model (in FORTRAN77) can be obtained from the same website and is licensed under the European Union Public License¹. The EUPL is an open source license and meets the conditions expressed by the Free Software Foundation:

- Freedom to use or run it for any purpose and any number of users;
- Freedom to obtain the Source Code (in order to study how the software works);
- Freedom to share, to redistribute copies of the software;
- Freedom to modify, adapt, improve the software according to specific needs and to share these modifications.

¹ <https://joinup.ec.europa.eu/software/page/eupl>

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However, although any responsibility for errors and/or updating is declined, you are kindly asked to report any errors or deficiencies. Other information or comments on the use of WOFOST are welcome as well.

Contact address:

A.J.W. De Wit
Alterra, Wageningen University & Research Centre
P.O. box 47, 6700 AA Wageningen
Netherlands
tel: +31-317-481914
e-mail: allard.dewit@wur.nl
<http://www.wageningenur.nl/wofost>

1.3 Main changes in relation to WCC 1.8 and WOFOST version 7.1.3

The main changes compared to WOFOST Control Centre 1.8 and WOFOST 7.1.3 are:

- The option to use monthly weather data has been removed from the WOFOST Control Centre, for two reasons:
 - The use of monthly weather data is strongly discouraged and is not necessary given that daily weather data is generally available.
 - The use of monthly weather data lead to strange results in WOFOST and given the point above we decide not to spend time fixing this problem.
- Improved charts in the WOFOST Control Centre correctly handling the case when simulations cross the year boundary. WOFOST itself has no problem with year boundaries whatsoever but the charts could be awkward in certain cases.
- Additional tab menu for setting parameters for the Timer (start of simulation, etc.)
- Small bug fixes in the WOFOST source code related to calculation of summary statistics for multi-year runs.

1.4 Main changes in relation to WCC 1.5 and WOFOST version 7.1.2

The main changes compared to WOFOST Control Centre 1.5 and WOFOST version 7.1.2 are:

- Windows 7 compatible installer and structure:
- Executables and documentation are placed under "Program files"
- Crop, Soil, weather and log files are placed under "All Users"
- FSEOPT removed from source tree
- Platform independent source code distribution. WOFOST has been compiled on Windows (XP), Linux 32/64 bit and Mac OSX (Tiger) using the GNU gfortran compiler.
- Bug fixes:

- ASTRO module was adapted to allow simulation at high latitudes with daylength=0 or 24 hours
- Start days of waterbalance (ISDAYB) is now interpreted in a different way. If the start day is before the sowing/emergence day it is applied for the same year. If the start day is after the sowing/emergence day the water balance is started the year before
- Path names up to 250 characters are now allowed.
- 8:3 Filename convention for weather, crop and soil files has been removed

1.5 Main changes in relation to WOFOST version 6.0

The main changes since WOFOST version 6.0 are:

- The method to enter input data is changed: the user has to provide all input data via graphical user interface: WCC (WOFOST Control Centre) or via files WCCTI.TIM (timer), WCCSI.SIT (site), WCCRE.RER (rerun) and RUNOPT.DAT (run options) when running in MS-DOS mode.
- Introduction of the following variable in the crop file:
 - DVSI = DVS at start of simulation. This is important for transplantation of rice.
 - Change of the following variable in the crop file:
- SSA becomes SSATB (specific stem area against DVS).
- KDIF becomes KDIFFTB (extinction factor for diffuse visible light against DVS).
- EFF becomes EFFTB (light use efficiency single leaf against DTEMP)
- The site file (WCCSI.SIT) has been extended with the variables SSI and SMLIM (see Section 6.5.2). These variables can also be changed in WCC.
- Descriptions formerly found in W6OMENU.DAT have been incorporated in the data files (crop, weather and soil files). Data files in respective directories will be automatically read in WCC. Therefore a number of 'fixed' data fields have to be filled in the data files (see Section 6.2, 6.3, 6.4).
- The Ångström coefficients were given in W6OMENU.DAT. In WOFOST version 7.1 the W6OMENU.DAT is removed and the Ångström coefficients always appear in the weather files. So in the WOFOST weather format (monthly and climate) Ångström coefficients are given. They are added as the fourth and fifth values (just after elevation). In the CABO weather format the Ångström coefficients are already in the file. The indicator whether measured radiation or sunshine duration is given in the CABO weather file consists of a minus sign. Negative values of the Ångström coefficients indicate measured radiation in the CABO weather files (see Section 6.4).
- Initialization of soil moisture content by running the water balance before emergence. The introduction of the variable ISDAY (start date water balance) in the timer file (WCCTI.TIM) (see Section 6.5.1).

1.6 Set up of this user's guide

This guide consists of six chapters:

- Chapter 1, the present chapter, provides a general introduction and information on this user's guide.
- Chapter 2 provides information on the hard- and software requirements, on the installation of WOFOST and the source code of WOFOST.
- In Chapter 3, the working of the WCC is described. Each different cluster of input and output data (tab) is presented and discussed. Running WOFOST from a command box (e.g. "terminal mode") is also explained. This chapter gives the user an impression of how the WCC and WOFOST should be used.
- In Chapter 4, the development, limitations and applications of WOFOST are discussed.
- In Chapter 5 the methodological approach underlying WOFOST, systems analysis and simulation, is introduced and the basic principles of crop growth simulation are presented.
- Chapter 6 describes the data files on crops, soils, weather and how additional data defining specific site conditions and crop calendar are grouped into clusters. The output files and log files are also discussed.

2 Installation of WOFOST Control Centre

2.1 System requirements and installation

The WOFOST Control Centre can be installed on computers running Windows XP, Windows Vista and Windows 7. Windows 8 has not been tested but it is expected that WCC will run fine on Windows 8 as well. Note that the *Borland Database Engine is not required anymore* to install WCC.

To install WCC, run the installation program which will ask you to accept the EUPL license and will ask for an installation directory. WCC MUST be installed in a directory where the user has read and write access! This means that WCC cannot be installed on “Program Files” but instead should be installed in a directory under the user’s home directory which usually means “c:\users\” on Windows 7.

The good side of this approach is that the installation of WCC does not need any administrative rights. Moreover, the WCC has no dependencies and makes no entries in the Windows Registry. The installation folder of WCC can therefore be copied or moved to another location and can even run from a USB device. The downside of this approach is that the installer of WCC will not make an entry in the Start Menu for starting WCC and the user will need to start the “WOFOST Control Centre.exe” from the installation folder (although the Start Menu entry can be created manually).

2.2 Source code of WOFOST

The source code of WOFOST version 7.1.7 is written in FORTRAN-77 and can be downloaded from <http://www.wageningenur.nl> as a separate package. This source code is described in Annex F. Annex F also presents a diagram of the model structure, most of the different subroutines and how they are related to each other.

The WOFOST related subroutines make use of standard subroutines (e.g. for opening and reading files) from the TTUTIL library v4 (Rappoldt and van Kraalingen, 1990). The TTUTIL library is included with the WOFOST source distribution and has been slightly adapted to allow longer path names.

To modify the source code, WOFOST must be recompiled and linked using a FORTRAN compiler. When changes made to the source code influence the input and output, the WOFOST Control Centre cannot be used anymore and WOFOST should be run from the Command Line (e.g. “terminal mode”). In this specific situation, the temporary input files (see Section 6.5), which the WCC generates on the sub directory ‘RUNIO’, can be used to edit input data.

WOFOST is known to run on Windows, Linux and Mac OSX computers without any problems. Information on how to compile and link WOFOST 7.1.7 on different platforms using the GNU FORTRAN compiler can be obtained from the README files included with the WOFOST source distribution.

3 Description of WOFOST Control Centre (WCC)

3.1 Introduction

Chapter 3 describes the WOFOST Control Centre (WCC) version 2.1. The WCC is a Graphical User Interface on top of WOFOST (version 7.1.7). With the WCC, you can edit and view the input data for WOFOST, run WOFOST, and view and analyze the output data in table or in graphical form. This chapter provides the description of the various functions and features in the WCC and serves as a reference for these details. When you encounter problems please read the appropriate sections in Chapter 3 and 6 and also check Annex C (troubleshooting).

In this chapter, illustrations for each different window and for each different tab within a window of the WCC are shown. The example provided is a run for potential and water limited production of winter wheat in the Netherlands, with fixed emergence on a coarse soil using daily weather data. The input and output files for this run are described in Chapter 6.

The choices you can make in the WCC are described in this chapter and are marked bold. This makes it easier to find a certain topic you are interested in.

This chapter consists of technical information on how to handle the WCC (Section 3.2) and the description of the following functions and features of WOFOST:

- general, controlling features: the menu and button bar (Section 3.3);
- editing input data of WOFOST (Section 3.4);
- viewing and analyzing detailed output data of WOFOST (Section 3.5);
- viewing and analyzing summary output data of WOFOST (Section 3.6);
- running WOFOST in terminal mode (Section 3.7).

3.2 Technical information on handling the WCC

The WOFOST Control Centre can be started by clicking on the file “Wofost Control Centre.exe” in the installation directory. The WCC log-on screen will appear followed by the main window of the WCC session. Technically the WCC has the following elements (see Figure 1):

- menu bar (options: File, Result, Help);
- button bar (options: Exit, Reset, Run, Result detailed, Result summary, Help);
- tabs (options: General, Crop, Weather, Soil, Nutrients, Reruns).

The button bar represents the most regularly used options of the menu bar so, all the options in the button bar are also available in the menu bar. You may activate the options in the WCC using the mouse or by using the ‘hot’ keys. The hot keys are activated by simultaneously pressing the ‘alt’ key and an underlined letter in the WCC. For example, the combination ‘alt’ with the letter ‘f’ will activate the File option (see Figure 1). Within a menu, you can choose an option by pressing on the keyboard the underlined letter of that option. Options within a

tab can also be operated using the 'tab' and up/down arrow keys. You can move from one tab to another by pressing the left/right arrow key.

In certain cases, choosing options or editing values is disabled. You will notice this by the grey colour of options or values instead of a white or black colour. Whether options or values are disabled depends on choices that were made earlier by the user. Finally, values changed by the user are checked whether they are between physically possible limits. This control takes place after you leave the field where you enter the value. In the rerun tab (Section 3.4.7), this control takes place when you activate the run function in the WCC or when you select a new variable.

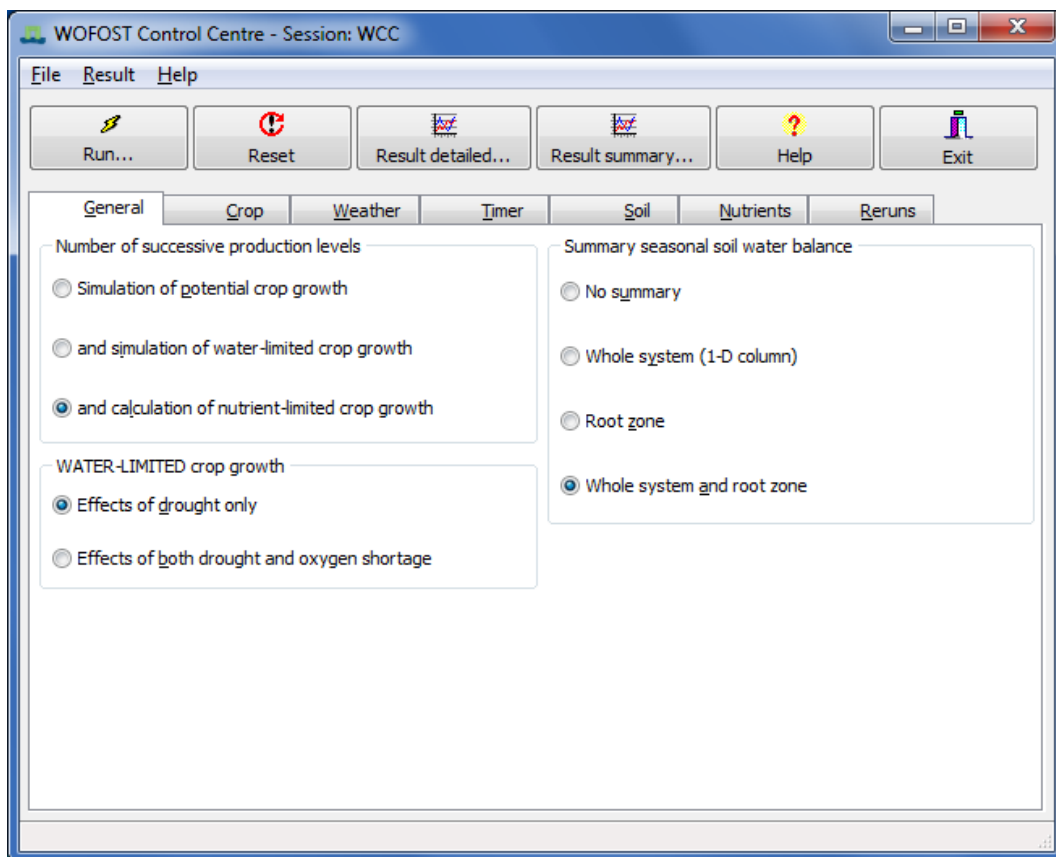


Figure 1. Example of the tab 'General' of the WOFOST Control Centre.

3.3 General, controlling features (menu and button bar)

The following features are relevant to control and work with the WCC:

- open and save (as) a session (menu bar) (Section 3.3.1);
- reset data (menu and button bar) (Section 3.3.2);
- run WOFOST 7.1.7 (menu and button bar) (Section 3.3.3);
- view and edit (log) files (menu bar) (Section 3.3.4);
- exit the WCC (menu and button bar) (Section 3.3.5);
- viewing and analyzing the detailed and summary results (menu and button bar) (section 3.3.6);
- help function (menu and button bar) (Section 3.3.7);

- about the WCC (menu bar) (Section 3.3.8);
- editing and viewing input data (tabs and additional windows) (Section 3.4).

In this section, all above listed items are described except for the different input tabs (Section 3.4) and the special windows for viewing and analyzing the results (Section 3.5 and 3.6).

3.3.1 Open and save (as) a session (menu bar)

When you start the WCC, it will read a set of input and output files with default names (Table 1). The content and format of these files are shown in Chapter 6. The contents of these files are always equal to the settings of the latest run.

Changes you make while working with the WCC are only saved:

- The moment you run WOFOST (see Section 3.3.3). The settings of the run are saved in the default files (Table 1);
- When you explicitly save the settings using the 'save (as)' option in the WCC (see below).

WCC gives you the possibility to save changes done in the input and output files under a different name. Choose 'File/Save session as' from the menu bar. In the 'Save file as' window under the directory ..\RUNIO, supply a filename for the session. The name 'WCC' is not allowed. This name is used inside the program as a work name. The name of the session you provide has a maximum of 6 characters. An extension is not permitted. Choosing 'File/Save session' from the menu bar saves your set of input and output (files).

One setting, the rerun checkbox is not saved when you use the save (as) functionality. So each time you want WOFOST to make reruns you have to enable the rerun function by clicking on the rerun checkbox.

It is also possible to open a specific set of files that has been saved in an earlier session. To open a session (set of input and output files), choose 'File/Open session' from the menu bar. Select in the 'File open' window the session you would like to open. The information of the input and output files is loaded in the WCC and if output files are available, they can be viewed and analyzed.

When you use the 'Save session (as)' option, the WCC copies all the default files as shown in Table 1 to files under the name supplied by the user. When you use the open session functionality, the WCC copies the files with the user defined name to the default files as shown in Table 1.

Table 1 The input and output files of one session

The input and output files	Description
WCC.WCC	File with run options
WCCTI.TIM	Timer file: time related data (weather, crop calendar)
WCCSI.SIT	Site file: concerns the default soil characteristics
WCCRR.RER	Rerun file: for series of consecutive runs
WCC.OUT	File with detailed output
WCC.PPS	File with summary results about the potential crop production
WCC.WPS	File with summary results about the water-limited crop production
WCC.SUM	File with summary results of both potential and water-

3.3.2 *Reset data (menu and button bar)*

A handy feature in the WCC is the reset option in the different tab pages. When you choose **'File/reset'** from the menu bar or the **'Reset'** button on the button bar, WCC loads the default values of variables into the WCC session. These values are implemented in the source code of the program and cannot be changed by the user.

3.3.3 *Run WOFOST 7.1.7 (menu and button bar)*

Choose 'File/run' from the menu bar or the 'Run' button on the button bar. WCC will automatically save the input settings to the default files (Table 1). These files will be used as input by WOFOST version 7.1.7 when WCC executes WOFOST.

When you run WOFOST version 7.1.7, a Command-box window appears with the message *'Running the simulation. Please wait...'*. After this message, three things can happen:

- The message *'Press any key to continue'* appears. Press any key and close the Command-box. A window with the message *'Simulation successful'* appears. You can now look at the results.
- The message *'Press any key to continue'* appears. Press any key and close the Command-box. A window with the message *'Runtime error while running the simulation. Show log-file?'* appears. In this case, you can have a look at the WCC.LOG that contains information on the simulation run. The log-file should lead you to the cause of the runtime error. Sometimes you may get a runtime error message in the Command-box.
- No message appears and the simulation seems to be taking longer than expected. Stop the simulation by pressing *'Enter'*. The message *'Press any key to continue'* appears. Press any key and close the Command-box. A window with the message *'Runtime error while running the simulation. Show log-file?'* appears. Have a look at the WCC.LOG that contains information on the simulation run. The log-file should lead you to the cause of the runtime error.

3.3.4 *View and edit (log) files (menu bar)*

The internal file viewer and editor can open/edit files of less than or equal to 32 Kbytes.

- A log file (plain ASCII) is created every time you run WOFOST. You can view this log file by choosing **'File/View log-File'** from the menu bar.
- The function **'File/View File'** from the menu bar enables you to view any plain ASCII file on your system. Choose the desired directory and file in the 'File/Open file' window.
- The **'File/Edit File'** option in the menu bar lets you edit any plain ASCII file on your system. Select the desired directory and file in the **'File/Open file'** window. However, for serious editing of files, you are better off installing a good text editor on your system

3.3.5 Exit the WCC (menu and button bar)

To leave WCC choose **'File/Exit'** from the menu bar or the **'Exit'** button on the button bar. You may also click on the **'x'** button at the upper right hand corner of the main window.

3.3.6 Viewing and analyzing the detailed and summary results (menu and button bar)

Choose **'Result/Detailed...'** from the menu bar or the **'Result detailed...'** button on the button bar to view and analyze the detailed results of a run with WOFOST. The detailed results are shown in a table format and can also be viewed in graphical form (see Section 3.5).

Choose **'Result/Summary...'** from the menu bar or the **'Result summary...'** button on the button bar to view and analyze the summarized results of a run with WOFOST. Special output windows will show the results of the run in the form of tables only (see Section 3.6). Summary results are only available when WOFOST has been run for two or more years.

3.3.7 Help function (menu and button bar)

Choose **'Help/Contents'** from the menu bar or the **'Help'** button on the button bar to display the user manual. The help function can also be activated by pressing 'F1'-key.

3.3.8 About the WCC (menu bar)

The **'Help/About'** option in the menu bar provides information on exact WCC and WOFOST version and.

3.4 Input data for WOFOST

The input data for WOFOST is described in several tabs (General, Crop, Weather, Timer, Soil, Nutrients, Reruns). In these tabs you can choose options, edit values, and choose crop, weather, and soil files. In the Reruns tab you can change the values of variables in the crop and soil files for a series of WOFOST runs (see Section 3.4.7). The contents of the weather file can only be changed by editing the weather file outside the WCC. If you would like to edit or change crop, soil and weather files you should work very carefully and follow the guidelines in Chapter 5 how to format these input files.

3.4.1 General data

The tab 'General' pertains to the selection of the production level(s) (Figure 1). In WOFOST, it is possible to choose 'Simulation of potential crop growth' only, or simulation of potential crop growth 'and simulation of water-limited crop growth', or simulation of potential and water-limited crop growth 'and calculation of nutrient-limited crop growth'.

Each of the three hierarchical levels of crop *growth* that are distinguished in the model (potential growth, water limited growth and nutrient limited growth) corresponds to a level of crop *production*: potential, water limited and nutrient limited production (Figure 20).

When you select 'Simulation of potential crop growth' or 'and simulation of water-limited crop growth', there is no need to enter data about nutrients so the 'Nutrients' tab is not shown. Furthermore in the water limited crop growth, you can choose between simulating the 'Effects of drought only' or 'Effects of both drought and oxygen shortage' (i.e. oxygen shortage in the root zone).

You can also choose to have or not to have a 'Summary seasonal soil water balance'. The summary can be for the whole soil system and/or for the root zone only (this zone extends as roots grow). The water balance is simulated for the period from emergence until the last day of simulation.

3.4.2 Crop data

In this tab (Figure 2), select the file with specified data about a certain crop or variety you want to simulate. The list of '**Available crops**' shows the crop name and a description, including an indication of the region where the variety is grown. The filename for each crop appears on the bottom bar when you click on the description. The crop file contains a large number of crop model parameters. The right pane shows the contents of the crop parameter files and allows you to scroll through the parameter file to have a look at the parameter values.

Crop parameter values can be changed by editing the parameter file, but often a more convenient way of assessing the impact of a variable is by running the model several times with different parameter values. This can be accomplished using the '**Rerun**' tab (Section 3.4.7).

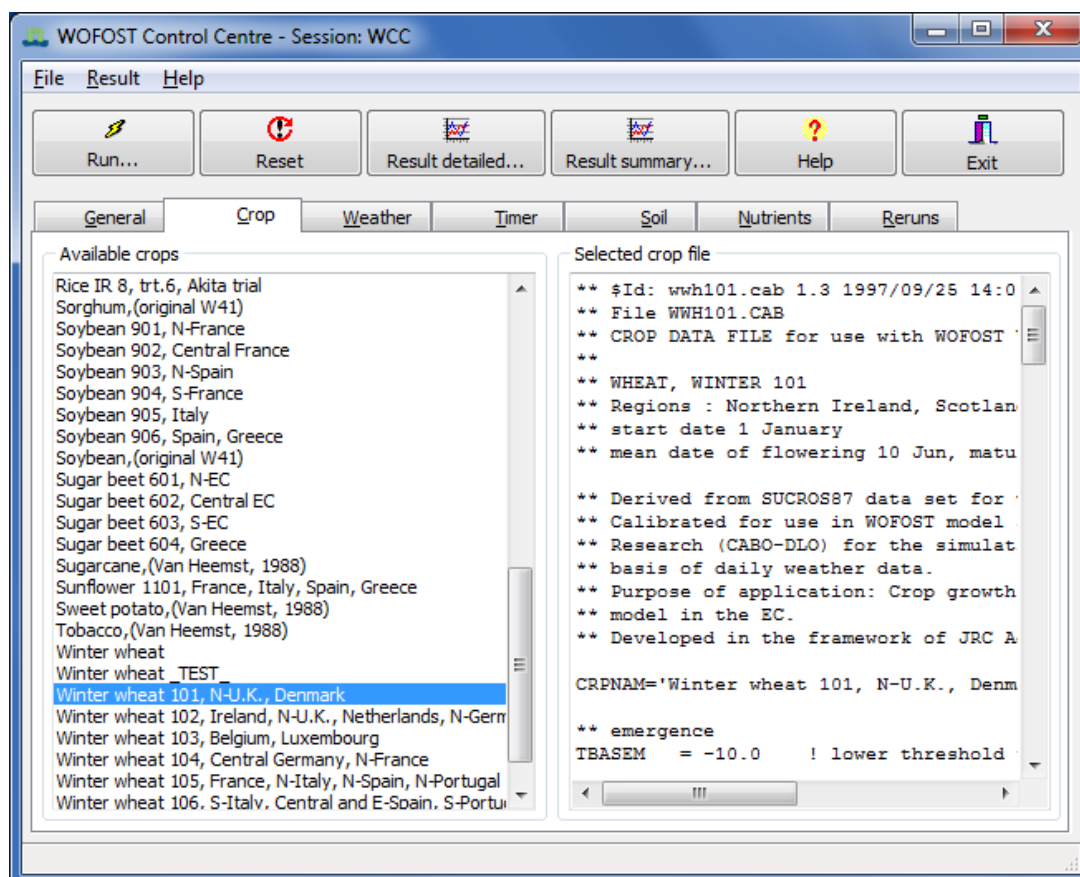


Figure 2. Example of WCC tab 'Crop'.

3.4.3 Weather data

In the tab '**Weather**' (Figure 3) you first have to choose the weather format. Previous versions of WOFOST supported the use of monthly or decadal weather data. However, this option has been abandoned because the use of monthly weather data is strongly discouraged. Therefore, the only supported weather format is the CABO format which stores daily values of several weather variables (<http://edepot.wur.nl/43010>).

Next you can select data from a weather station or a location for which CABO weather files are available. The first and last year available are also shown on the right of the window.

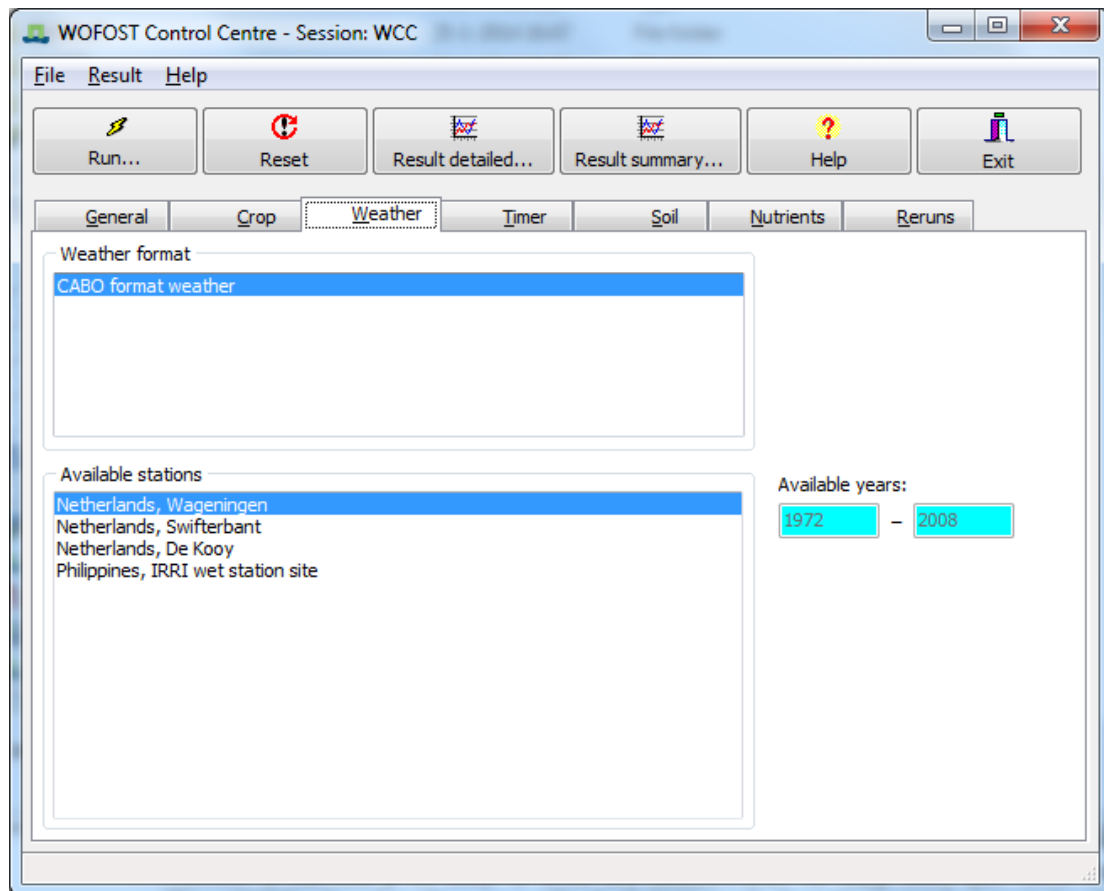


Figure 3. Example of the WCC tab 'Weather'.

3.4.4 Timer data

Under the 'Timer' tab all settings are arranged that deal with the timer, the start of the simulation, the number of years to simulate and the options for starting and ending the crop (Figure 4).

The date is always expressed as *day number of the year (doy)*, hence 1 January is doy 1 and 31 December is doy 365 (or 366 in leap years). The WCC checks the specified doy and duration and corrects the doy and duration for values smaller than 1 (WCC sets value on 1) and greater than 366 (WCC sets value on 366). See Annex D for a table with calendar dates and their corresponding doy.

First of all, the general timer options must be selected: 1) the output interval which is usually one day and 2) the start day of the water balance. The interpretation of the start day of the water balance depends on the start day of the crop simulation. If the start day of the water balance is after the start of the water balance, it is assumed to lie in the year preceding the start day of the crop simulation.

Next, the start 'Start year' must be provided in which the crop simulation must start. The default value is the first year for which meteorological data is available. The start year can be the only year you are interested in or the first year of a series of years for which you want to simulate crop growth. Specify the number of 'Consecutive years' (seasons) for which crop growth should be simulated, starting from the year indicated in the start year. This value, however, should not exceed the number of available years after the start year.

Finally, the options for starting and ending the crop simulation must be specified. First the user must specify the crop calendar day when the simulated growing period should start. When a 'Fixed emergence date' is selected, simulation starts at the day you indicate. When 'Fixed sowing date' is selected, simulation starts on the day of emergence, calculated on the basis of the thermal time needed for emergence (Section 5.3.3). When you select 'Variable sowing date', the 'best moment' for sowing is determined by the physical conditions of the soil (humidity, workability), which depend on soil characteristics and the weather before and during the potential sowing season (Section 5.3.5). To determine this best moment, the calculations start 10 days prior to the first possible sowing day. The user must specify the earliest and latest possible sowing day.

For the end day option, select 'Fixed end date' when the end of the growing period is not determined by physiological maturity. Indicating a fixed end date means the simulation has to stop, irrespective of the development stage of the crop. This can be the case with, for example, sugar beet, which is harvested, in the vegetative stage.

Select the option 'Maturity (<= max. duration)' if you want the simulation to stop at crop maturity. If you select this option, you will also be asked to provide the maximum duration, i.e. the maximum number of days the crop can be in the field. Provide the maximum number of days the crop can grow in one growing season. This option is added to prevent errors like a crop that continues growth for an unrealistically long time because the thermal time needed to reach maturity is not attained due to low temperatures in fall. Maximum duration refers to the number of days after emergence, not to the day of the year!

When you choose the option 'Earliest of both dates', simulation will stop when the crop is mature, unless the fixed end day or the maximum duration is reached before maturity.

Note that the YEAR in the various screens, dropdown lists, charts and output windows of WCC will always refer to the 'Start year', despite the fact that the simulation can start in the previous year (for example in case of early water balance start) or end in the next year (crop crossing the year boundary).

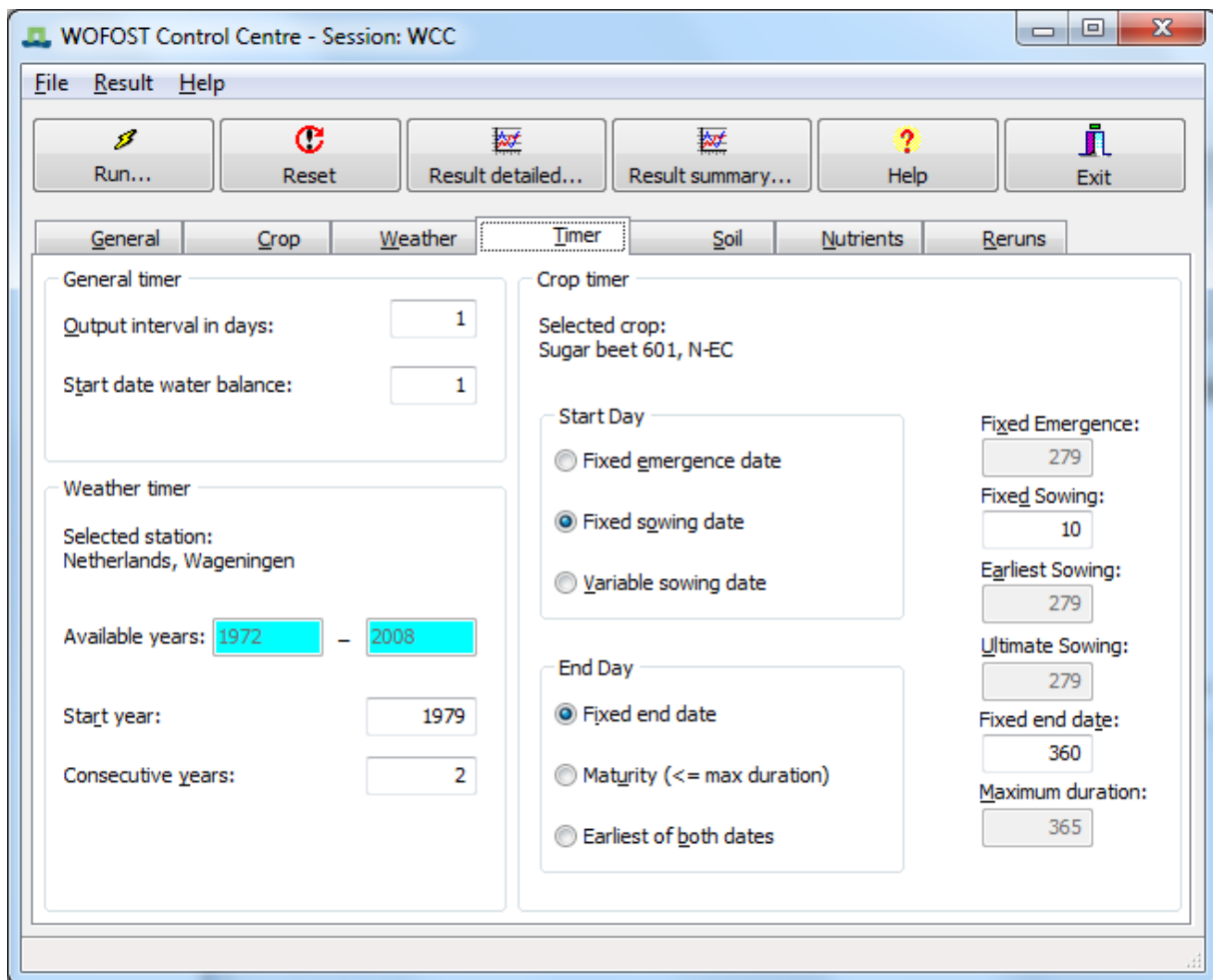


Figure 4. Example of the WCC tab "Timer".

3.4.5 Soil data

In the tab 'Soil' (Figure 5) you can choose the soil type and specify the hydrological characteristics of the field. The water supply to the crop depends, in addition to rainfall, on the hydrological characteristics of the crop field.

The user is expected to provide the values to characterize field conditions. Select a soil type in the menu 'Available soil types'. Each soil type is described in a separate soil file. Clicking on the soil type will show its filename at the bottom bar. The soil types delivered with WOFOST consist of two groups: EC (European Community)/SR ('Staringreeks')-group and the texture/AWC (available water capacity per meter soil depth)-group.

The files starting with 'EC' have been developed in connection to the soil map of the EC (CEC, 1985; Reinds et al., 1992). Files starting with 'SR' are connected to the 'Staringreeks' (Wösten et al., 1994). Soil types starting with EC and SR can be used in simulation of water-limited crop growth with free drainage as well as with groundwater influence. Soil types indicated by AWC values can only be used for simulation with free drainage, as information on hydraulic conductivity is not available. When you simulate potential crop growth, you also need to indicate a soil type because it may be used to determine the optimum sowing date.

Besides the soil type you have to supply other variables related to the hydrology. 'Initial surface storage' enables you to give an initial value for the surface storage at emergence (e.g. for transplanting rice). 'Maximum surface storage' capacity depends on slope and furrow depth of the surface (relief and micro-relief).

The 'Initial available soil water' is the quantity of soil water available for crop growth in the potential root zone at the beginning of the simulation. The potential root zone is given in the crop file (maximum root depth of mature crop) and the field 'Maximum rooting depth of soil'. WOFOST selects the minimum of both rooting depth values. Available soil water means the actual amount of water in the soil in excess of the amount at permanent wilting point (Section 5.3.4). The maximum available water is the amount of water between saturation and permanent wilting point.

It is possible to set a maximum soil moisture content for the given initial rooting depth ('Maximum initial moisture content in the initial rooting depth'). This way you can start the simulation with dry conditions in the topsoil (maximum) and wet conditions in the sub soil (by supplying a high initial available soil water content). The value for the 'Maximum initial moisture content in the initial rooting depth' is checked for values lower than moisture content at wilting point and values higher than moisture content at saturation for the chosen soil type. If you like to have the maximum at the level of wilting point just type a '0'; for saturation just type a '1'. The WCC will automatically adjust the values into the right values for wilting point and saturation.

When you provide a higher 'Initial available soil water' value than the potential root zone can contain, the model assumes the soil water content to be at saturation in the potential root zone. The surplus of the initial water is supposed to have percolated to greater depth.

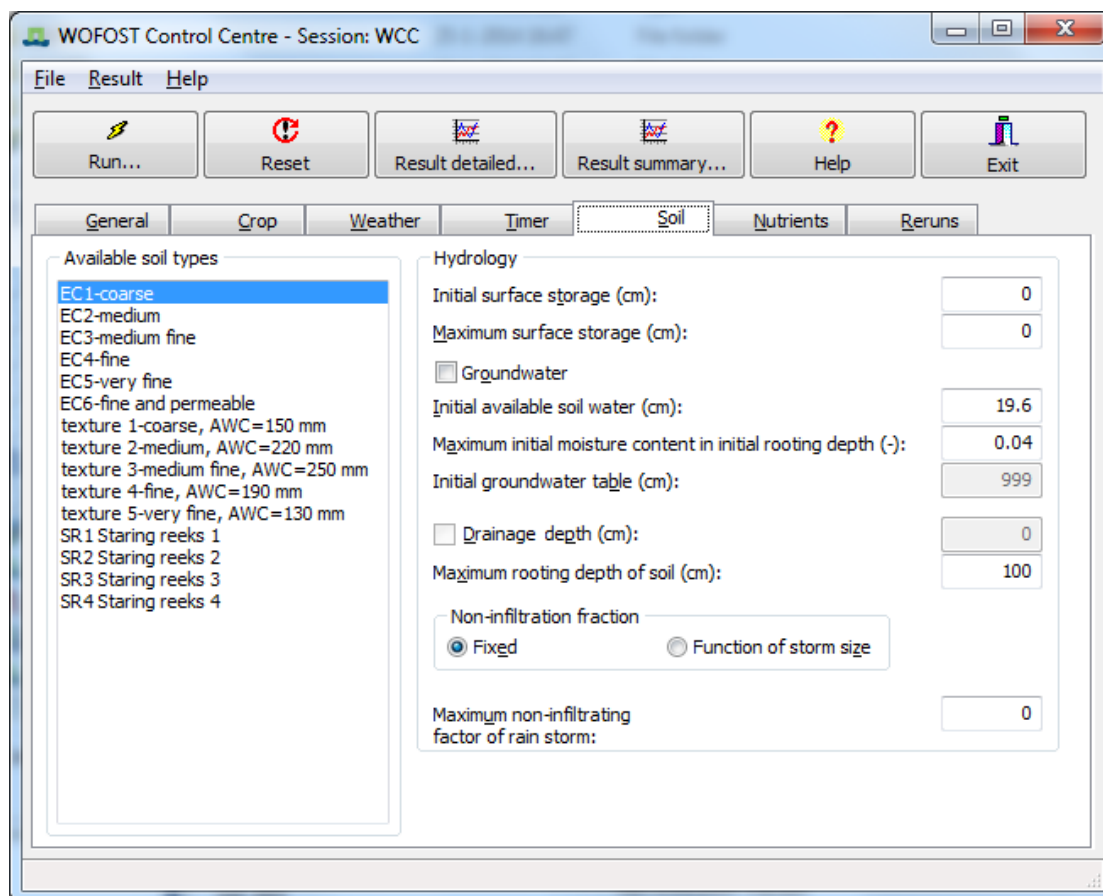


Figure 5. Example of tab 'Soil'.

When you provide a smaller 'Initial available soil water'-value than the potential root zone can contain, WOFOST first allocates this water to the initial rooting depth (usually 10 cm) until this layer is at the maximum moisture content ('Maximum initial moisture content in the initial rooting depth'). Excess water is evenly distributed over the remainder of the potential root zone.

You can choose to have 'Groundwater influence' on crop growth or not. Without groundwater influence, the water supply to the crop depends on:

- the water storage capacity of the soil (available water capacity, AWC);
- the initial available soil water content ('Initial available soil water' corrected for the maximum moisture content in the initial rooting depth);
- rainfall during the growing period only.

With groundwater influence, the water supply to the crop will be provided by capillary rise of water from the ground water to the rooting zone. When this option is selected, 'Initial available soil water' and 'Maximum initial moisture content in the initial rooting depth' are not relevant anymore and are disabled. Provide the value for 'Initial groundwater table'. Simulation results for soils with groundwater influence are not yet very reliable.

With ground water influence, you may activate the use of a drainage system by clicking on 'Drainage depth'. Activating the drainage system can lead to a decrease in the soil water content above the drains. Because of the time needed

for the water to enter the drains, the ground water table can temporarily be located above the drains.

The 'Maximum rooting depth of soil' is dictated by soil characteristics (profile depth, presence of ground water, etc.). A maximum rooting depth is also given in the crop file. WOFOST selects the smaller value of rooting depth for simulation.

The 'Non-infiltrating fraction' of rainfall can be fixed (constant) or can depend on the rainfall intensity. The infiltrating fraction of the rain is directly added to the soil water. The non-infiltrating fraction is stored on the soil surface first and may subsequently infiltrate while it may be subject to evaporation and/or run-off. If you selected 'Fixed', the amount of rain that does not infiltrate is the amount of rain (cm d⁻¹) times NOTINF (the 'Maximum non-infiltrating fraction' which is in the range 0-1). If you select 'Function of storm size', the maximum non-infiltrating fraction (NOTINF) is multiplied by a fraction NINFTB (range 0 - 1) that depends on the amount of rain. Up to 0.5 cm d⁻¹, NINFTB = 0 and all rain infiltrates; above 1.5 cm d⁻¹, NINFTB = 1 and the fraction non-infiltrating rain equals its maximum NOTINF; between 0.5 and 1.5 cm d⁻¹, NINFTB increases linearly.

3.4.6 Nutrient data

In the tab 'Nutrients' (Figure 6), specify data on the fertility of the soil. Calculations for nutrient-limited crop growth are based on the 'Basic soil supply' of the macro nutrients 'Nitrogen (N)', 'Phosphorus (P)' and 'Potassium (K)'. Calculations of the nutrient requirements for potential and water limited production are based on the 'Basic soil supply' of the nutrients and the 'Apparent recovery fraction' of extra fertilizer applied to the crop needed to reach the potential and water limited production level.

The basic soil supply of a nutrient is the amount of nutrient in the unfertilized soil that is potentially available for uptake by a standard crop in one growing season of 120 days. This module has been developed originally for maize in Kenya. The default values of the maximum basic soil supplies characterize a moderate inherent soil fertility leading to unfertilized maize crop yields of around 2500 kg ha⁻¹ dry matter. Since soil supply is assumed to be for a crop with a growing cycle of 120 days, the values for basic supply of nutrients in the detailed output file are not necessarily the same as the ones you provide here. If the growing cycle exceeds 120 days the basic supply is higher and vice versa (also see Section 5.3.6)

The apparent recovery fraction is the ratio of the additional nutrient uptake by the crop due to fertilizer application and the quantity of the nutrient applied. In reality the values for basic nutrient supply from the soil and fertilizer recovery fraction are dependent on soil, climate and past and current land use. The standard settings of the nutrient tab allow to estimate the possible contribution of soil nutrients to yield formation or inversely to quantify the required amount of fertilizer to reach potential and water limited yields. Depending on the choice of input values different kinds of information can be obtained from the model. For example, if you assume a soil with a basic supply of 0 kg ha⁻¹ for each element, and a fertilizer recovery fraction of 1.0, the model calculates the balanced nutrient uptakes needed for reaching the potential and water-limited yields.

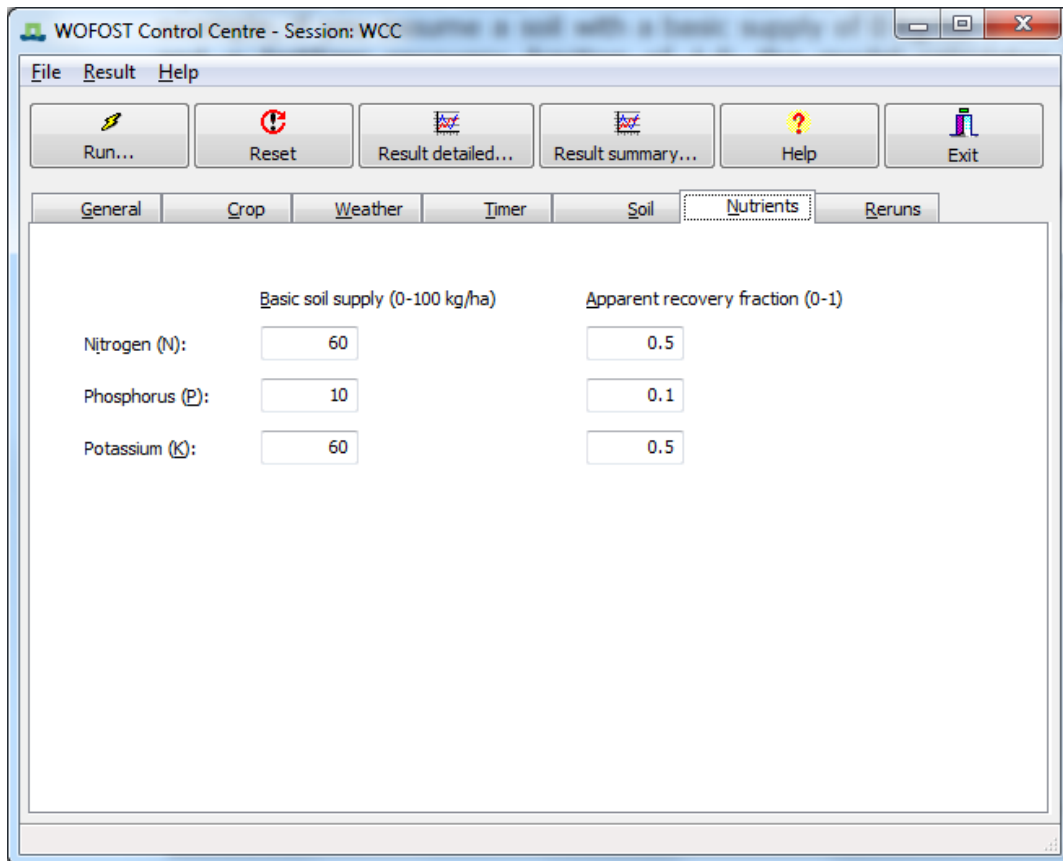


Figure 6. Example of tab 'Nutrients'.

3.4.7 Rerun data

In the tab 'Rerun' (Figure 7), click on the 'Use reruns' box to have several consecutive WOFOST-runs wherein you may vary values of input variables. Define additional runs by clicking on the 'Add rerun' button. Select variables with the 'Select variables' button. Values of the variables are edited in the matrix shown on the rerun tab page.

To remove a rerun, click on the specified run and activate the button 'Remove rerun'. The last rerun cannot be removed. The name of the run is the name of the session (WCC or the name you supplied with the save (as) session function on the menu bar) combined with a number. This name will be used in the output windows to select results for the different runs with WOFOST.

You can select one or more variables ('Select variables...') for which you would like to vary the value in the different runs. A new window will appear that will guide you through the selection of variables (Figure 8). The 'Select group' lets you choose between different groups of variables ('Crop', 'Soil', 'Timer', 'Site'). This differentiation is based on the contents of different input files of WOFOST (crop (Section 6.2), soil (Section 6.3), timer (Section 6.5.1) and site (Section 6.5.2)). It is not possible to select variables related to weather. If you would like to change values of weather variables, you have to edit the specified weather file.

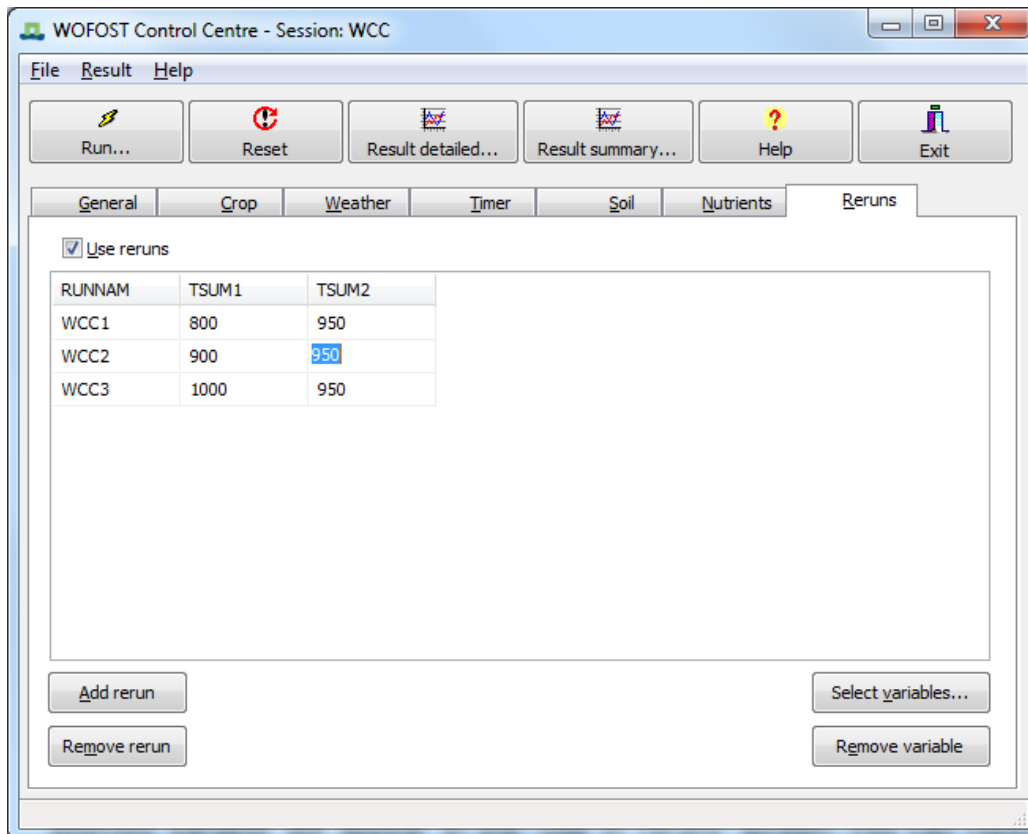


Figure 7. Example of tab 'Reruns'.

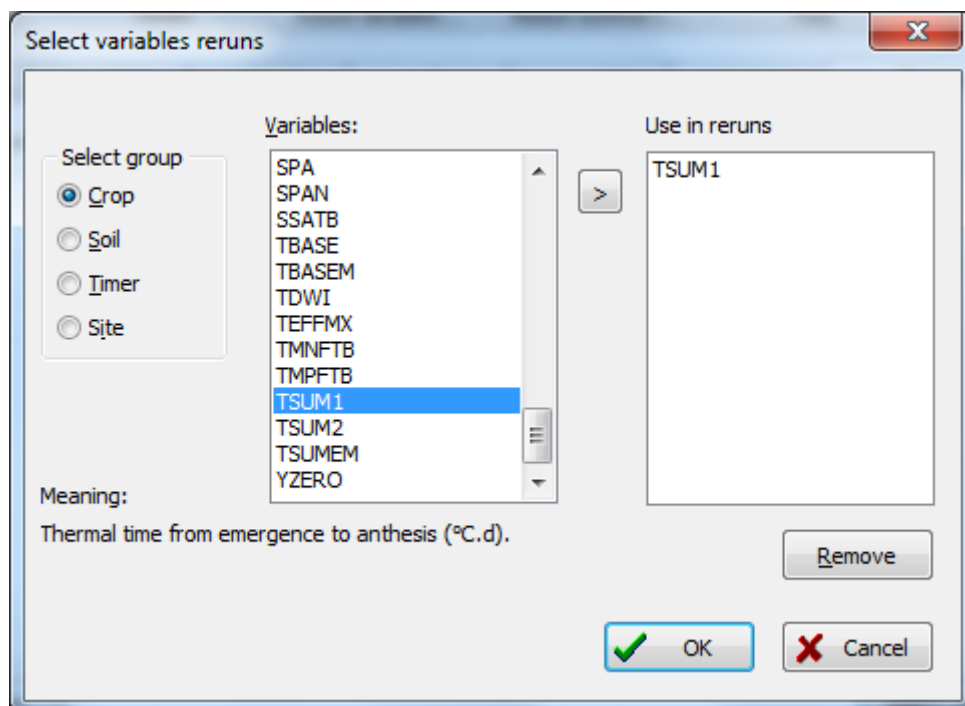


Figure 8. Example of tab 'Select variables'.

Choose the desired variable in the 'Variables' list and click on the '>' button. The selected variable will appear in the 'Use in reruns' screen. You can repeat the selection for more variables. The 'Meaning' of each variable is explained in the

lower left part of the window. You can also remove variables by clicking on the variable in the 'Use in reruns' screen and pressing the 'Remove' button. Choose the 'OK' or 'Cancel' button to return to the 'Reruns' tab.

To remove variables in the 'Reruns' tab (Figure 7), click on one of the fields of the variable and activate the 'Remove variable' button. You can change the values of the variables by entering the fields in the matrix. Two-dimensional variables (arrays) can be edited by clicking on the right mouse button. A new window appears ('Edit Rerun variable') with the name and the description of the variable and a matrix that can be edited. The matrix contains the value of the variable and the index (could be: development stage, temperature or soil moisture tension) for which the value is given. You can edit both the index and the value of the variable.

Variables that are not included in the reruns keep their values as defined in the other input tabs (general, crop, weather, soil, nutrients) and as defined in the selected crop, weather and soil files.

When the user wants to fill in relatively low or high values for a certain variable (e.g. because of sensitivity analysis) it is possible that the WCC replies with the message 'INVALID INPUT' together with the allowed range of values for this variable. It is possible to change these upper and lower limits. Therefore you have to exit the WCC and edit the file WCC_VAR.csv on the main WCC directory. Annex E shows the lower and upper limits of the variables used in WOFOST.

3.5 Detailed results of WOFOST

To view results of a WOFOST run, click 'Result detailed...' on the button bar of the WCC. The 'Detailed output' window is activated (). This window consists of:

- Pull down menus to choose a run ('RUNNAM') and a simulation year ('YEAR'). The rainfall year ('RAIN') is related to monthly weather data which is not supported anymore and has been disabled. The selection in these pull down menus determines the results that are shown in the different tabs;
- Buttons to open other output files ('Open'), to create graphs ('Graph'), to leave the detailed output window ('Close') and to export the results of a selection (run, simulation year, rainfall year) to Excel ('Excel');
- Several tabs to view tables with results for potential crop growth (Section 3.5.1), water-limited crop growth (Section 3.5.2), the simulated water balance (Section 3.5.3) and the nutrient limited crop growth (Section 3.5.4).

3.5.1 Potential results

The ('Potential') result tab (Figure 9) shows general information on:

- 'WEATHER:' description and file name of chosen weather;
- 'RAIN:' (rainfall option used) (see Section 3.4.3): this will always state 'belonging to weather station' because only daily weather data from CABOWE files is supported.
- 'CROP:' description and file name of chosen crop;
- 'SOIL:' description and file name of chosen soil;

- 'START:' data on the start conditions: sowing date and emergence data. A value of '-99' for sowing date indicates a fixed emergence option.

Results for 'POTENTIAL CROP PRODUCTION' in table format are shown for different time steps ('DAY') according to the value you specified in the 'Output interval in days' in the input tab 'General'. The column headings and their description are provided in Table 2. A 'SUMMARY' of results is also given for the potential production results (Table 3).

Table 2. Description of the output of Potential Crop Production table window.

<i>Column</i>	<i>Description</i>
YEAR	year of the simulation time step
DAY	day of year of the simulation time step (1-366)
IDSEM	number of days since emergence (d)
DVS	development stage of crop (-)
TSUM	thermal time since emergence (°C d)
WLW	dry weight of living leaves (kg ha ⁻¹)
WST	dry weight of living stems (kg ha ⁻¹)
WSO	dry weight of living storage organs (kg ha)
TAGP	total above ground production (dead and living plant organs) (kg ha ⁻¹)
LAI	leaf area index (leaf area)/(soil area) (ha ha ⁻¹)
TRA	transpiration rate (mm d ⁻¹)
GASS	gross assimilation rate (kg (CH ₂ O) ha ⁻¹ d ⁻¹)
MRES	maintenance respiration rate (kg (CH ₂ O) ha ⁻¹ d ⁻¹)
DMI	rate of dry matter increase (kg ha ⁻¹ d ⁻¹).

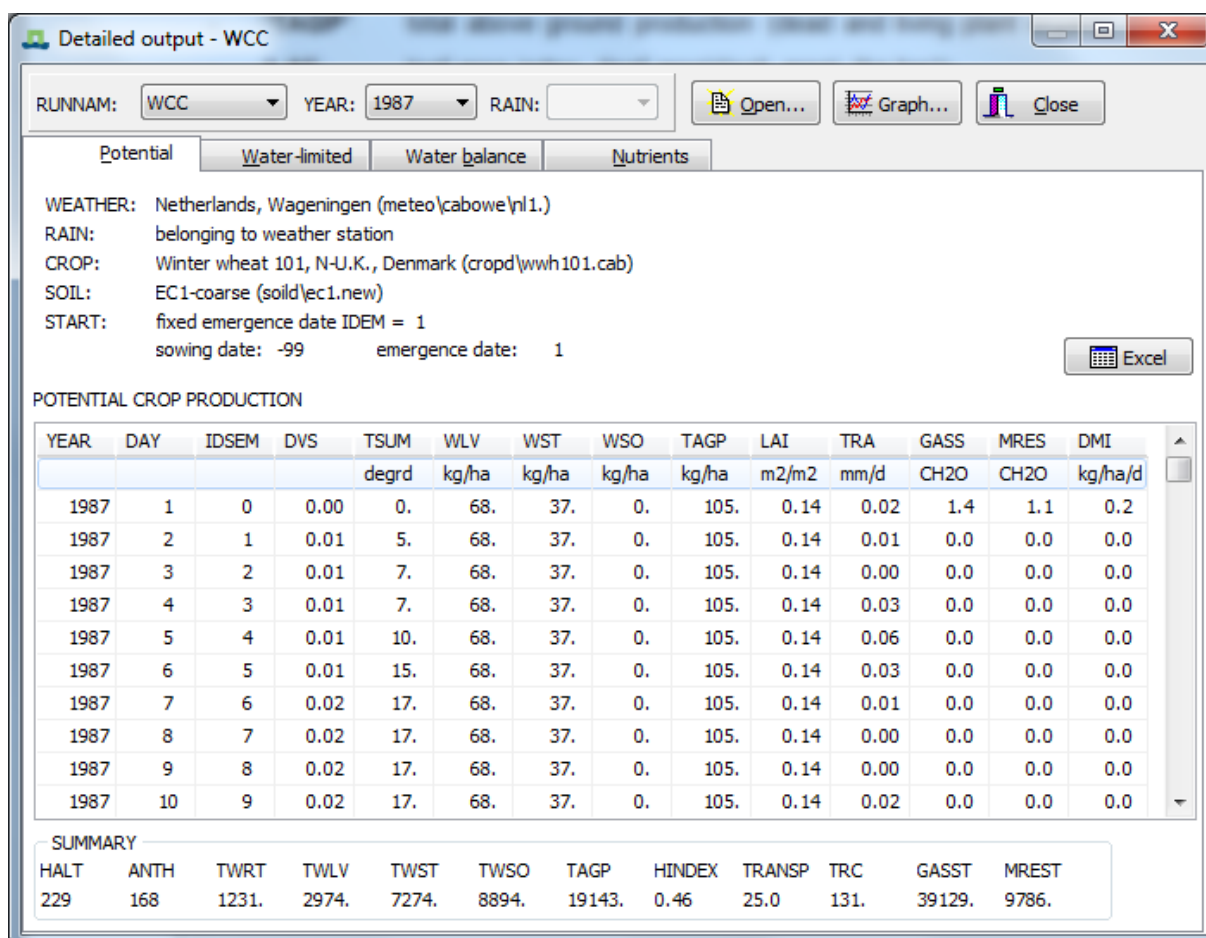


Figure 9. Example of window 'Detailed output' – tab 'Potential'.

Table 3. Description of the summary results for the potential crop production run.

Column	Description
HALT	day number at harvest (day of the year)
ANTH	duration of pre-anthesis phase (d)
TWRT	total dry weight of roots (dead and living) (kg ha ⁻¹)
TWLV	total dry weight of leaves (dead and living) (kg ha ⁻¹)
TWST	total dry weight of stems (dead and living) (kg ha ⁻¹)
TWSO	total dry weight of storage organs (dead and living) (kg ha ⁻¹)
TAGP	total above ground production (dead + living) (kg ha ⁻¹)
HINDEX	harvest index: weight of storage organs / weight of total above ground crop (-)
TRANSP	total transpiration (cm water)
TRC	transpiration coefficient rate (kg (water) / kg (dry matter))
GASST	total gross assimilation (kg (CH ₂ O) ha ⁻¹)
MREST	total maintenance respiration (kg (CH ₂ O) ha ⁻¹).

The 'Graph' button enables you to draw graphs of specified output data of the potential crop growth (Figure 10). These are the same output data as shown in the table of the result tab 'Potential'. There is also an option to present one graph

showing the total above ground production (dry weight of living and dead plant organs) and its components: dry weight of living stems, dry weight of living storage organs and dry weight of living storage organs. The 'Graph' window offers you to load another output file ('Output file 2...'). With the buttons 'Y-axis 1' and 'Y-axis 2' you can control the position of the y-axis (left and right).

Finally, the graph window allows you to control how the simulation results from different years are synchronized on the chart. Results from different simulation years are synchronized by plotting them as day number since the 1st of January. However, this can cause problems for simulations crossing the year boundary. Therefore, you can choose for synchronizing the results for different years on the 1st of January of the harvest year (Figure 11) or the year of sowing/emergence (Figure 12). The former option will cause days before the 1st of January of the year of the harvest to be plotted as negative numbers.

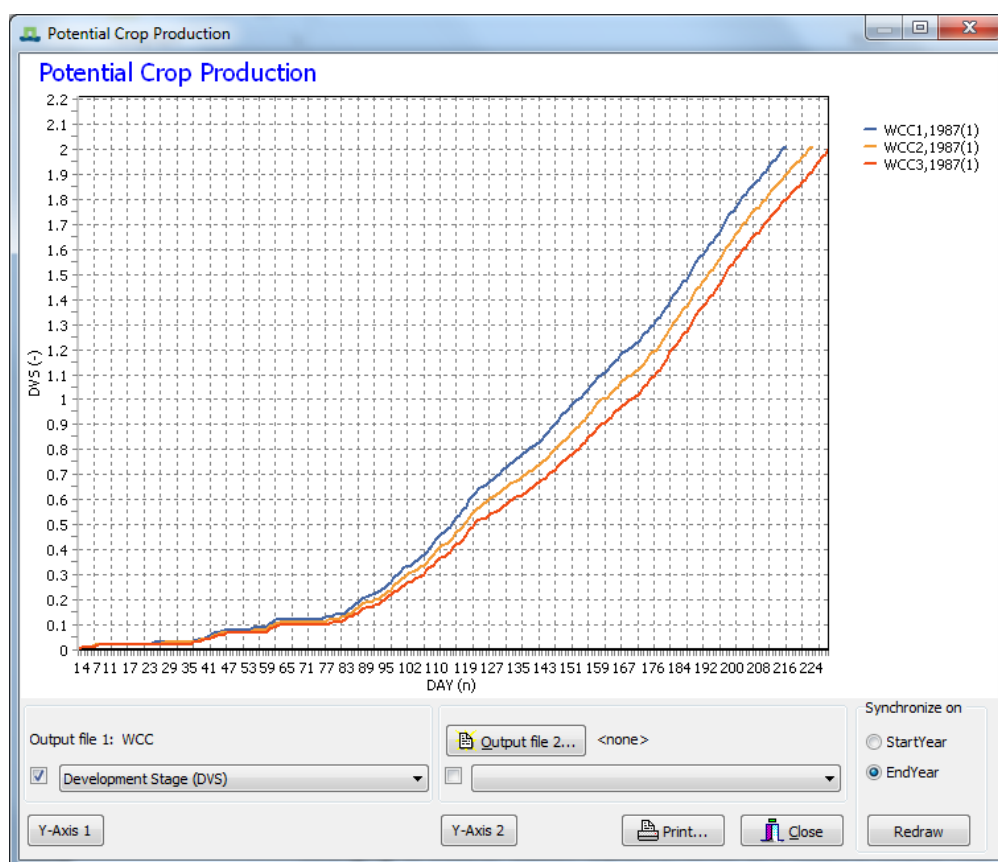


Figure 10. Example of 'Graph' window for potential production for three different reruns.

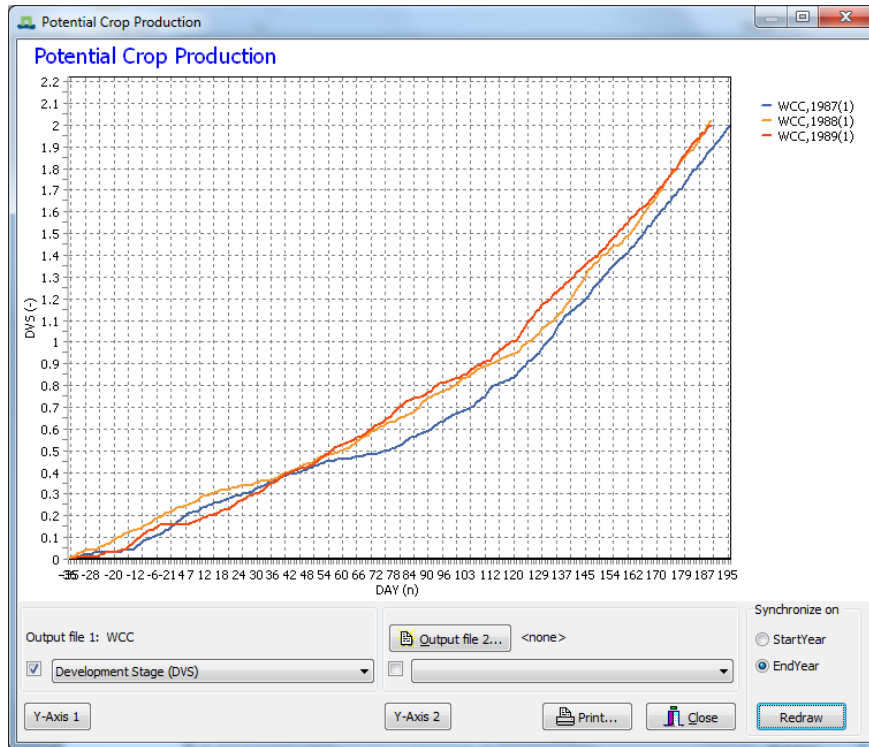


Figure 11. Chart window showing the simulation results for the years 1987, 1988, 1989 synchronized on the year of harvest (EndYear). Simulation time-steps before January 1 are shown as negative numbers.

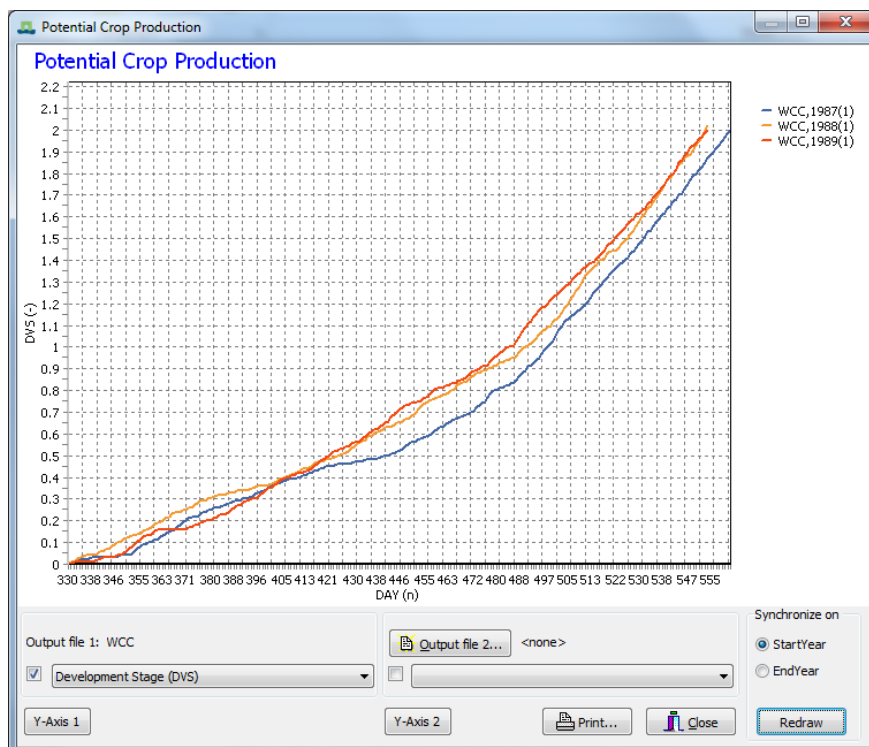


Figure 12. Chart window showing the simulation results for the years 1987, 1988, 1989 synchronized on the year of sowing (StartYear). Simulation time-steps after 31 December of the year of sowing/emergence are shown as numbers > 365.

3.5.2 Water-limited results

The 'Water-limited' result tab (Figure 13) gives results only when simulation of water-limited crop growth is chosen. The following general information is presented:

- 'WEATHER:' description and file name of chosen weather;
- 'RAIN:' rainfall option used (see Section 3.4.3): This will always read 'belonging to weather station' because the use of monthly weather data is not supported anymore.
- 'CROP:' description and file name of chosen crop;
- 'SOIL:' description and file name of chosen soil;
- 'START:' data on the start conditions: sowing date and emergence data. A value of '-99' for sowing date indicates a fixed emergence option.
- a title 'WATER (AND O2) LIMITED CROP PRODUCTION WITH(OUT) GROUNDWATER' that indicates whether WOFOST has been executed with or without groundwater influence and with or without the effect of oxygen shortage (see input tab 'Soil');
- soil related data (a summary of the options chosen in the input tab 'Soil');
- indication how amount of infiltrated rainfall is determined. It can be a 'fixed fraction' or 'variable fraction';
- 'RDMso': maximum rooting depth allowed by soil (cm) (see input tab 'Soil');
- 'NOTinf': maximum fraction of rain not-infiltrating into soil (-) (see input tab 'Soil');
- 'SMO': soil moisture content of saturated soil ($\text{cm}^{-3}(\text{water}) / (\text{cm}^{-3}(\text{soil}))$);
- 'SMFC': soil moisture content at field capacity ($\text{cm}^{-3}(\text{water}) / (\text{cm}^{-3}(\text{soil}))$);
- 'SMW': soil moisture content at wilting point ($\text{cm}^{-3}(\text{water}) / (\text{cm}^{-3}(\text{soil}))$);
- 'SMLIM': maximum initial soil moisture content of the initial rooting depth ($\text{cm}^{-3}(\text{water}) / (\text{cm}^{-3}(\text{soil}))$) (see input tab 'Soil');
- 'RDM': maximum rooting depth used in simulation (determined by crop and soil) (cm);
- 'WAV': initial amount of available water in total rootable zone (soil moisture content above wilting point (cm water) (same as 'Initial available soil water' in input tab 'Soil');
- 'SSmax': maximum surface storage capacity (cm water) (see input tab 'Soil').

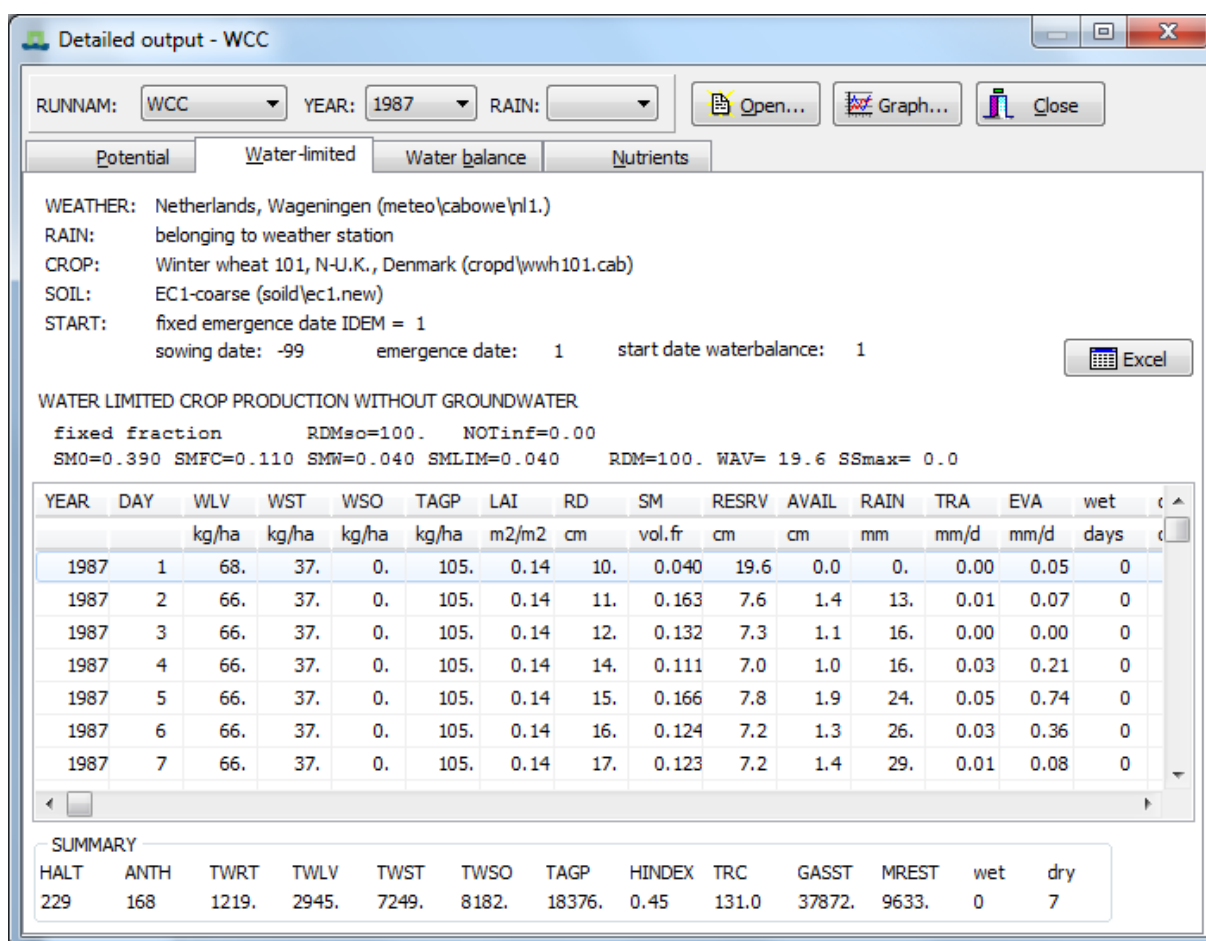


Figure 13. Example of window 'Detailed output' – tab 'Water-limited'.

Results in table format are shown for different time steps ('DAY') according to the value you gave in the 'Output interval in days' in the input tab 'General'. The matrix is filled only when WOFOST has been run for water limited production (Table 4), moreover summary results are provided at the bottom of the window (Table 5).

Table 4. Description of the output of Water-Limited Crop Production table window.

Column	Description
YEAR	year of the simulation time step
DAY	day of year of the simulation time step (1-366)
WLW	dry weight of living leaves (kg ha ⁻¹)
WST	dry weight of living stems (kg ha ⁻¹)
WSO	dry weight of living storage organs (kg ha ⁻¹)
TAGP	total above ground production (dead and living plant organs) (kg ha ⁻¹) (only given when simulated without groundwater influence)
LAI	leaf area index (leaf area)/(soil area) (ha ha ⁻¹)
RD	depth of actual root zone (cm)
SM	soil moisture content in actual root zone (cm ⁻³ (water) / (cm ⁻³ (soil))
RESRV	available soil water in potential root zone (in and below actual root zone) (cm water) (only given when simulated without groundwater influence)

AVAIL	amount of water available in actual root zone (cm water) (only given when simulated without groundwater influence)
RAIN	total rainfall in the simulation period (mm)
TRA	transpiration rate (mm d ⁻¹)
EVA(P)	evaporation rate from soil or from water stored on soil surface (mm d ⁻¹)
SS	surface storage (cm water)
ZT	depth of groundwater table (cm below soil surface)
wet	days characterized by reduced crop growth due to oxygen shortage (d)
dry	days characterized by reduced crop growth due to water shortage (d).

Table 5. Summary results provided for the Water-Limited Crop Production simulation.

Column	Description
HALT	day number at harvest (day of the year)
ANTH	duration of pre-anthesis phase (d)
TWRT	total dry weight of roots (dead and living) (kg ha ⁻¹)
TWL	total dry weight of leaves (dead and living) (kg ha ⁻¹)
TWST	total dry weight of stems (dead and living) (kg ha ⁻¹)
TWSO	total dry weight of storage organs (dead and living) (kg ha ⁻¹)
TAGP	total above ground production (dead and living plant organs) (kg ha ⁻¹)
HINDEX	harvest index weight of storage organs / weight of total above ground crop (-)
TRC	transpiration coefficient rate (kg (water) / kg (dry matter))
GASST	total gross assimilation (kg (CH ₂ O) ha ⁻¹)
MREST	total maintenance respiration (kg (CH ₂ O) ha ⁻¹)
wet	total number of days characterized by reduced crop growth due to oxygen shortage (d)
dry	total number of days characterized by reduced crop growth due to water shortage (d).

The 'Graph' button enables you to draw graphs of specified output data of the water-limited crop growth (Figure 10). These are the same output data as shown in the table of the result tab 'Water-limited'. There is also an option to present one graph showing available soil water in potential root zone (in and below actual root zone) together with the amount of water available in actual root zone. The 'Graph' window offers you to load another output file ('Output file 2...'). With the buttons 'Y-axis 1' and 'Y-axis 2' you can control the position of the y-axis (left and right).

3.5.3 Water balance results

The ('Water balance') result tab (Figure 14) shows water balances of the whole system ('WATER BALANCE WHOLE SYSTEM') and the root zone ('WATER BALANCE ROOT ZONE'). The water balance for the whole system provides information on:

- initial and the final water content and their difference, either for the maximum rooting zone or, when ground water influence is assumed, for the first 10 m;
- initial and final surface storage of water and their difference;
- irrigation (always 0, since there is no option for irrigation in WOFOST);
- rainfall;
- evaporation (from the soil or surface water) and transpiration (by the crop) together: water loss to atmosphere);
- runoff, percolation to the ground water, and, the water loss through the drains (when groundwater is present).

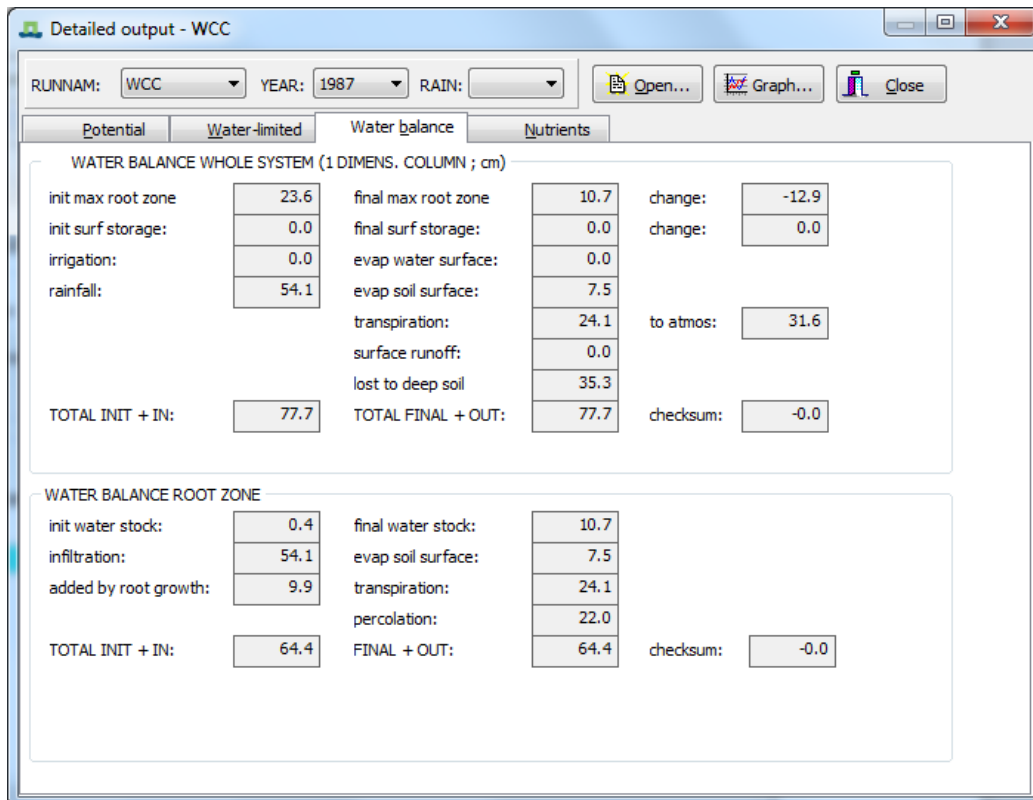


Figure 14. Example of window 'Detailed output' – tab 'Water balance'.

The checksum is used to check the water balance by subtracting the final water content and the water lost (TOTAL FINAL + OUT) from the initial water content and the water that entered the system (TOTAL INIT + IN). Checksum should be 0.0 or, due to rounding errors, close to 0.0. The water balance for the root zone provides information on:

- initial and final water content in the root zone;
- infiltration into the root zone (i.e. rainfall minus runoff);
- evaporation (from the soil) and transpiration (by the crop);
- increase in available water due to root growth;
- percolation to the ground water;
- capillary rise (when groundwater is present).

The checksum ((TOTAL INIT + IN) - (FINAL + OUT)) should be 0.0 or, due to rounding errors, close to 0.0.

The 'Graph' button enables you to draw bar diagrams of the water balances for the whole system and/or root zone (Figure 15). The bar diagram consists of two columns:

- on the left: initial water content and the water that entered the system ('INIT + IN');
- on the right: the final water content and the water lost ('FINAL + OUT').

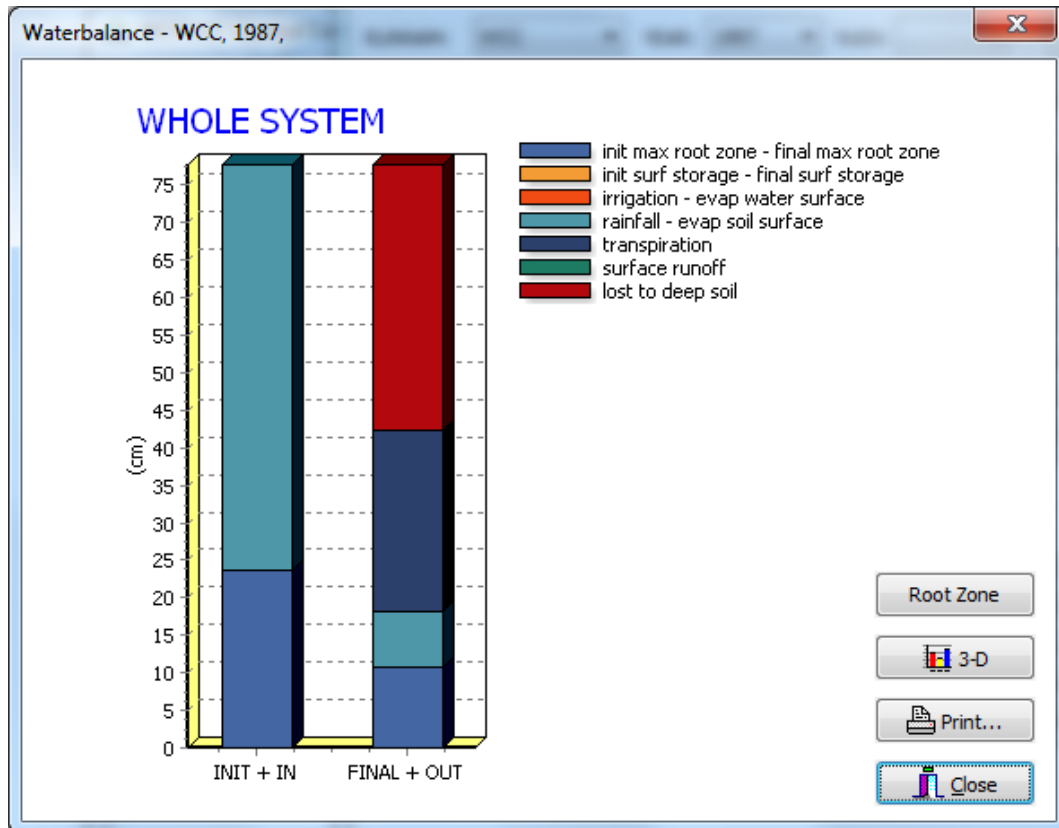


Figure 15. Example of 'Graph' window for water balances.

The different components of the column are explained in the legend. If a component appears in both columns (initial value (left) and final value (right)) this component has one colour. If a water balance was simulated for both the whole system and root zone (see input tab 'General'), a button appears to switch from both options ('Root zone' or 'Whole system').

3.5.4 Nutrient results

The ('Nutrients') result tab (Figure 16) is only available when 'and calculation of nutrient-limited crop growth' is chosen in the input tab 'General'. This tab first provides calculated values for the basic soil supply of nutrients and the recovery fractions for additional fertilizers, followed by the results for potential, nutrient limited, and water-limited production. The simulated yield of leaves, stems and storage organs (dry weight (kg ha^{-1})), the ratio (storage organ / (leaves + stems)) and the harvest index (storage organs / total above ground biomass) is provided. Subsequently, the amount of fertilizer that would be needed to obtain potential and water-limited production is given in element form (kg ha^{-1}). The fertilizer requirements are calculated on the basis of balanced nutrient supply

assuming that the element concentrations in the biomass are the average of minimum and maximum.

The nutrient limited yield is calculated according to a much more complicated scheme, taking into account an optimum balance between the three nutrients. The nutrient limited yield is therefore sometimes relatively higher than the water limited yield. This becomes visible when the nutrient and water limited production levels are of the same order of magnitude. Moreover, the nutrient limited yield and water limited yield are estimated independently so the nutrient limited yield can exceed the calculated water limited yield, even in terms of total biomass. According to the hierarchical approach this should not be possible. The correct interpretation is that without supplementary irrigation the nutrient limited yield cannot be obtained.

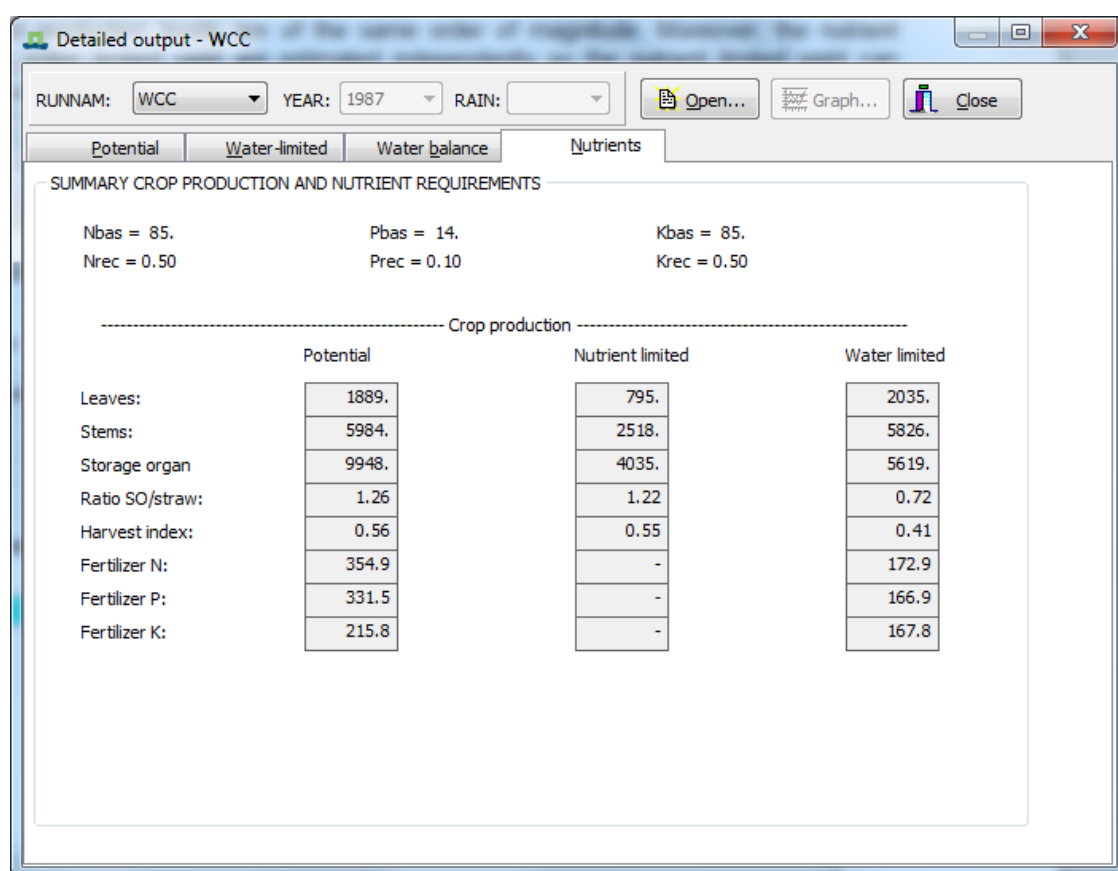


Figure 16. Example of window 'Detailed output' – tab 'Nutrients'.

The example (Figure 16) shows an apparent anomaly: the amount of leaf biomass in the water limited production exceeds the potential leaf biomass. The reason is that the potential yield is given for the latest of three years, while the water limited yield is given as the average over three years.

3.6 Summary results of WOFOST

To view the summary of results of a WOFOST run, click on 'Result summary...' on the button bar in the main window. A message 'No Summary results available' will appear if only one weather year was simulated. The 'Summary output'

consists of three tabs: Potential, Water-limited and Summary which will be described in the following sections.

3.6.1 Potential results

The ('Potential') result tab (Figure 17) shows general information on:

- 'WEATHER:' description and file name of chosen weather;
- 'CROP:' description and file name of chosen crop;
- 'SOIL:' description and file name of chosen soil.

The 'Excel' button exports the results of a selected run to Excel. This button is only valid for the first table and not for the statistical table.

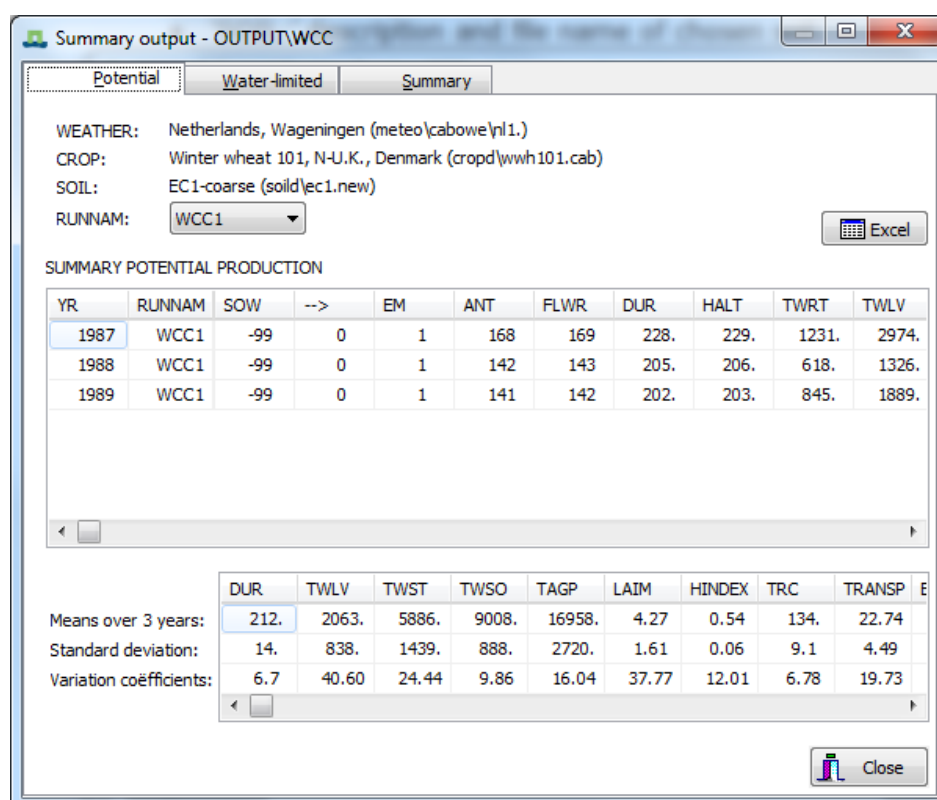


Figure 17. Example of window 'Summary output' – tab 'Potential'.

Summary results for potential production ('SUMMARY POTENTIAL PRODUCTION') are given in table format. One line is given for each growing season and run (Table 6). Moreover, a table is filled with means ('Means over x years'), standard deviation ('Standard deviation'), and variation coefficients ('Variation coefficients') when a run for two or more weather years is made (Table 7).

Table 6. Description of the WOFOST summary output table for potential crop production.

Column	Description
YR	simulation year, which always refers to the year when the simulation has started (e.g. sowing or emergence)
RUNNAM	name of the simulation run
SOW	sowing date (day in year) (in case of fixed emergence value is -99) days between sowing and emergence (d) (in case of fixed emergence value is 0)

EM	emergence date (day in year)
ANT	duration of pre-anthesis phase (d)
FLWR	day of flowering (day in year)
DUR	duration of simulation period (d)
HALT	day number at harvest (day in year)
TWRT	total dry weight of roots (dead and living) (kg ha ⁻¹)
TWLV	total dry weight of leaves (dead and living) (kg ha ⁻¹)
TWST	total dry weight of stems (dead and living) (kg ha ⁻¹)
TWSO	total dry weight of storage organs (dead and living) (kg ha ⁻¹)
TAGP	total above ground production (dead and living plant organs) (kg ha ⁻¹)
LAIM	maximum leaf area index (ha ha ⁻¹)
HINDEX	harvest index weight of storage organs / weight of total above ground crop (-)
TRC	transpiration coefficient rate (kg (water) / kg (dry matter))
GASST	total gross assimilation (kg (CH ₂ O) ha ⁻¹)
MREST	total maintenance respiration (kg (CH ₂ O) ha ⁻¹)
TRANSP	total transpiration (cm water)
EVSOL	total evaporation from soil surface (cm water).

Table 7. Description of the WOFOST summary statistics table for potential crop production.

Column	Description
DUR	duration of simulation period (d)
TWLV	total dry weight of leaves (dead and living) (kg ha ⁻¹)
TWST	total dry weight of stems (dead and living) (kg ha ⁻¹)
TWSO	total dry weight of storage organs (dead and living) (kg ha ⁻¹)
TAGP	total above ground production (dead and living plant organs) (kg ha ⁻¹)
LAIM	maximum leaf area index (ha ha ⁻¹)
HINDEX	harvest index as weight of storage organs / weight of total above ground crop biomass (-)
TRC	transpiration coefficient rate (kg (water) / kg (dry matter))
TRANSP	total transpiration (cm water)
EVSOL	total evaporation from soil surface (cm water).

3.6.2 Water-limited results

The ('Water-limited') result tab (Figure 18) shows general information on:

- 'WEATHER:' description and file name of chosen weather;
- 'CROP:' description and file name of chosen crop;
- 'SOIL:' description and file name of chosen soil;
- 'RAIN:' indication which rainfall option is used. This will always read 'belonging to weather station' because the use of monthly or dekadal weather data has been abandoned.
- '(NO) GROUNDWATER' indication whether there is groundwater influence.

The general information is valid only for the first default run and not for additional runs, which you can choose in 'RUNNAM'. Therefore the general information has a grey colour (disabled) in case an additional run is chosen.

The 'Excel' button exports the results of a selected run to Excel. It is only valid for the first table and not for the statistical table.

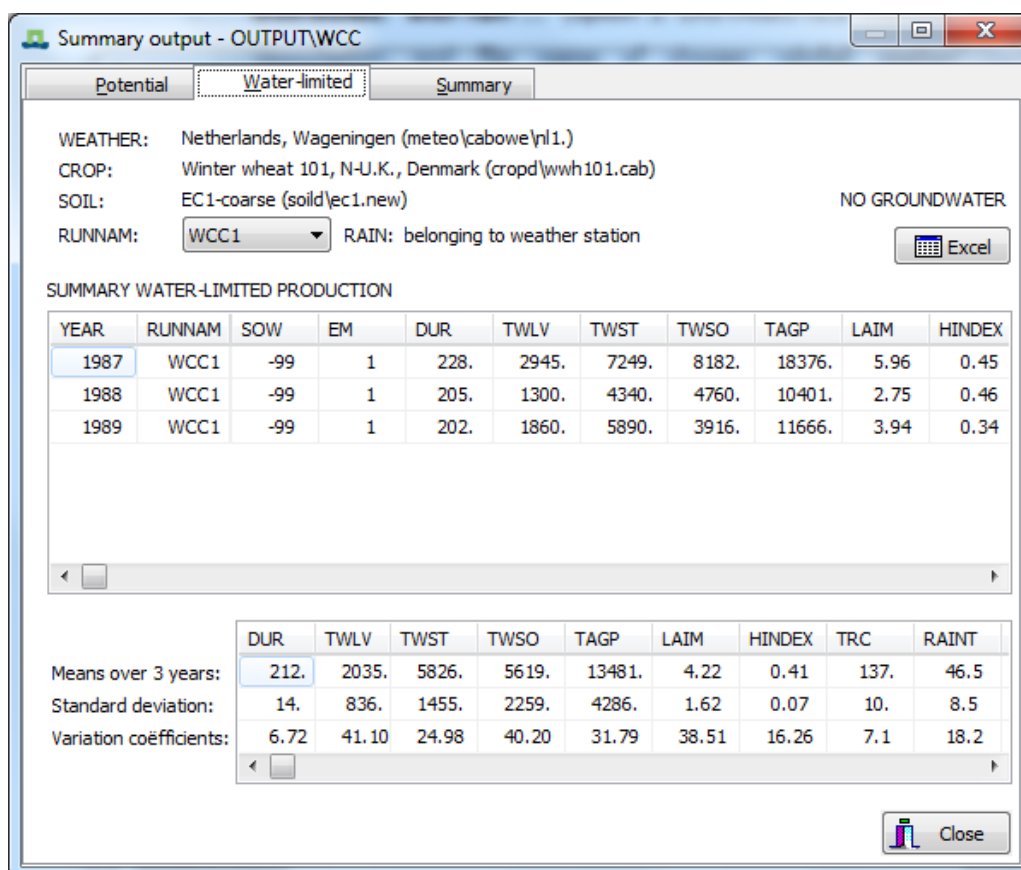


Figure 18. Example of window 'Summary output' – tab 'Water-limited'.

Summary results for water-limited production ('SUMMARY WATER-LIMITED PRODUCTION') are given in table format (Table 8). One line is given for each simulation year (weather year) and RUNNAM. Furthermore, a table is filled with means ('Means over x years'), standard deviation ('Standard deviation') and variation coefficients ('Variation coefficients') when a run for two or more years is made (Table 9).

Table 8. Description of the WOFOST summary output table for water-limited crop production.

Column	Description
YEAR	simulation year
RUNNAM	name of the simulation run
SOW	sowing date (day in year) (in case of fixed emergence value is -99)
EM	emergence date (day in year)
DUR	duration of simulation period (d)
TWLV	total dry weight of leaves (dead and living) (kg ha ⁻¹)
TWST	total dry weight of stems (dead and living) (kg ha ⁻¹)

TWSO	total dry weight of storage organs (dead and living) (kg ha ⁻¹)
TAGP	total above ground production (dead and living plant organs) (kg ha ⁻¹)
LAIM	maximum leaf area index (ha ha ⁻¹)
HINDEX	harvest index weight of storage organs / weight of total above ground crop (-)
TRC	transpiration coefficient rate (kg (water) / kg (dry matter))
RAINT	total rainfall in the simulation period (cm water)
DELWAT	difference between final and initial available water in the root zone (cm water)
TRAT	total transpiration (cm water)
EVSOL	total evaporation from soil surface (cm water)
LOSST	total water percolated to deep soil, not available for plant growth (cm water)
TSR	total surface runoff during simulation period (cm water)
RYLD	relative yield water-limited yield / potential yield (%)
RAGP	relative total above ground production water-limited production / potential production (%)

Table 9. Description of the WOFOST summary statistics table for water-limited crop production.

Column	Description
DUR	duration of simulation period (d)
TWLV	total dry weight of leaves (dead and living) (kg ha ⁻¹)
TWST	total dry weight of stems (dead and living) (kg ha ⁻¹)
TWSO	total dry weight of storage organs (dead and living) (kg ha ⁻¹)
TAGP	total above ground production (dead and living plant organs) (kg ha ⁻¹)
LAIM	maximum leaf area index (ha ha ⁻¹)
HINDEX	harvest index weight of storage organs / weight of total above ground crop (-)
TRC	transpiration coefficient rate (kg (water) / kg (dry matter))
RAINT	total rainfall in the simulation period (cm water)
DELWAT	difference between final and initial available water in the root zone (cm water)
TRAT	total transpiration (cm water)
EVSOL	total evaporation from soil surface (cm water)
LOSST	total water percolated to deep soil, not available for plant growth (cm water)
RYLD	relative yield water-limited yield / potential yield (%)
RAGP	relative total above ground production water-limited production / potential production (%)

3.6.3 Summary results

The ('Summary') result tab (Figure 19) shows means of variables over simulated weather (and rainfall) years) for:

- different runs with WOFOST;
- for potential and optionally water-limited crop growth.

This is a repetition of the information given the 'Potential' and 'Water limited' result tabs but now ordered in one clear overview (Table 10).

Note: This 'Summary' tab on the 'Summary output' window is filled only when WOFOST is run for more than two weather years and more than one run is used in the 'Rerun' tab.

PS	RUNNAM	IZT	SOW	EM	DUR	TWLV	TWST	TWSO	var%	TAGP	var%
PP	WCC1	0	-99.	1.	212.	2063.	5886.	9008.	9.86	16958.	16.0
WP	WCC1	0	-99.	1.	212.	2035.	5826.	5619.	40.20	13481.	31.7
PP	WCC2	0	-99.	1.	206.	1547.	4597.	8660.	17.96	14804.	24.2
WP	WCC2	0	-99.	1.	206.	1521.	4546.	6547.	35.33	12615.	34.5

PS	RUNNAM	IZT	SOW	EM	LAIM	HINDEX	RYLD	RAGP	TRC	RDMSOL
PP	WCC1	0	-99.	1.	212.	2063.				
WP	WCC1	0	-99.	1.	212.	2035.	63.18	78.74	137.	100.
PP	WCC2	0	-99.	1.	206.	1547.				
WP	WCC2	0	-99.	1.	206.	1521.	75.45	84.45	133.	100.

Figure 19. Example of window 'Summary output' – tab 'Summary'.

Table 10. Description of the different fields in the window 'Summary output' – tab 'Summary'.

Column	Description
PS	production level (PP = potential WP = water-limited)
RUNNAM	name of the simulation run
IZT	influence of ground water (0 = no influence 1 = influence)
SOW	sowing date (day in year) (in case of fixed emergence value is -99)
EM	emergence date (day in year)
DUR	duration of simulation period (d)
TWLV	total dry weight of leaves (dead and living) (kg ha ⁻¹)
TWST	total dry weight of stems (dead and living) (kg ha ⁻¹)
TWSO	total dry weight of storage organs (dead and living) (kg ha ⁻¹)
var%	variation coefficient of total dry weight of storage organs (dead and living) (kg ha ⁻¹)
TAGP	total above ground production (dead and living plant organs) (kg ha ⁻¹)

var%	variation coefficient of total above ground production (dead and living plant organs) (kg ha ⁻¹)
LAIM	maximum leaf area index (ha ha ⁻¹)
HINDEX	harvest index weight of storage organs / weight of total above ground crop (-)
RYLD	relative yield water-limited yield / potential yield (%)
RAGP	relative total above ground production water-limited production / potential production (%)
TRC	transpiration coefficient rate (kg (water) / kg (dry matter))
RDMSOL	maximum rooting depth allowed by soil (cm).

3.7 Running WOFOST from the Command Prompt

WOFOST can be run from a command prompt or a terminal (linux, Mac OSX) by executing the wofost executable ("*wofost.exe*" on windows systems) within the main directory. This option becomes important when you want to change the source code of WOFOST and these changes influence the input and/or output of WOFOST. In that case, the graphical user interface WCC cannot be used anymore and WOFOST should be run as stand-alone. Moreover, the WCC is not available on computers running Linux or Mac OSX so for these systems running WOFOST from a terminal is the only available option.

When WOFOST is run from the command prompt, input of WOFOST can be edited through the different run files described in Section 6.5. Crop, soil, and weather files should not be edited. These files are chosen in the run files. If changes have to be made in the crop, soil, or weather files, new crop, soil, or weather files should be created. Results can be viewed and analyzed in the output files described in Section 6.6.

4 Introduction into WOFOST

4.1 General description

4.1.1 Introduction

WOFOST is a tool for the quantitative analysis of the growth and production of annual field crops. As with all tools, you should know what you could do with it and what not. This chapter provides some insight in this matter.

Like all mathematical models of agricultural production, WOFOST is a simplification of reality. In practice, crop yield is a result of the interaction of ecological, technological and socio-economic factors. In WOFOST, only ecological factors are considered under the assumption that optimum management practices are applied.

4.1.2 Production levels

To be able to deal with the ecological diversity of agriculture, three hierarchical levels of crop growth can be distinguished: potential growth limited growth and reduced growth. Each of these growth levels corresponds to a level of crop production: potential, limited and reduced production (Figure 20).

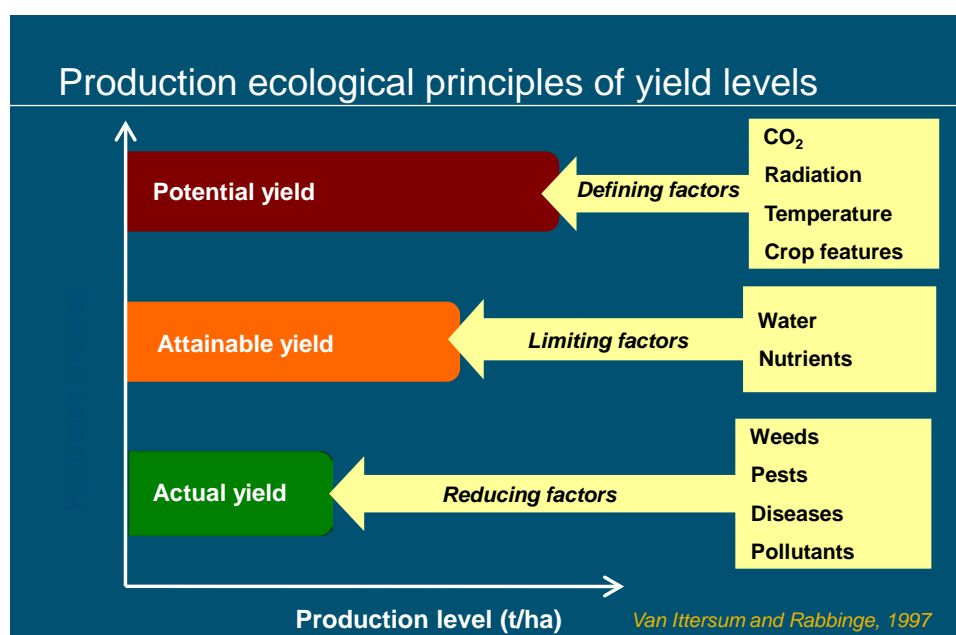


Figure 20. Theoretical production levels.

Reality rarely corresponds exactly to one of these growth/production levels, but it is useful to reduce specific cases to one of them, because this enables you to focus on the principal environmental constraints to crop production, such as light, temperature, water and the macro nutrients nitrogen (N), phosphorus (P) and potassium (K). Other factors can often be neglected because they do not

influence the crop's growth rate (De Wit, 1986; Rabbinge and De Wit, 1989; Penning de Vries et al., 1989).

Potential production represents the absolute production ceiling for a given crop when grown in a given area under specific weather conditions. It is determined by the crop's response to the temperature and solar radiation regimes during the growing season. In practice, this ceiling can only be reached with a high input of fertilizers, irrigation and thorough pest and weed control. In addition, crop establishment should be perfect, there should be no losses caused by traffic or grazing, and there should be no damage to the crop by wind, hail, frosts. Because potential yield is also determined by crop properties, yield potential varies over crop varieties and can be increased by breeding. In the computer model, potential yield depends on the choice of crop variety, sowing date and weather data set. Near to potential yield levels are realized on some arable and grassland farms in Western Europe, and sometimes in (glasshouse) horticulture. In these cases, the weather conditions and crop characteristics exclusively determine the potential growth rate. When the canopy fully covers the soil, the increase in biomass, expressed in dry matter, is typically between 150 and 350 kg ha⁻¹ day⁻¹.

The water-limited production level takes into account the effect of periods of soil moisture deficit on crop growth, and the water-limited yield represents the maximum yield that can be obtained under rain-fed conditions. The yield limiting effect of drought depends on the soil moisture availability as determined by the amounts of rainfall and evapotranspiration, and their distribution over the growing season, by soil type, soil depth and groundwater influence. The difference between potential and water-limited production indicates the production increase that could be achieved by irrigation.

A special case of water-limited conditions is related to an excess of soil moisture, causing oxygen shortage for the plant roots. So oxygen limited production would be a more appropriate term. Its effect depends on soil properties and drainage measures and is difficult to quantify by modelling.

The nutrient limited production corresponds to a situation that no manure or fertilizers are added to the soil. Then, nutrient availability depends on the supply of nutrients to the plant roots and is estimated from soil characteristics, for which the QUEFTS model (Janssen et al., 1990) is included in WOFOST. Only macro nutrients N (nitrogen), P (phosphorus) and K (potassium) are taken into account.

The QUEFTS estimates have been derived for maize crops in Kenya with a growing season of 120 days. The soil nutrient supply values in other ecological regions may be different. The yield effect of fertilizer applications can be quantified when their uptake efficiency is known. The yield levels with and without fertilizer together give a one-time impression. A more complete understanding of the soil nutrient status, time trends and management requirements can only be obtained from multi-year analysis of the nutrient turnover on the basis of annual net soil nutrient budgets (Stoorvogel and Smaling, 1998), but a module for such calculations is not linked to the WOFOST model.

Finally, the reduced production level indicates the production level for farming without pest and/or weed control (Rabbinge and De Wit, 1989; Van Diepen et al., 1989). The risks of occurrence of yield reductions are partly determined by ecological conditions, but the control of weeds, pests and diseases and the resulting effect on yield is primarily determined by management measures, and not included in the WOFOST model.

With WOFOST, you can calculate potential production and two levels of limited production: water-limited and nutrient-limited production. Production-reducing factors are not taken into account. The production levels are hierarchical within WOFOST. Potential biomass production is nearly always higher than water-limited production, but in some cases the simulated water-limited grain production is above the potential yield, because of a more favourable grain/straw ratio. In the water-limited situation a slight drought stress may limit the growth during the vegetative growth stage, while still sufficient green leaf area is formed to effectuate maximum assimilation rate. The lower amount of vegetative biomass leads to lower maintenance requirements for the crop, so that more assimilates remain available for the growth of the grains. In situations of heavily fertilized soils a similar growth pattern can be observed, a very heavy vegetative growth, leading to a lower harvest index and a risk of lodging in cereals.

Usually in (sub)-humid climates, the water-limited yield is higher than the nutrient-limited yield, so that yields can be increased by nutrient application without irrigation, but in cases of severe droughts the nutrient-limited yield may exceed the water-limited yield, and then water should be applied to increase yield.

4.1.3 Temporal and spatial scale

In each run, WOFOST simulates the growth of a specific crop, given the selected soil and weather data. For each simulation, you must select specific boundary conditions, which comprise, amongst others, the crop calendar and the soil's nutrient status and water balance. Crop growth and the soil water balance are described with a time resolution of one day, while nutrient uptake is calculated for the growing season as a whole.

Crop growth is simulated using daily weather data of many years and different parameters for each relevant soil type within a region. If required for a particular study, calculated values, e.g. yields, biomasses produced or water use, can be averaged over the simulated years or aggregated over soil types.

WOFOST is a one-dimensional simulation model, i.e. without reference to geographic scale. Its application to regions relies on the selection of representative points, followed by spatial aggregation or interpolation.

Variation in timing of crop production can be taken into account by varying the starting date of the growing season and/or by selecting crop cultivars with different growth duration. WOFOST offers several options for positioning the crop calendar in the year. The start of the simulation can be at a fixed date of crop emergence, at a fixed date of sowing or at a variable date of sowing. The end of the simulated season is determined by crop maturity, or crop death, or set at a

fixed end date, e.g. for crops harvested immature, like silage maize and sugar beet.

The crops simulated are grown in single stands of one crop per year/growing season. For mixed-cropping (more than one crop at the same site and moment) no options have been implemented. Options for crop rotations involving more than one crop/growing season in one year (multiple cropping) will be being implemented in a successive model version.

The soil physical properties required by WOFOST are often derived from soil maps. The rules applied to derive these properties from map units are still rather tentative, and only a small number of standard data sets are provided with the model.

4.2 Development of current and earlier versions WOFOST

WOFOST originated in the framework of interdisciplinary studies on world food security and on the potential world food production by the Center for World Food Studies (CWFS) in cooperation with the Wageningen Agricultural University, Department of Theoretical Production Ecology (WAU-TPE) and the DLO-Center for Agrobiological Research and Soil Fertility (AB-DLO), Wageningen, the Netherlands. After cessation of CWFS in 1988, the DLO Winand Staring Centre (SC-DLO) has continued development of the model in cooperation with AB-DLO and WAU-TPE.

WOFOST is a member of the family of models developed in Wageningen by the school of C.T. De Wit (Bouman et al., 1996). Related models are the successive SUCROS models (Simple and Universal CROp growth Simulator) (Van Keulen et al., 1982; Spitters et al., 1989; Van Laar et al., 1992; 1997), ARID CROP (Van Keulen, 1975; Van Keulen et al., 1981), Spring wheat (Van Keulen and Seligman, 1987; Stol et al., 1993), MACROS (Penning de Vries et al., 1989) and ORYZA1 (Kropff et al., 1993). Wolf et al. (1986) has documented the first WOFOST model. Two of the successive model updates have been documented: version 3.0 by Rappoldt (1986) and version 4.1 by Van Diepen et al. (1988). Documentation of WOFOST 6.0 is given by Supit et al. (1994). Hijmans et al. (1994) gave a technical description of WOFOST 6.0.

All these Wageningen models follow the hierarchical distinction between potential and limited production, and share similar crop growth sub models, with light interception and CO₂ assimilation as growth driving processes, and crop phenological development as growth controlling process. However, the sub models describing the soil water balance and crop nutrient uptake are diverse in approach and level of detail.

The development of WOFOST has been connected to the need for its application in various studies. Although most of these studies did not have the specific purpose to develop the model as such, efforts were made to maintain parts of the software developed as options in the subsequent model versions.

WOFOST was originally developed as a crop growth simulation model for the assessment of the yield potential of various annual crops in tropical countries (Van Keulen and Wolf, 1986; Van Diepen et al., 1988; Van Keulen and Van

Diepen, 1990). At first it was tried to restrict the need for input data as much as possible, by using average input values. However, it soon became clear that the variability in the environmental conditions determining crop growth, both in space and time, had to be taken into account. The use of long-term mean monthly weather data, mean sowing dates, and averaged soil data as model input may lead to a false impression of the agro-ecological potential of a region. This implies that original rather than averaged data must be used as model input and that if needed, averaging can be done only after the simulation. In other words: calculate first and average later (De Wit and Van Keulen, 1987; Nonhebel, 1994).

The WOFOST 6.0 has been developed to simulate the production of annual field crops all over Europe. It was developed in the years 1989-1994 by the DLO Winand Staring Centre (SC-DLO), jointly with the Research Institute for Agrobiological and Soil Fertility (AB-DLO) in Wageningen for the Joint Research Center (JRC-Ispra Site) of the Commission of the European Communities. One of the products was the Advanced Agricultural Information System for the European Union, of which the Crop Growth Monitoring System (CGMS) is the agrometeorological component (see Annex A for all the abbreviations). WOFOST version 6 was incorporated in CGMS to provide objective data for regional crop state monitoring and yield forecasting at regional and national scales on individual years, to serve as a basis for comparison of crop growth conditions over regions and years.

In CGMS WOFOST is fully linked to a geographical information system and to a relational data base management system. However, for tests and validation studies with WOFOST, for training purposes and as a starting point for its application in other studies, it was considered appropriate to have a 'stand-alone' model version (WOFOST version 6.0), which could run on any computer platform, independent of CGMS.

WOFOST has been developed further in 1997 and 1998 in the framework of the SysNet Project, which stands for the collaborative Systems Research Network to develop Systems Methodology for Ecoregional Land Use Planning in Support of Sustainable Resource Management in Tropical Asia. SysNet is coordinated by the International Rice Research Institute. At the same time this model development served also the requirements of the study to estimate the regional production potential on the Russian Federation, carried out by the Dokuchaiev Soil Institute in Moscow. This resulted in WOFOST version 7.1

Main change was the development of graphical user interface. WOFOST version 6.0 ran on a personal computer with MS-DOS operating system. It was a FORTRAN program with several modes of use, ranging from interactive mode, requiring typing of menu choices and data specifications to batch mode, where the program read all input from files, requiring file editing by the user (Hijmans et al., 1994). However, its use required specific skills (requiring two days of exercise to learn it), it was time consuming and not flexible enough, e.g. all questions were in a fixed order and it was not possible to go back to earlier questions. Moreover, the output was in the form of tables and could not be displayed graphically. Therefore, a MS-Windows based user interface called

WOFOST Control Centre (WCC, version 1.5) was created as a shell around the Fortran-file based program, and all interactive manipulations have been brought together in a few menu screens, allowing quick familiarization with the model, and fast model use. The possibility of browsing and modifying data reduces the chance of making accidental errors.

WOFOST version 7.1 can still be used without WCC as a stand-alone FORTRAN executable in the batch mode, the interactive mode has been stripped because its function had been replaced by WCC. The FORTRAN source code can be adapted by the user to its own specific purpose. In that case a FORTRAN compiler should be available. As long as the in- and output specifications do not change, WCC can be used as user interface with the adapted executable.

Currently the latest version of FORTRAN WOFOST is WOFOST Control Centre 2.1 and WOFOST 7.1.7. Main change compared to the previous version is an upgrade for the latest OS like Windows 7. In addition a number of bugs have been solved (see section 1.3 and 1.4). The version management of WOFOST has been automated, including several examples of input files.

4.3 Applications of current and earlier versions of WOFOST

Over the last twenty-five years, the successive WOFOST versions and their derivatives have been used in many studies. WOFOST has been applied as a tool for the analysis of:

- yield risk and inter-annual yield variability;
- yield variability over soil types, or over a range of agro-hydrological conditions;
- differences among cultivars;
- relative importance of growth determining factors;
- sowing strategies;
- effects of climate change;
- critical periods for use of agricultural machinery.

The model has also been used for predictive purposes, in quantitative land evaluation, such as:

- regional assessments of crop yield potential in the form of maximum yield levels;
- estimation of maximum benefits from irrigation or from fertilizer use;
- detection of adverse growing conditions by simulation-monitoring the agricultural season;
- regional yield forecasts.

Some WOFOST users have extended the growth model to forest and grass, and have replaced the soil water module by more detailed sub models.

For a list of recent applications and publications related to WOFOST, please see the documentation at the web site: <http://www.wageningenur.nl/wofost>

4.4 Limitations of WOFOST

It should be stressed again that WOFOST is a model, hence a simplification of reality. The user always has to be cautious when drawing conclusions from the simulation results. Keep in mind that the quality of the model results cannot surpass the quality of the input data. A model merely elucidates the consequences of the user's opinions and data (Driessen, 1986b). Therefore, the careful selection of the input data is of utmost importance. As a general rule, you should not simulate crop growth without experimentation. Experimentation is needed to obtain specific parameters and to calibrate and verify the model results.

In the validation process, crop growth as observed in reality can be compared with the simulation results. This provides an impression of the adequacy of WOFOST's predictions. When differences occur, you may need to adapt values of model-parameters (calibration). Then, the model should again be checked, against an independent set of observations. A problem in this respect is that there are an enormous number of parameters while only a few can be validated at a time. One should also realize that although calibration may improve the model results for a specific purpose, it can diminish its general applicability.

A weakness of WOFOST and all other crop growth simulation models is that some parameters are fixed whereas in practice they are known to vary, for example those concerning the relation between development stage and partitioning (Passioura, 1996). This problem arises when the processes at a lower integration level are insufficiently known.

5 Theoretical background of WOFOST

5.1 Introduction

This guide explains how to work with WOFOST, and not how WOFOST works. However, to be able to work with WOFOST in a meaningful way, some basic knowledge of its principles is indispensable. Therefore, a brief overview is presented of the concepts used in WOFOST and in most other dynamic crop growth models. A complete system description of WOFOST is made by Supit et al. (1994). For extensive literature on the principles of crop growth simulation and system analysis you are referred to e.g. Van Keulen and Wolf (1986), Penning de Vries et al. (1989), Rabbinge et al. (1989), Leffelaar (1993), Goudriaan and Van Laar (1994), Joergensen (1994) and Kropff and Van Laar (1993).

5.2 Systems analysis and simulation

In WOFOST, systems analysis and simulation are applied to agricultural production. This approach is characterized by the terms: systems, models and simulation. A system is a limited part of reality that contains interrelated elements. A model is a simplified representation of a system. Simulation is the building of mathematical models and the study of their behaviour in reference to that of the system they represent (De Wit, 1993; Rabbinge and De Wit, 1989).

In this guide, the system considered is an annual crop, growing in a specific physical environment. WOFOST is a model of this system. By running WOFOST you can simulate the system.

There are different kinds of models. Distinction can be made between mathematical and non-mathematical models. Non-mathematical models include e.g. maps and scale models of buildings. Mathematical models can be divided in descriptive (statistical, stochastic) models and explanatory (deterministic, process) models.

A descriptive model usually describes the behaviour of a model in a relatively simple manner and reflects little or none of the mechanisms that are the cause of that behaviour. It is derived from statistical relationships between the variables studied.

An explanatory model consists of a quantitative description of the main processes involved. Within the model, these processes are related to each other based on comprehension of their interaction. Thus, processes acting at a lower integration level, like e.g. the photosynthesis-light response curve of a single leaf, are integrated with other processes to explain system behaviour at a higher integration level, e.g. crop growth. A third distinction that can be made is between dynamic models, that include time as a variable, and static models that do not.

WOFOST is a dynamic, explanatory model. It simulates crop growth with time steps of one day, based on knowledge of processes at a lower level of integration. Nevertheless, some parts of the model are descriptive and/or static. This is mainly due to the fact that some of the processes involved are as yet not adequately understood.

In WOFOST the state-rate variable approach has been used. This approach is based on the assumption that the state of the system can be quantified at any moment, and that changes in the system can be described by mathematical equations. In such a model, state, rate and driving variables are distinguished. State variables are quantities such as biomass or the amount of water in the soil. Driving variables (or forcing functions) characterize the influence of external factors on the system, but are not influenced by the processes within the system. Examples are macro-meteorological variables such as radiation, air temperature and precipitation. Rate variables indicate the rate at which the state variables change at a certain moment, and over a certain time step Δt . Rate variables are calculated on the basis of the state and driving variables (De Wit, 1993).

After calculating the values of all rate variables, they are used to calculate the new values of the state variables by rectangular numerical integration according to Equation 1.

$$STATE(t + \Delta t) = STATE(t) + RATE(t) \Delta t \quad (1)$$

This procedure provides the values for the state variables at $(t+\Delta t)$. The state variables and the driving variables at $(t+\Delta t)$ are used to calculate the rate variables at $(t+\Delta t)$. These rate variables are then used to calculate the state variables at $(t+2\Delta t)$, according to Equation 1, and so forth. In WOFOST, and in many other crop growth simulation models, the time step Δt is fixed on one day.

A simple example of a state determined dynamic model is that of exponential growth of a population. The rate is calculated according to Equation 2, the state according to Equation 1.

$$RATE(t) = STATE(t) \times constant \quad (2)$$

5.3 Crop growth simulation

5.3.1 General characteristics

In WOFOST, crop growth is simulated on the basis of eco-physiological processes. The major processes are phenological development, light interception, CO_2 -assimilation, transpiration, respiration, partitioning of assimilates to the various organs, and dry matter formation. This is illustrated in Figure 21.

Potential and water-limited growth is simulated dynamically, with a time step of one day. Nutrient-limited production is calculated statically, on the basis of soil characteristics and the water-limited production.

The core of the WOFOST's crop growth sub model has been taken from the SUCROS model (Spitters et al., 1989; Van Laar et al., 1992). The principles of WOFOST's water module are described in Van Keulen and Wolf (1986). Nutrient-

limited production is calculated according to the principles of the QUEFTS model (Janssen et al., 1990). In the following sections, an outline of the main calculation procedures used in WOFOST is provided.

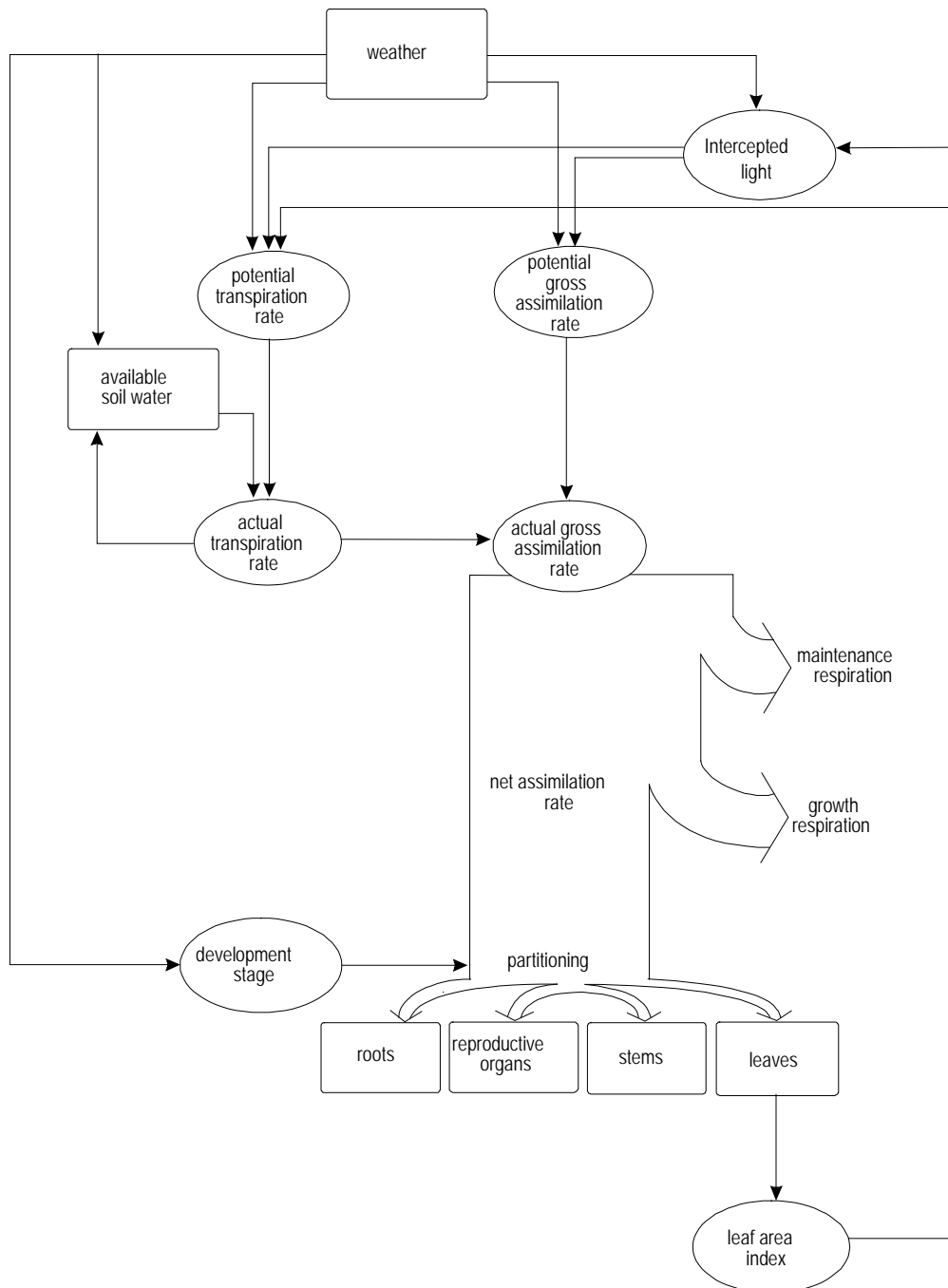


Figure 21. Simplified general structure of a dynamic, explanatory crop growth model (after Kropff and Van Laar, 1993)

5.3.2 Assimilation and respiration

The daily gross CO₂-assimilation rate of a crop is calculated from the absorbed radiation (I_a), and the photosynthesis-light response curve of individual leaves. This response is dependent on temperature and leaf age. The absorbed radiation is calculated from the total incoming radiation and the leaf area. Because photosynthesis responds to light intensity in a non-linear way, variation in radiation level has been taken into account.

One kind of variation occurs in the canopy along the vertical plane, because upper leaves receive more light than lower leaves. This is accounted for by dividing the canopy in different leaf layers. The intercepted radiation by each leaf layer is calculated on the basis of the radiation flux at the top of the canopy and the transmission by overlying layers. On the basis of the photosynthesis-light response curve for individual leaves, the assimilation of each leaf layer is calculated. The variation in the horizontal plane, e.g. the effect of plant rows, is not accounted for.

The second kind of variation is temporal, caused by the daily cycle of the sun. On a clear day, the radiation level at the top of the canopy, I_0 , equals the solar constant I [$J m^{-2} s^{-1}$] multiplied by the sine of the angle (β) between the sun and the earth's surface:

$$I_0 = I \sin \beta \quad (3)$$

Only half of the incoming radiation is Photosynthetically Active Radiation (PAR, wavelength 400-700 nm). The total amount of daily radiation is input to WOFOST. Equation 3 is used to distribute the radiation over the day. In this calculation, distinction is made between direct and diffuse radiation, as has been discussed by Spitters et al. (1986) and Spitters (1986). The canopy reflects part of the PAR. The reflection coefficient (ρ) is a function of solar elevation, leaf angle distribution, and reflection and transmission properties of the leaves. The complementary fraction ($1-\rho$) is potentially available for absorption by the canopy.

The radiation flux decreases more or less exponentially with increasing leaf area within the canopy. This is described by Equation 4, in which LAI_L is the cumulative leaf area index at depth L ($[m^2$ (leaf) m^{-2} (ground)]; counted from the top of the canopy downwards), I_L is the net radiation flux at depth L , and k is the extinction coefficient. The extinction coefficient is radiation (direct or diffuse) specific and a function of solar elevation, leaf angle distribution and the scattering coefficient of individual leaves (Spitters et al., 1989).

$$I_L = (1 - \rho)I_0 e^{-k LAI_L} \quad (4)$$

The decline in radiation flux is a measure for its adsorption by the leaf layers. This can be described by Equation 5, obtained by taking the derivative of Equation 4 with respect to L . I_{aL} is the adsorbed radiation by leaf layer L .

$$I_{aL} = \frac{dI_L}{dL} = k(1 - \rho)I_0 e^{-k LAI_L} \quad (5)$$

The instantaneous assimilation rate of a leaf layer can now be described by Equation 6, where A_L is the gross assimilation rate [$\text{kg}(\text{CO}_2) \text{m}^{-2}(\text{leaf}) \text{s}^{-1}$]. A_m is the maximum gross assimilation rate, i.e. the gross assimilation rate at light saturation [$\text{kg}(\text{CO}_2) \text{m}^{-2}(\text{leaf}) \text{s}^{-1}$] and ε is the initial light use efficiency [$\text{kg}(\text{CO}_2) \text{J}^{-1}$ (absorbed PAR)] of individual leaves (Spitters et al., 1989).

$$A_L = A_m \left(1 - e^{-\varepsilon \frac{I_{aL}}{A_m}} \right) \quad (6)$$

The calculations on light interception and assimilation as performed by WOFOST proceed along these lines but are more complex. You are referred to Supit et al. (1994) for the exact description.

Both ε and A_m in Equation 6 are temperature-dependent. k , ρ and A_m are crop specific. Generally, A_m of C_4 crops are higher than that of C_3 crops (Penning de Vries et al., 1989). This is illustrated in Figure 22.

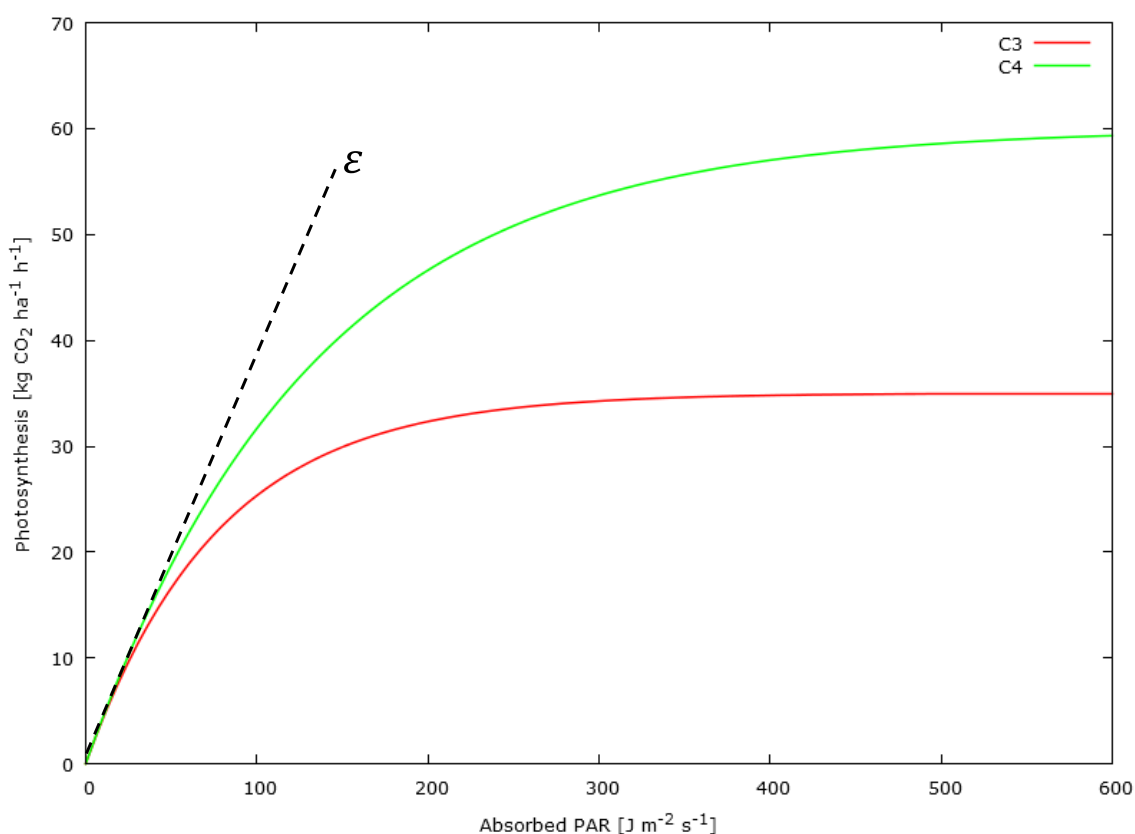
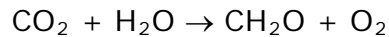


Figure 22. Photosynthesis-light response curves of individual leaves for a C_3 (barley) and a C_4 (maize) crop, with an A_m of 35 and 60 $\text{kg ha}^{-1} \text{h}^{-1}$, respectively and both with $\varepsilon = 0.40$ ($\text{kg ha}^{-1} \text{h}^{-1}$)/($\text{J m}^{-2} \text{s}^{-1}$). Measured at 340 vvp $\mu\text{m CO}_2$ and A_m at optimum temperatures and ε at a low temperature (data from Penning de Vries et al., 1989).

Daily gross CO₂ assimilation is obtained by integrating the assimilation rates over the leaf layers and over the day. For the integration over the day, a sinusoidal course of incoming radiation over the day is assumed and a three-point Gaussian integration method is applied as described by Goudriaan (1986).

In CO₂-assimilation, or photosynthesis, CO₂ is reduced to carbohydrates (CH₂O) using the energy supplied by the adsorbed light:



Part of the formed assimilates is used for maintenance respiration. The remaining carbohydrates are converted into structural plant material, such as cellulose and proteins. There is some net loss of carbohydrates due to this conversion, called the growth respiration (Figure 21). Maintenance respiration is estimated on basis of the dry weight of the different organs and their chemical composition, modified by ambient temperature (roughly 0.01-0.03 g g⁻¹) (Penning de Vries, 1975; Penning de Vries et al., 1989).

5.3.3 Phenological development

The order and the rate of appearance of vegetative and reproductive organs characterize phenological development of a crop. The order of appearance is a crop characteristic, which is independent of external conditions. The rate of appearance can vary strongly, notably under the influence of temperature and photoperiod (day-length) (Van Keulen and Van Diepen, 1990). In WOFOST phenology is described by the dimensionless state variable development stage (DVS). For most annual crops, DVS is set to 0 at seedling emergence, 1 at flowering and 2 at maturity. To calculate the time between sowing and emergence of a crop, WOFOST uses an additional set of thermal time variables.

Phenological development in WOFOST is calculated by incrementing the development stage with the development rate (DVR) at each time-step. The DVR is a crop/cultivar specific function of ambient temperature, possibly modified by photoperiod (Van Keulen and Van Diepen, 1990).

To account for the effect of temperature on development rate, the concept of thermal time is applied, sometimes called temperature sum or heat sum (see e.g. Ritchie, 1991). Thermal time is the integral over time of the daily effective temperature, T_e , after crop emergence. T_e is the difference between the daily average temperature, T , and a base temperature below which no development occurs, T_{base} , i.e. $T_e = \max((T - T_{\text{base}}), 0)$. Above a certain maximum effective temperature ($T_{\text{max-e}}$) T_e remains constant. Between $T_{\text{max,e}}$ and T_{base} , the daily increase in thermal time is obtained by linear interpolation (Figure 23).

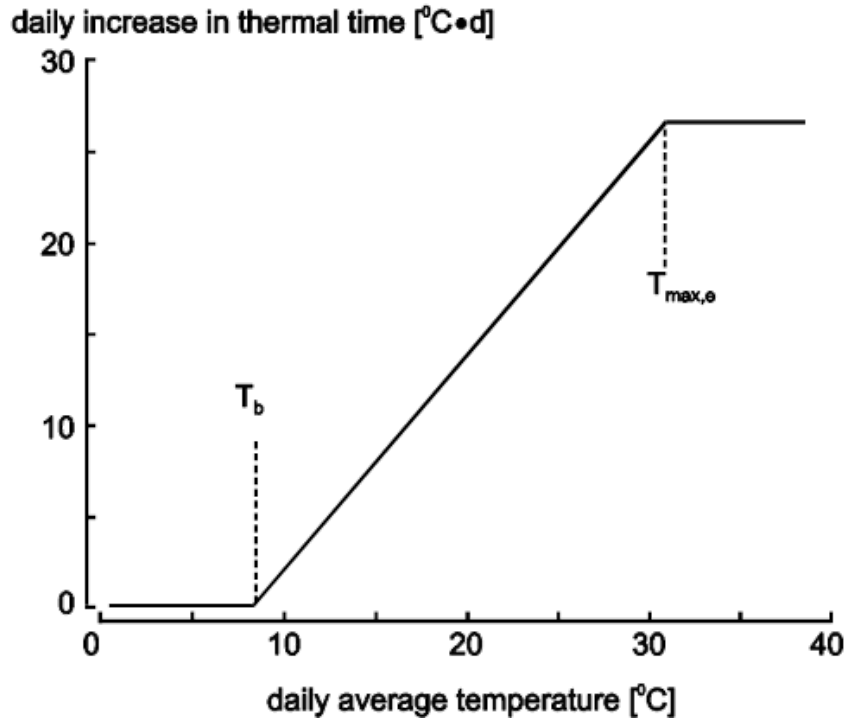


Figure 23. An example of the relation between daily average temperature (°C) and daily increase in the thermal time [°C d], for the calculation of the development stage of a crop ($T_b = 8$ °C, $T_{max,e} = 27$ °C)

The development rate (DVR) is calculated by dividing the daily effective temperature T_e [°C] by the thermal time required to pass to the next development stage, T_{req} [°C d] (Equation 7).

$$DVR = \frac{T_e}{T_{req}} \quad (7)$$

The phenological development rate of some crops is also influenced by photoperiod (P). This phenomenon is treated in WOFOST through a photoperiod reduction factor (F_{pr}) for the development rate until flowering, based on an optimum (P_o) and a critical photoperiod (P_c). F_{pr} is calculated according to Equation 8, and the development rate according to Equation 9 (see also Figure 24).

$$F_{pr} = \frac{P - P_c}{P_o - P_c}; \quad 0 \leq F_{pr} \leq 1 \quad (8)$$

$$DVR = F_{pr} \frac{T_e}{T_{req}} \quad (9)$$

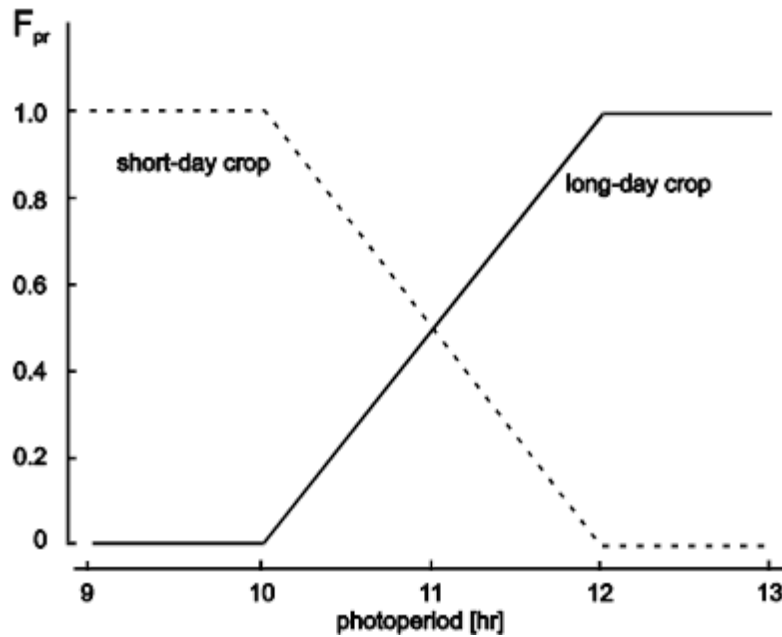


Figure 24. The relation between F_{pr} and P for a short-day crop ($P_o = 10$ hrs and $P_c = 12$ hrs) and for a long-day crop ($P_o = 12$ hrs and $P_c = 10$ hrs)

The development stage determines, among other things, the assimilate partitioning over the organs (leaves, stems, roots, storage organs; Figure 21). After germination, most assimilates are converted into leaf and root tissue and later into stem tissue. The partitioning to root tissue gradually diminishes and is zero if the development stage equals 1 (anthesis in cereals). From then on, the storage organs receive most of the available assimilates. This is illustrated in Figure 25.

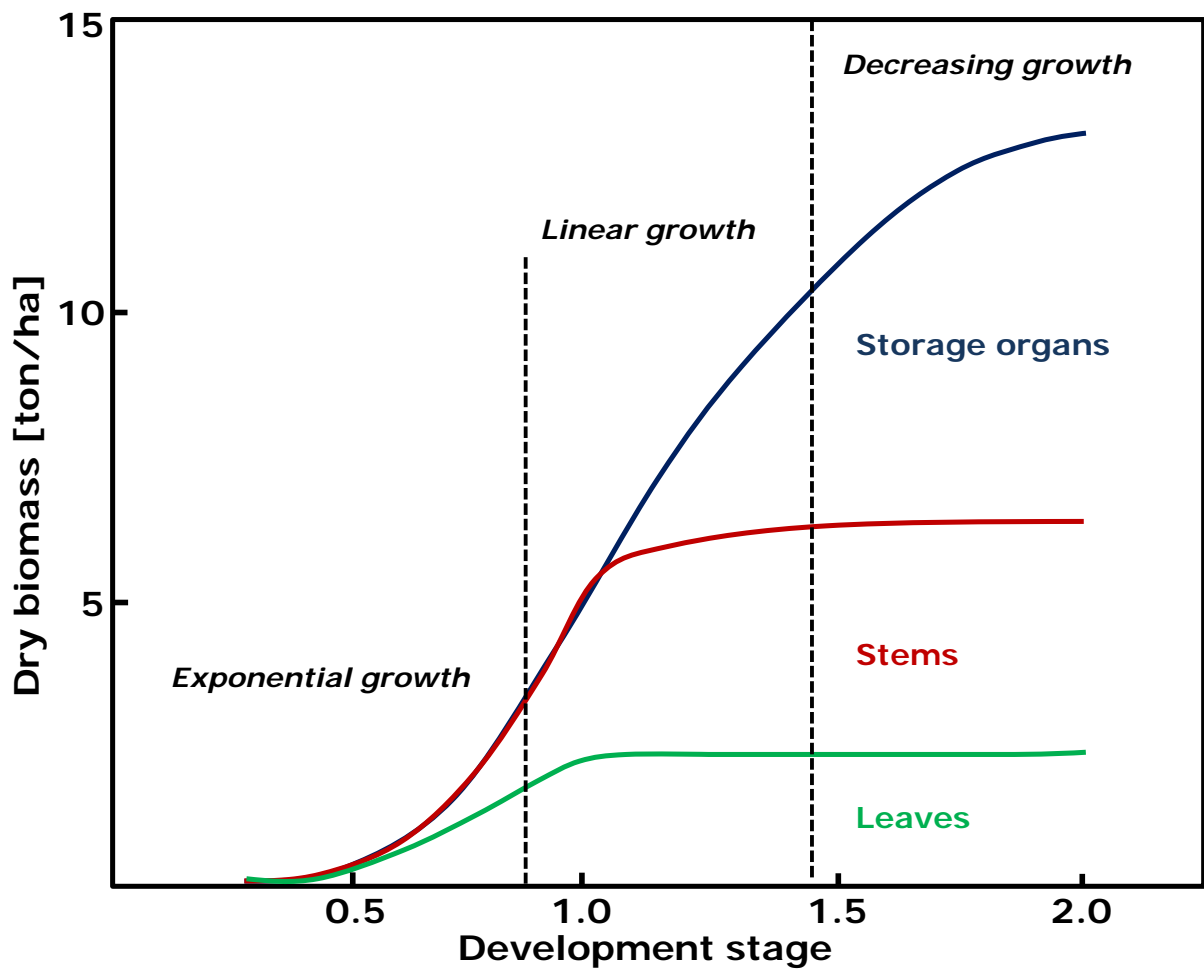


Figure 25. Example of dry matter allocation to the above-ground organs in relation to development stage (barley in the Netherlands, simulated). The three different growth phases have been indicated as well.

In the calculations, a fraction of the assimilates is assigned to the roots first, the remainder is divided over the above-ground organs (including below ground storage organs such as tubers). To initiate the simulation, the dry weight [kg ha^{-1}] of the crop at emergence must be known. The initial leaf area index [$\text{m}^2 \text{m}^{-2}$ or ha ha^{-1}] is derived from the initial dry weight through the partitioning mechanism at $\text{DVS}=0$.

From the outset of crop growth, the supply of assimilates to the leaves determines the increase in leaf area, calculated by multiplying the dry matter weight of the leaves [kg ha^{-1}] with specific leaf area [ha kg^{-1}]. However, leaf area expansion may be limited by the maximum daily increase in leaf area index (i.e. a maximum rate of cell division and extension), that is temperature dependent. The increase in leaf area leads to a higher (potential) light interception, and, consequently, to a higher potential growth rate (λ). This leads to exponential crop growth, that lasts until nearly all light is intercepted (leaf area index ≥ 3). From then on, the growth rate is constant, until the leaf area and its photosynthetic capacity decrease because of senescence of the crop (Figure 25).

5.3.4 Transpiration

Transpiration is the loss of water from a crop to the atmosphere. Water loss is caused by diffusion of water vapour from the open stomata to the atmosphere. The stomata need to be open to exchange gasses (CO_2 and O_2) with the atmosphere. To avoid desiccation, a crop must compensate for transpiration losses, by water uptake from the soil. In WOFOST, an optimum soil moisture range for plant growth is determined as function of the evaporative demand of the atmosphere (reference potential transpiration of a fixed canopy), the crop group and total soil water retention capacity. Within that range, the transpiration losses are fully compensated. Outside the optimum range, the soil can either be too dry or too wet. Both conditions lead to reduce water uptake by the roots, in a dry soil due to water shortage, in a wet soil due to oxygen shortage.

A crop reacts to water stress with closure of the stomata. As a consequence, the exchange of CO_2 and O_2 between the crop and the atmosphere diminishes, and hence CO_2 -assimilation is reduced. This effect is quantified assuming a constant ratio of transpiration to gross assimilation. This is done according to Equation 10, where the assimilation rate A is the product of the potential assimilation rate A_p (both [$\text{kg ha}^{-1} \text{d}^{-1}$]) and the ratio of the actual (water-limited) transpiration rate T_a and the potential transpiration rate T_p (both mm d^{-1}) (Van Keulen and Wolf, 1986).

$$A = \frac{T_a}{T_p} A_p \quad (10)$$

The potential transpiration rate depends on the leaf area and the evaporative demand of the atmosphere. The evaporative demand is characterized by radiation level, vapour pressure deficit and wind speed. In WOFOST, potential transpiration is calculated according to the Penman formula (Penman, 1956), adapted according to Frère and Popov (1979). The potential transpiration is calculated for a reference crop. Differences between crops can be accounted for

with a correction factor, having a value of 1.0 for most crops. A plausible range for this factor is 0.8 for water saving crops and 1.2 for crops spending relatively much water.

The relation between soil water content (Section 5.3.5) and the ratio T_a/T_p is shown in Figure 26. Between the critical soil moisture content (θ_{cr}) and field capacity (θ_{fc}), the ratio is 1, allowing potential transpiration. Outside this range, the ratio is smaller than 1, leading to reduced transpiration. At the permanent wilting point, θ_{wp} , and at the saturation point θ_{st} , transpiration and hence crop growth, come to a halt. θ_{wp} , θ_{fc} and θ_{st} depend on soil type. θ_{cr} depends on crop type and weather. A combination of high evaporative demand and a drought-sensitive crop leads to high values of θ_{cr} . A crop's drought-tolerance is indicated with a soil depletion number, within the range of 1.0 for drought-sensitive crops and 5.0 for drought tolerant crops (Driessen 1986a; Doorenbos and Kassam, 1979).

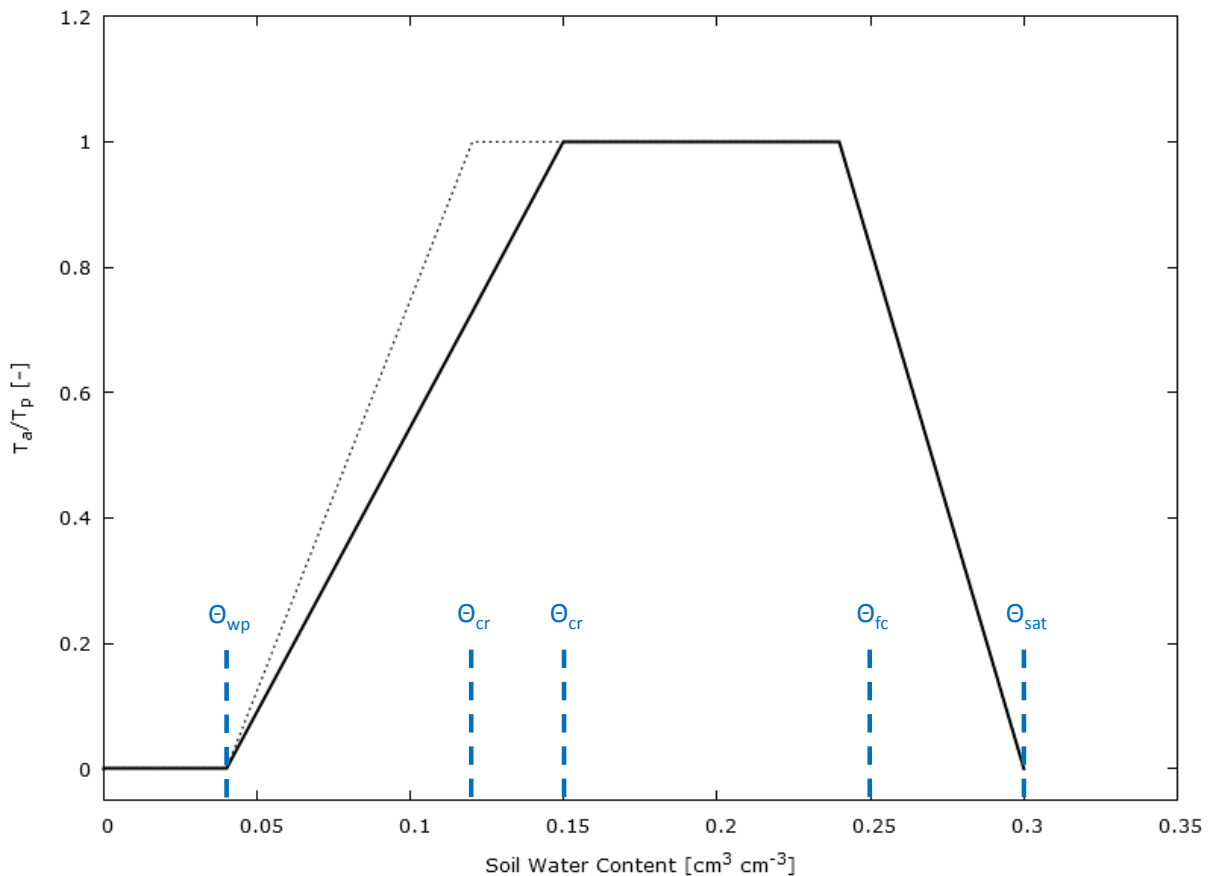


Figure 26. The relation between soil water content, θ , and T_a/T_p for a crop/soil combination. θ_{wp} , θ_{cr} , θ_{fc} and θ_{st} represent the water content of the soil at wilting point, the critical point for potential transpiration, field capacity and saturation, respectively. The dashed line represents either a more drought resistant species under the same field conditions, or the same species under a lower evaporative demand, caused by different weather conditions (Penning de Vries et al., 1989; Van Laar et al., 1992)

5.3.5 *Water balance of the soil*

The moisture content in the root zone follows from the daily calculation of the water balance. In WOFOST three different soil water sub models are distinguished. The first and most simple soil water balance applies to the potential production situation. Assuming a continuously moist soil, the crop water requirements are quantified as the sum of crop transpiration and evaporation from the shaded soil under the canopy.

The second water balance in the water limited production situation applies to a freely draining soil, where groundwater is so deep that it cannot have influence on the soil moisture content in the rooting zone. The soil profile is divided in two compartments, the rooted zone and the lower zone between actual rooting depth and maximum rooting depth. The subsoil below rooting depth rooting depth is not defined. The second zone merges gradually with the first zone as the roots grow deeper.

The principle of this soil water balance is a cascade (overflowing bucket). The rainfall infiltrates, a part may be temporarily stored above the surface or runs off. Evapotranspiration loss is calculated. The infiltrated water that exceeds the retention capacity of a soil compartment percolates downward. There is no capillary rise.

The third water balance is for water limited production on soils having influence of shallow groundwater in the rooting zone. The principles are similar to the freely draining situation. Different is that the soil moisture retention capacity is determined by the depth of the groundwater, as is the percolation rate. There is capillary rise if the rooted soil dries out. The groundwater level can be controlled by artificial drainage and the moisture content within the root zone does not vary with depth.

The soil is divided in three compartments: the actual rooting zone (RD_{act}), the zone between actual rooting zone and groundwater table, and the groundwater zone down to a depth of 1000 cm below the soil surface. The maximum rooting zone is RD_m . The ground water table is at depth Z (Figure 27). When ground water enters the rooting zone, the rooted zone is subdivided in a water-saturated and a non-saturated zone.

The calculations on the water fluxes include the parameters rainfall (R), surface storage (SS), surface run-off (SR), soil surface evaporation (E), crop transpiration (T), percolation from the root zone to deeper layers (PC) and capillary rise into the root zone (CR) (Figure 27). Water supply by irrigation or surface run-off from higher positions on the slope is not taken into account in WOFOST.

A separate module serves to calculate the earliest possible sowing date, if required. It has been calibrated for Dutch conditions only. This module mimics the soil water status of the top soil layer. The user must specify the earliest and latest possible dates. WOFOST searches for a suitable sowing date by simulating the water excess in the topsoil, by accounting for rainfall minus water loss from percolation and evaporation. It is assumed that the water percolates from the

seedbed to the subsoil at a rate equal to a constant rate (SPO^{**}) plus a fraction (SPA^{**}) of the instantaneous water excess. The variables SPO^{**} and SPA^{**} are soil specific and are related to the depth of the required seedbed (see Annex B). Deep and shallow seedbeds are distinguished. The values are higher for sandy soils than for clay soils, and also higher for shallow seedbeds than for deep seedbeds. The values currently applied in WOFOST are the result of empirical calibration and are meaningful only when the surface layer of a wet soil must become drier to allow seedbed preparation. When the water content of the seedbed falls below an externally defined threshold, that day is counted as a workable day. Seeding takes place at the third consecutive workable day, or at the latest possible sowing date.

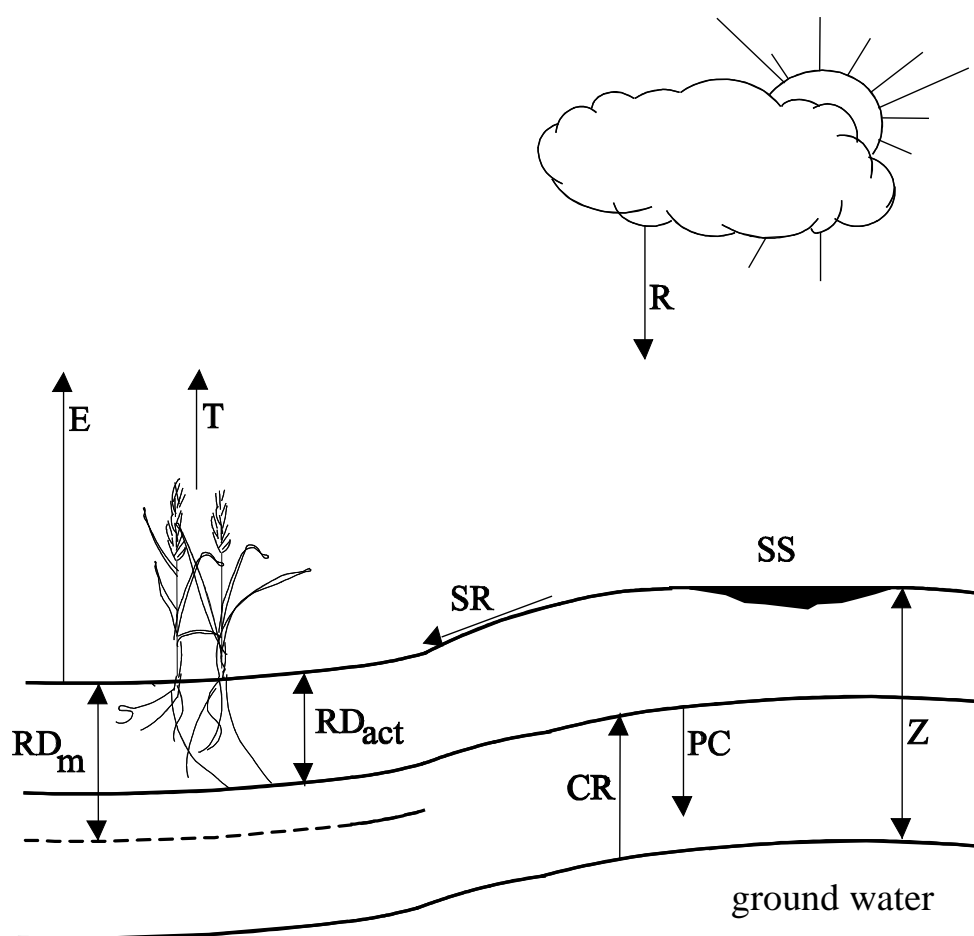


Figure 27. The components of the daily soil water balance.

5.3.6 Nutrients

WOFOST can calculate nutrient-limited production under non-fertilized soils and the amount of plant nutrients needed to attain potential and water-limited production levels. Only the three macro nutrients, N, P and K are accounted for. The calculations are performed according to the QUEFTS model (QUAntitative Evaluation of the Fertility of Tropical Soils) (Janssen et al., 1990; Smaling and Janssen, 1993), which has been integrated in WOFOST. How elements of QUEFTS

work in WOFOST and what kind of data are required can be found in Keulen and Wolf (1986) and Keulen (1982).

Biological nitrogen fixation by crops, e.g. in symbiosis with *Rhizobium* spp. has been included in WOFOST. The crop parameter NFIX determines the fraction of the total nitrogen supply that is supplied by biological fixation. Note that NFIX is defined as a constant, while in reality nitrogen fixation is, amongst other things, dependent on the amount of mineral nitrogen available in the soil.

Nutrient-limited production is calculated on the basis of the availability of the macro nutrients N, P and K in non-fertilized soils. In addition the nutrient requirements for potential production are calculated for the last season simulated, those for water-limited production for the average yield for the last series of runs. In the calculations for potential and water limited production the model assumes fertilizer is applied to reach these production levels. For the fertilizers a constant apparent fertilizer recovery is used, i.e. the ratio between nutrient uptake and nutrient application.

The uptake of e.g. nitrogen is a function of both the potential supply of nitrogen and that of other nutrients from the soil. The potential supply of nutrients is defined as the amount that is taken up by a crop when all other nutrients are non-limiting. This amount is crop-specific and can be determined through an experiment where all other nutrients are in ample supply. This requires a large number of field trials over a number of years. When repeated over different soil types the potential supply of nutrients can be related to soil properties like pH, organic carbon content, P-Olsen and exchangeable potassium (Janssen et al., 1990).

QUEFTS gives rules for estimating potential supply from chemical soil characteristics, but this part of QUEFTS is not incorporated in the WOFOST model. Therefore the user must specify the potential supply before running WOFOST. As reference for estimating the supply of nutrients from the soil is used the nutrients uptake by a rainfed maize having a cropping season of 120 days. When the growing season is shorter the basic nutrient supply from the soil is reduced proportionally with the reduction in growth duration. When the growing season is longer the basic nutrient supply from the soil is enlarged less than proportionally with the enlargement in growth duration.

For the calculation of nutrient-limited yield the uptake of each nutrient is calculated on the basis of the potential supply of that nutrient, taking into account the supply of the other two nutrients, and the maximum and minimum nutrient concentrations in the vegetative and generative organs. These concentrations are given in the crop files (see Section 6.2).

Figure 28 illustrates the relation between the potential supply of nitrogen and the actual nitrogen uptake by a crop, dependent on the (fixed) potential supply of another nutrient, e.g. phosphorus (Janssen et al., 1990; Pulles et al., 1991).

actual uptake of N [$\text{kg}\cdot\text{ha}^{-1}$]

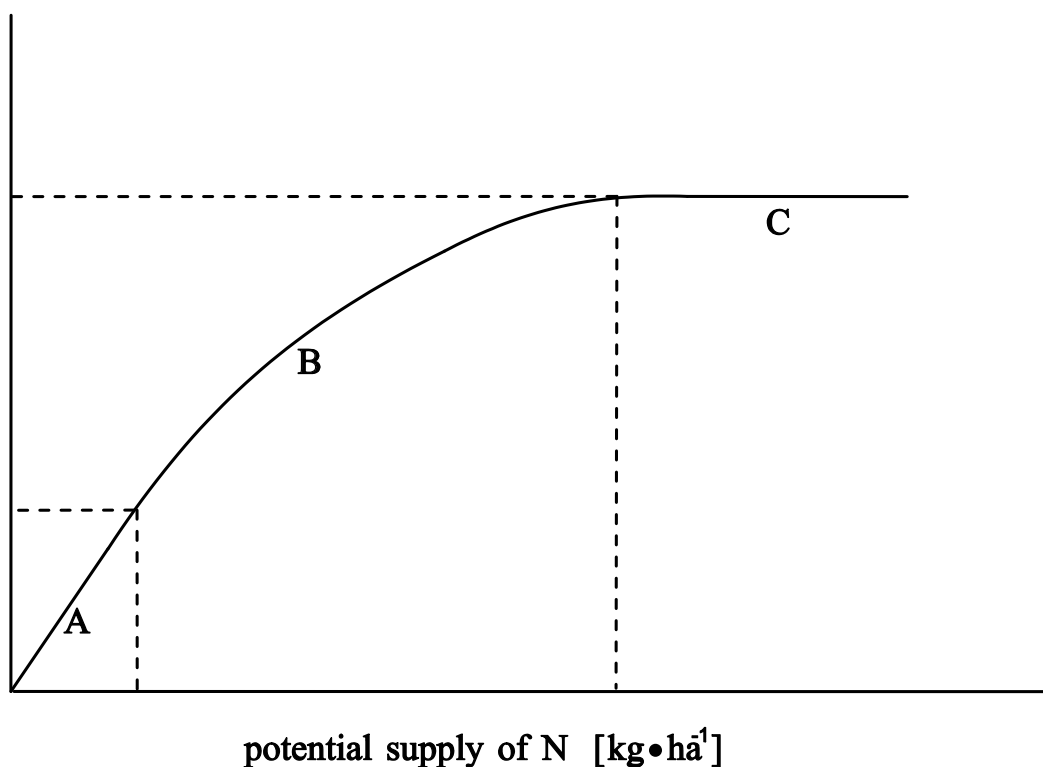


Figure 28. The relation between potential supply and actual uptake of nitrogen as affected by a second nutrient.

In Figure 28, three situations can be distinguished:

- A) The potential supply of nitrogen is very low compared to that of phosphorus, and hence, the uptake of nitrogen by the crop is equal to the potential supply.
- C) The potential supply of nitrogen is very high compared to that of phosphorus, and an increase in the N supply does not lead to a higher nitrogen uptake by the crop.
- B) In situation B, a transition between A and C takes place. The ratio $\delta(\text{N-uptake})/\delta(\text{N-supply})$ decreases from 1 to 0. This decrease is assumed to be linear, leading to a curvilinear relation between uptake and supply.

After determining the actual uptake of a nutrient, yield estimates can be made for each of the three pairs of nutrients. The relation between actual uptake and yield is depicted in Figure 29, where the uptake of nitrogen varies with the level of phosphorus uptake (Pulles et al., 1991).

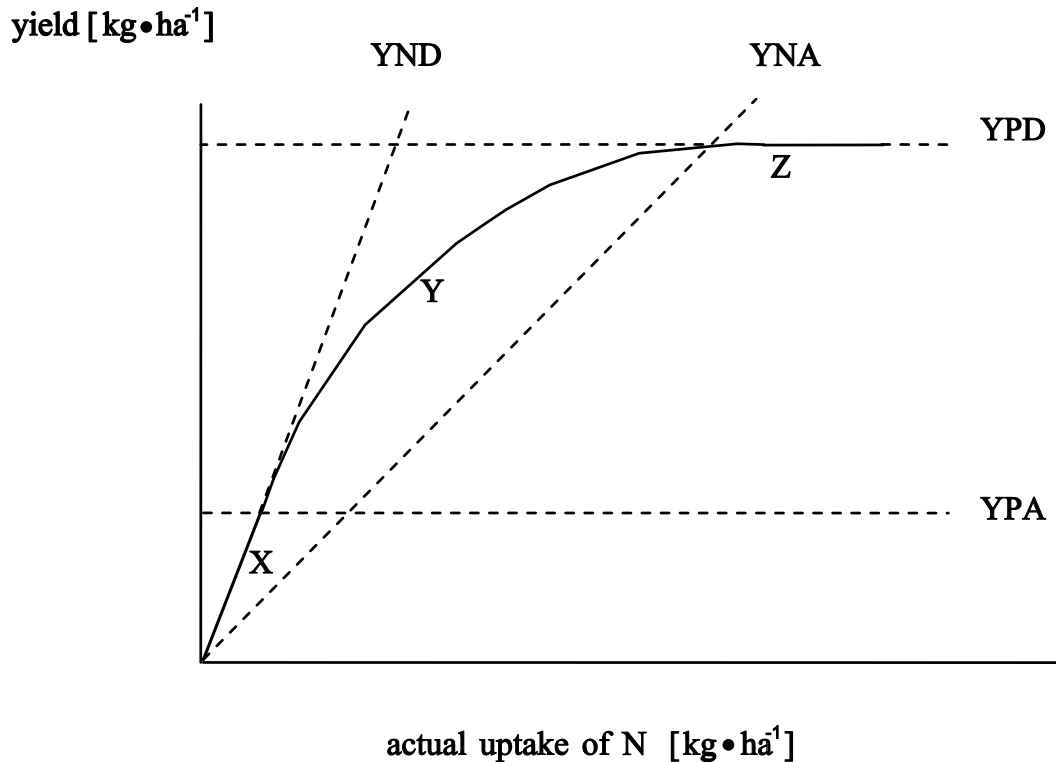


Figure 29. The relation between actual uptake of nitrogen and yield as affected by the yield range of phosphorus.

Again, three situations can be distinguished:

- X) Production is not limited by P, the element is at its maximum accumulation level YPA (Yield when Phosphorus is at maximum Accumulation level), while nitrogen is at its maximum dilution level YND (Yield when Nitrogen is at maximum Dilution level).
- Y) Both N and P limit crop production.
- Z) Only P limits crop production, being at its maximum dilution level YPD, while nitrogen is at its maximum accumulation level YNA.

For each pair of nutrients two yield estimates are calculated, for example that for the actual nitrogen uptake in dependence of the yield range for P uptake, that for the actual P uptake in dependence of the yield range for N uptake, etc. This leads to six combinations describing the uptake of one nutrient given maximum dilution or accumulation of another.

The nutrient-limited yield is estimated by averaging the six yield estimates for paired nutrients (Janssen et al., 1990). In this procedure, an estimate based on two nutrients may not exceed the upper limit of the yield range of the third nutrient, i.e. the concentration of a nutrient cannot be lower than its maximum dilution level.

6 Input and output files of WOFOST

6.1 Introduction

In principle, WOFOST can simulate the growth of any annual crop growing at any location. To facilitate this, the specific crop, soil and weather parameters have been put in separate data files. This makes it relatively easy to add a new file with e.g. the parameters of a specific crop you work with, or data from a nearby weather station. Additional information is given in run files named WCCTI.TIM (weather and crop calendar related data), WCCSI.SIT (default values for soils that are not given in the soil file), WCCRR.RER (to define series of consecutive WOFOST-runs) and WCC.WCC (general information on names of files etc.).

This chapter describes the structure of:

- crop files (Section 6.2);
- soil files (Section 6.3);
- weather files (Section 6.4);
- run files (Section 6.5);
- output files (Section 6.6);
- log-files (Section 6.7).

The variables used in the data files are explained in Annex B. For a complete description of the variables and their function in WOFOST, you are referred to Supit et al. (1994).

The WCC does not check the values of parameters given in the crop, soil and weather files. Only when the user selects those parameters in the rerun tab (Section 3.4.7) the WCC does such tests. Also WOFOST does not carry out a full control of lower and upper limits of given input. So it is important to fill in right values in the crop, soil and weather files without mistakes. For example it is possible to fill in a negative number for TSUM1 in the crop file. WCC and WOFOST will execute the run with this erroneous value without any problem. However, the simulation results are wrong (negative development stage). Another example can be given for the CABO-weather files (Section 6.4.2). If you make mistakes in the day number (e.g. day 77 is followed by day 79) WOFOST does not signal any problem but the results are wrong. So the advice is to work very careful when editing and building new crop, soil and weather files.

The collection of basic data is treated in Van Keulen and Wolf (1986) and in Penning de Vries et al. (1989).

6.2 Crop files

For each crop (or cultivar) you want to simulate, you have to provide WOFOST with a specific set of parameters. These parameters refer to, amongst other things, phenology, assimilation and respiration characteristics, and partitioning of assimilates to plant organs. These parameters are specified in a crop file that is stored in the directory \Wofost Control Centre\CROPD\. In the WCC you can

choose the file in the tab 'Crop' (see Section 3.4.2); when running WOFOST in the terminal mode you supply the file name in the timer file (see Section 6.5). The file extension of the crop files is divers and does not have meaning.

See Annex B for the meaning of the variable names. The syntax of the crop files is presented in Figure 30. There are no specific rules for the file names. An example of a crop file is presented in Table 11.

- The file consists of names and values of variables, separated by an equal => sign.
- The name of a variable cannot exceed six characters.
- Each variable may appear only once.
- Variables may appear in the file in any order.
- More than one variable and value can be written on one line as long as they are separated by a semi-colon < ; >.
- With the exception of array variables, the variable and its value have to be on the same line.
- Only the first 80 characters of each line are read.
- Comment lines start with an asterisk < * > in the first column or an exclamation mark < ! > in any column.
- Blank lines are allowed.
- No tabs or other control and extended ASCII characters are allowed.
- In case of array variables, more than one numerical value may follow the equal sign, separated by commas < , >.
- Identical values in an array may be given as < n * numerical value >, e.g. < 5 * 10 > instead of < 10, 10, 10, 10, 10 >
- Arrays may be written on successive lines, as long as the continuation character < , > is used (e.g. AMAXTB in Fig. 29).
- Somewhere (advisable just after the header) the WCC variable CRPNAM (for crops) or SOLNAM (for soils) has to be given. To this variable a description (character string) of the crop or soil is assigned that is enclosed with obligated quotes < ' >

Figure 30. Syntax rules of the crop and soil files (Van Kraalingen, 1991).

Most of the crop files included in WOFOST have been developed for simulation of crop growth in the EC (Boons-Prins et al., 1993). The differences among the different files of one species are usually very small. The regions of the EC to which the data sets pertain are indicated in the comment in the files.

The crop files are ready for use, but you may want to change them or use completely new files. For instance when you want to simulate a specific variety or a crop not included. Because a large number of data is needed (), creating new crop files can be cumbersome. Some values can be retrieved from the literature (e.g. Van Heemst, 1988; Penning de Vries et al., 1989) but you may need to obtain others by experimentation. Consult e.g. Van Keulen (1986) on the collection of plant data.

While the measurement of some plant-parameters requires a lot of work, others are more easy to obtain, e.g. the thermal time needed to reach a certain phenological stage (TSUM1, TSUM2) can be easily observed. If you want to change such parameters, the use of rerun files can be very helpful (Section 6.5).

Table 11. Example of a crop file (WWH101.CAB).

```

** $Id: ww101.cab 1.3 1997/09/25 14:07:03 LEM release $
** File WWH101.CAB
** CROP DATA FILE for use with WOFOST, June 1992
**
** WHEAT, WINTER 101

```

```

** Regions : Northern Ireland, Scotland, northern UK (R71), Denmark
** start date 1 January
** mean date of flowering 10 Jun, mature 15 Aug

** Derived from SUCROS87 data set for wheat.
** Calibrated for use in WOFOST model at the Centre for Agrobiological
** Research (CABO-DLO) for the simulation of crop growth and yield on the
** basis of daily weather data.
** Purpose of application: Crop growth monitoring with agrometeorological
** model in the EC.
** Developed in the framework of JRC Agriculture Project Action 3.

CRPNAM='Winter wheat 101, N-U.K., Denmark'

** emergence
TBASEM = -10.0    ! lower threshold temp. for emergence [cel]
TEFFMX = 30.0    ! max. eff. temp. for emergence [cel]
TSUMEM = 0.      ! temperature sum from sowing to emergence [cel d]

** phenology
IDSL   = 0       ! indicates whether pre-anthesis development depends
                ! on temp. (=0), daylength (=1) , or both (=2)
DLO    = -99.0   ! optimum daylength for development [hr]
DLC    = -99.0   ! critical daylength (lower threshold) [hr]
TSUM1  =1000.    ! temperature sum from emergence to anthesis [cel d]
TSUM2  = 950.    ! temperature sum from anthesis to maturity [cel d]
DTSMTB = 0.00, 0.00,    ! daily increase in temp. sum
                30.00, 30.00,    ! as function of av. temp. [cel; cel d]
                45.00, 30.00
DVSI   = 0.      ! initial DVS
DVSEND = 2.00   ! development stage at harvest (= 2.0 at maturity [-])

** initial
TDWI   = 210.00  ! initial total crop dry weight [kg ha-1]
LAIEM  = 0.1365  ! leaf area index at emergence [ha ha-1]
RGRLAI = 0.00817 ! maximum relative increase in LAI [ha ha-1 d-1]

** green area
SLATB  = 0.00, 0.00212, ! specific leaf area
                0.50, 0.00212, ! as a function of DVS [-; ha kg-1]
                2.00, 0.00212
SPA    = 0.000   ! specific pod area [ha kg-1]
SSATB  = 0.0, 0.0,    ! specific stem area [ha kg-1]
                2.0, 0.0    ! as function of DVS
SPAN   = 31.3    ! life span of leaves growing at 35 Celsius [d]
TBASE  = 0.0     ! lower threshold temp. for aging of leaves [cel]

** assimilation
KDIFTB = 0.0, 0.60,    ! extinction coefficient for diffuse visible
                2.0, 0.60    ! light [-] as function of DVS
EFFTB  = 0.0, 0.45,    ! light-use effic. single leaf [kg ha-1 hr-1]
                40.0, 0.45    ! j-1 m2 s] as function of daily mean temp.
AMAXTB = 0.00, 35.83, ! maximum leaf CO2 assimilation as function
                1.00, 35.83, ! of DVS
                1.30, 35.83,
                2.00, 4.48
TMPFTB = 0.00, 0.01,   ! reduction factor of AMAX
                10.00, 0.60, ! as function of av. temp. [cel; -]
                15.00, 1.00,
                25.00, 1.00,
                35.00, 0.00
TMNFTB = 0.00, 0.00,   ! red. factor of gross assim. rate
                3.00, 1.00   ! as function of low min. temp. [cel; -]

** conversion of assimilates into biomass
CVL    = 0.685   ! efficiency of conversion into leaves [kg kg-1]
CVO    = 0.709   ! efficiency of conversion into storage org. [kg kg-1]
CVR    = 0.694   ! efficiency of conversion into roots [kg kg-1]
CVS    = 0.662   ! efficiency of conversion into stems [kg kg-1]

```

```

** maintenance respiration
Q10      = 2.0    ! rel. incr. in resp. rate per 10 Cel temp. incr. [-]
RML      = 0.0300 ! rel. maint. resp. rate leaves [kg CH2O kg-1 d-1]
RMO      = 0.0100 ! rel. maint. resp. rate stor.org. [kg CH2O kg-1 d-1]
RMR      = 0.0150 ! rel. maint. resp. rate roots [kg CH2O kg-1 d-1]
RMS      = 0.0150 ! rel. maint. resp. rate stems [kg CH2O kg-1 d-1]
RFSETB   = 0.00, 1.00, ! red. factor for senescence
          2.00, 1.00   ! as function of DVS [-; -]

** partitioning
FRTB     = 0.00, 0.50, ! fraction of total dry matter to roots
          0.10, 0.50, ! as a function of DVS [-; kg kg-1]
          0.20, 0.40,
          0.35, 0.22,
          0.40, 0.17,
          0.50, 0.13,
          0.70, 0.07,
          0.90, 0.03,
          1.20, 0.00,
          2.00, 0.00
FLTb     = 0.00, 0.65, ! fraction of above-gr. DM to leaves
          0.10, 0.65, ! as a function of DVS [-; kg kg-1]
          0.25, 0.70,
          0.50, 0.50,
          0.646, 0.30,
          0.95, 0.00,
          2.00, 0.00
FSTB     = 0.00, 0.35, ! fraction of above-gr. DM to stems
          0.10, 0.35, ! as a function of DVS [-; kg kg-1]
          0.25, 0.30,
          0.50, 0.50,
          0.646, 0.70,
          0.95, 1.00,
          1.00, 0.00,
          2.00, 0.00
FOTB     = 0.00, 0.00, ! fraction of above-gr. DM to stor. org.
          0.95, 0.00, ! as a function of DVS [-; kg kg-1]
          1.00, 1.00,
          2.00, 1.00

** death rates
PERDL    = 0.030 ! max. rel. death rate of leaves due to water stress
RDRRTB   = 0.00, 0.000, ! rel. death rate of roots
          1.50, 0.000, ! as a function of DVS [-; kg kg-1 d-1]
          1.5001, 0.020,
          2.00, 0.020
RDRSTB   = 0.00, 0.000, ! rel. death rate of stems
          1.50, 0.000, ! as a function of DVS [-; kg kg-1 d-1]
          1.5001, 0.020,
          2.00, 0.020

** water use
CFET     = 1.00 ! correction factor transpiration rate [-]
DEPNR    = 4.5 ! crop group number for soil water depletion [-]
IAIRDU   = 0 ! air ducts in roots present (=1) or not (=0)

** rooting
RDI      = 10. ! initial rooting depth [cm]
RRI      = 1.2 ! maximum daily increase in rooting depth [cm d-1]
RDMCR    = 125. ! maximum rooting depth [cm]

** nutrients
** maximum and minimum concentrations of N, P, and K
** in storage organs in vegetative organs [kg kg-1]
NMINSO   = 0.0110 ; NMINVE = 0.0030
NMAXSO   = 0.0310 ; NMAXVE = 0.0105
PMINSO   = 0.0016 ; PMINVE = 0.0004
PMAXSO   = 0.0060 ; PMAXVE = 0.0020
KMINSO   = 0.0030 ; KMINVE = 0.0070
KMAXSO   = 0.0080 ; KMAXVE = 0.0280

```

YZERO	= 200.	! max. amount veg. organs at zero yield [kg ha-1]
NFIX	= 0.00	! fraction of N-uptake from biol. fixation [kg kg-1]

After collecting crop data and comparing model results with the observations, calibration may be necessary to improve model performance. This may improve the results for the specific area, but will reduce general applicability of the model (Penning de Vries and Spitters, 1991).

6.3 Soil files

A soil file contains information on physical soil characteristics. This comprises data on water retention, hydraulic conductivity and workability. These soil data are used in the calculation of the daily water balance of the soil needed to simulate water-limited growth, and to determine the optimal sowing date. Chemical soil properties are not included in this file. The default values of chemical properties are included in the site file (Section 6.5.2).

Table 12. Example of a soil file (EC1.NEW).

```

** $Id: ec1.new 1.2 1997/09/18 17:33:54 LEM release $
**
** SOIL DATA FILE for use with WOFOST, June 1990
**
** EC1-coarse

SOLNAM='EC1-coarse'

** physical soil characteristics

** soil water retention
SMTAB  = -1.000,  0.390,  ! vol. soil moisture content
          1.000,  0.380,  ! as function of pF [log (cm); cm3 cm-3]
          1.300,  0.360,
          1.491,  0.332,
          2.000,  0.185,
          2.400,  0.086,
          2.700,  0.056,
          3.400,  0.040,
          4.204,  0.040,
          6.000,  0.040
SMW    = 0.040 ! soil moisture content at wilting point [cm3/cm3]
SMFCF  = 0.110 ! soil moisture content at field capacity [cm3/cm3]
SMO    = 0.390 ! soil moisture content at saturation [cm3/cm3]
CRAIRC = 0.090 ! critical soil air content for aeration [cm3/cm3]

** hydraulic conductivity
CONTAB = 0.000,  1.999,  ! 10-log hydraulic conductivity
          1.000,  1.381,  ! as function of pF [log (cm); log (cm/day)]
          1.300,  1.004,
          1.491,  0.708,
          1.700,  0.100,
          2.000, -1.125,
          2.400, -3.060,
          2.700, -3.959,

```

```

3.000, -4.620,
3.400, -5.328,
3.700, -6.000,
4.000, -6.585,
4.204, -7.201

K0      = 99.770 ! hydraulic conductivity of saturated soil [cm day-1]
SOPE    = 12.47  ! maximum percolation rate root zone[cm day-1]
KSUB    = 24.03  ! maximum percolation rate subsoil [cm day-1]

** soil workability parameters
SPADS   = 0.800 ! 1st topsoil seepage parameter deep seedbed
SPODS   = 0.040 ! 2nd topsoil seepage parameter deep seedbed
SPASS   = 0.900 ! 1st topsoil seepage parameter shallow seedbed
SPOSS   = 0.070 ! 2nd topsoil seepage parameter shallow seedbed
DEFLIM  = 0.000 ! required moisture deficit deep seedbed

```

The soil files are stored in \Wofost Control Centre\SOILD. In the WCC, you can choose the file in the tab 'Soil' (see Section 3.4.5); when running WOFOST in the TERMINAL mode you supply the file name in the site file (see Section 6.5).

The soil types delivered with WOFOST consist of two groups: EC (European Community) / SR('Staringreeks')-group and the texture/AWC(available water capacity per meter soil depth)-group. Soil types starting with EC and SR (files with extension *.NEW) can be used in simulation of water-limited crop growth with free drainage as well as with groundwater influence. Soil types indicated by AWC values (files with the extension *.AWC) can only be used for simulation with free drainage, as information on hydraulic conductivity is not available.

The files starting with 'EC' have been developed in connection to the soil map of the EC (CEC, 1985; Reinds et al., 1992). The files starting with 'SR' are connected to the 'Staringreeks' (Wösten et al., 1994).

The collection of soil data is described in Driessen (1986c). Table 12 provides an example of a soil file. The syntax is identical to that of the crop files.

6.4 Weather files

Weather files contain the meteorological data used in the simulation model. This concerns radiation (sunshine), air temperature, rainfall (precipitation), air humidity and wind speed. As with all data, you should always check the weather data you use. Using your common sense may help you find typing errors, errors due to instrument failure, etc. Van Keulen and Van Heemst (1986) describe the meteorological data needed.

In previous version of WOFOST, two different types of weather files could be used: the WOFOST-format containing monthly weather data and the CABO-format for daily weather data (<http://edepot.wur.nl/43010>). However, the option to use monthly weather data has been removed from the WOFOST Control Centre, for two reasons:

- The use of monthly weather data is strongly discouraged and is not necessary given that daily weather data is generally available.
- The use of monthly weather data lead to strange results in WOFOST and given the point above we decide not to spend time fixing this problem.

For completeness the description of the WOFOST weather format for monthly data has been retained, but it is not supported anymore.

6.4.1 WOFOST-format

Note: Monthly weather data in WOFOST format is no longer supported!

The WOFOST-format files contain either long-term monthly averages (WOFOST-climate) or time-series of monthly averages (WOFOST-weather) of the relevant meteorological variables. Their syntax is presented in Table 13 with examples in Table 14 and Table 15. The first three lines in the files are comments with variables that are important for the WCC to recognize the weather station and present characteristics of this station in the WCC. The files are located in the directory `../WCC/METEO/CLIMD`. In the WCC, you can choose the file in the tab 'Weather' (see Section 3.4.3); when running WOFOST in the TERMINAL mode you supply the file name in the timer file (see Section 6.5). There are no special rules for the names of the WOFOST-format weather files.

Table 13. Syntax of WOFOST-format files.

line 1:	the WCC-variable 'WCCDESCRIPTION' with the description of the weather station.
line 2:	the WCC-variable 'WCCFORMAT' with an indication for the weather format. WCCFORMAT=1 indicates long-term monthly averages (WOFOST-climate). WCCFORMAT=0 indicates time-series of monthly averages (WOFOST-weather).
line 3:	the WCC-variable 'WCCYEARS' that gives the years. WOFOST-climate: WCCYEARS = 1000. WOFOST-weather: WCCYEARS will be one or a row of years. Missing years are not allowed. In case there are missing years you have to split the data into different files.
(lines 1 to 3 are preceded with <code><*></code> indicating these are comment lines. Note the double asterisks that are obligated). Also keep in mind that no extraneous tabs/spaces should be placed after the WCCDESCRIPTION, WCCFORMAT and WCCYEARS lines.	
line 4:	information of the weather station.
line 5:	year, latitude, altitude, the coefficients A and B for the Ångström formula (Supit et al. (1994)).
lines 6-17:	average monthly weather data; one line per month, from January to December:
	Column 1: minimum temperature (°C) 2: maximum temperature (°C) 3: irradiation (MJ m ⁻² d ⁻¹) 4: vapor pressure (hPa) 5: wind speed (m s ⁻¹) 6: precipitation (mm month ⁻¹) 7: number of days with rain (d)
The values should be separated by at least one space character. In case of WOFOST climate files (with long term average weather), the year should be set at 1000. Missing values are not allowed. The last line of the file should be followed by a hard return .	

Table 14. Excerpt from a WOFOST-weather file (S08536.WOF).

<pre> ** WCCDESCRIPTION=Portugal, Lisboa/Portela ** WCCFORMAT=0 </pre>
--

```

** WCCYEARS=1961-1981
8536 LISBOA/PORTELA
1961 38.7 95. 0.18 0.55
5.9 14.4 7.609 10.4 4.1 35. 15.
8.6 17.8 10.943 12.9 4.1 22. 12.
11.6 20.4 13.752 12.5 4.2 66. 14.
10.4 20.0 19.201 13.8 4.3 43. 10.
15.1 23.9 22.000 15.6 4.2 48. 10.
16.4 25.6 24.477 17.1 4.5 17. 5.
17.9 28.0 25.992 17.3 4.8 0. 2.
19.4 29.8 23.678 16.4 4.4 0. 0.
15.7 25.9 18.194 18.2 4.0 20. 6.
12.2 22.2 12.974 15.5 3.6 39. 9.
9.2 18.1 8.738 11.9 3.8 217. 13.
8.6 16.9 6.969 12.9 3.9 109. 15.
(...)
8536 LISBOA/PORTELA
1981 38.7 95. 0.18 0.55
7.6 16.1 9.108 8.9 4.1 12. 1.
7.0 16.2 10.943 10.6 4.1 76. 12.
9.2 18.0 13.752 10.5 4.2 109. 14.
10.8 20.4 19.201 11.1 4.3 54. 10.
12.8 21.6 22.000 12.5 4.2 44. 10.
15.5 24.7 24.477 14.6 4.5 16. 5.
18.8 28.9 25.198 13.6 4.8 4. 1.
17.5 27.9 23.678 17.3 4.4 0. 0.
16.2 26.3 18.194 16.4 4.0 33. 6.
14.1 24.1 13.995 13.3 3.6 30. 4.
9.9 18.9 8.738 11.9 3.8 93. 13.
10.1 18.4 5.734 12.5 3.9 257. 18.

```

Table 15. Example of a WOFOST-climate file (M296.WOF).

```

** WCCDESCRIPTION=Spain, Santander
** WCCFORMAT=1
** WCCYEARS=1000
296 SANTANDER
1000 43.5 68. 0.18 0.55
6.7 11.9 4.496 8.8 4.5 119. 16.
6.5 11.9 6.785 8.8 2.5 89. 14.
8.4 14.7 10.136 10.0 4.2 74. 13.
9.4 15.2 13.670 11.0 3.6 82. 14.
11.4 17.0 15.925 13.0 3.4 88. 15.
14.1 19.7 17.381 15.6 3.4 66. 13.
16.1 21.5 17.365 17.4 3.1 59. 12.
16.4 22.2 15.421 18.1 2.8 84. 14.
14.9 21.6 11.822 16.7 2.8 114. 14.
12.4 18.3 8.390 13.6 3.4 134. 14.
9.6 14.9 5.346 10.8 4.2 134. 16.
7.4 12.3 3.840 9.3 4.5 155. 18.

```

6.4.2 CABO-format

Files with CABO-format contain daily weather data. Each file contains the weather data for one station and one year. Their syntax is presented in Table 16 with an excerpt of a CABO-format file presented in

Table 17. The CABO file naming convention defines the filename as:

<location name><station number>.<last 3 numbers of the year>

Where the <location name> is a string, the <station number> is a number between 1 and 999 (at least 1 character) and the extension consists of the last three numbers of the year. For example, NL3.987 stands for the Netherlands, station 3 (De Kooy), year 1987. The entire length of the CABO name plus the full path cannot be longer than 250 characters.

WOFOST comes with data from three stations in the Netherlands: Wageningen, Swifterbant and De Kooy. CABO-format weather files have been developed at CABO (Van Kraalingen et al., 1991). The files are stored in the directory \METEO\CABOWE. In the WCC, you can choose the file in the tab 'Weather' (see Section 3.4.3); when running WOFOST in the TERMINAL mode you supply the file name in the timer file (see Section 6.5).

Table 16. Syntax of CABO-weather files (Van Kraalingen et al., 1991).

<p>File header: a continuous block of lines that start with a <*> in the first column. The file header contains general information about the data and their origin.</p> <p>The file header ends with three WCC-variables proceeded with <*> as comment leader (note that double asterisks are obligated):</p> <ul style="list-style-type: none">- the WCC-variable 'WCCDESCRIPTION' with the description of the weather station (this description must be exactly the same (including spaces) for different files of the same weather station, otherwise WCC will not recognize these files as belonging to the same station).- the WCC-variable 'WCCFORMAT' with an indication for the weather format. WCCFORMAT=2 indicates daily weather data (CABO-format).- the WCC-variable 'WCCYEARNR' that gives the year. <p>Keep in mind that no extraneous tabs/spaces should be placed after the WCCDESCRIPTION, WCCFORMAT and WCCYEARS lines.</p> <p>Lines that follow the header:</p> <p>line 1: the longitude, latitude, altitude and coefficients A and B for the Ångström formula (Supit et al. (1994). The last two parameters serve also as indicator if global radiation is derived from sunshine hours or has been measured. If global radiation has been measured, the Ångström coefficients are preceded with a minus sign. The values do not have to be written in a strict format but should be separated by at least one space character.</p> <p>line 2 - 368: daily weather data. One line relates to one day.</p> <table><tr><td>Column</td><td>1: station number</td></tr><tr><td></td><td>2: year</td></tr><tr><td></td><td>3: day number</td></tr><tr><td></td><td>4: irradiation ($\text{kJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)</td></tr><tr><td></td><td>5: minimum temperature ($^{\circ}\text{C}$)</td></tr><tr><td></td><td>6: maximum temperature ($^{\circ}\text{C}$)</td></tr><tr><td></td><td>7: early morning vapor pressure (kPa)</td></tr><tr><td></td><td>8: mean wind speed at 2 m above ground ($\text{m}\cdot\text{s}^{-1}$)</td></tr><tr><td></td><td>9: precipitation ($\text{mm}\cdot\text{d}^{-1}$)</td></tr></table> <p>Day numbers range from 1 to 365 (366 in leap years). The values should be separated by at least one space character. For missing values see Figs. 36 and 37. The last line of the file should be followed by a hard return. It is not allowed to add comments after the last line.</p>	Column	1: station number		2: year		3: day number		4: irradiation ($\text{kJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)		5: minimum temperature ($^{\circ}\text{C}$)		6: maximum temperature ($^{\circ}\text{C}$)		7: early morning vapor pressure (kPa)		8: mean wind speed at 2 m above ground ($\text{m}\cdot\text{s}^{-1}$)		9: precipitation ($\text{mm}\cdot\text{d}^{-1}$)
Column	1: station number																	
	2: year																	
	3: day number																	
	4: irradiation ($\text{kJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)																	
	5: minimum temperature ($^{\circ}\text{C}$)																	
	6: maximum temperature ($^{\circ}\text{C}$)																	
	7: early morning vapor pressure (kPa)																	
	8: mean wind speed at 2 m above ground ($\text{m}\cdot\text{s}^{-1}$)																	
	9: precipitation ($\text{mm}\cdot\text{d}^{-1}$)																	

Table 17. Excerpt of a CABO-weather file (NL1.987).

```

-----*
* Station name: Wageningen (Haarweg), Netherlands
* Year: 1987
* Author: Willem Stol en Vitale Nuzzo
* Source: Natuur- en Weerkunde - data invoer: Hennie de Ruiter
(...)
*
** WCCDESCRIPTION=Netherlands, Wageningen
** WCCFORMAT=2
** WCCYEARNR=1987
-----*
  5.67  51.97    7.  -0.18 -0.55
1 1987  1  470.   3.0  7.9  0.770  2.8  13.0
1 1987  2  620.  -3.9  7.3  0.660  5.4  2.7
1 1987  3 2420.  -6.4  4.0  0.500  1.9  0.1
(...)
1 1987 168 12750.  5.3 13.6  1.060  3.0  3.5
1 1987 169 18130.  6.9 15.9  1.020  3.2  0.0
1 1987 170  7950.  6.9 14.4  1.260  2.1  7.0
(...)
1 1987 363   710.  8.3 11.9  1.010  5.2  2.9
1 1987 364  1400.  7.8 11.3  1.100  3.5  5.0
1 1987 365  2000.  7.4 10.0  0.980  3.8  0.0

```

Daily weather data are often incomplete. There are several ways to handle this problem when using the CABO-format (Table 18). Missing data can be estimated automatically, by linear interpolation between the available data. There are, however, some exceptions. Because precipitation is too erratic, it is not interpolated but set at zero when missing. Automatic interpolation is impossible when there are no data on either side e.g. at the beginning and the end of the year. It is sometimes possible to derive the missing values in a different way. For instance, data from a weather station in the vicinity or the long term daily averages from the same station can be used. An example of a part of a CABO-format file with missing data is presented in Table 19.

Table 18. The treatment of missing values in CABO-format weather files (Van Kraalingen et al., 1991).

Missing data in a CABO weather file can be treated in three different ways:

1. Put -99 in place of the missing value; the value will then be calculated by linear interpolation between the available data (except for precipitation).
2. If all data are missing for a particular day, you can leave the complete day (line) out. All data will then be calculated by linear interpolation between the available data (except for precipitation).
3. The missing data can be estimated with data from e.g. other weather stations or with long-term averages from the same station.

If you replace missing values yourself, this should be marked in the data file by inserting a status line beginning with -999 and followed by eight values (see Fig. 37). The first two are dummy values for year and station; the remaining six are attributes for the weather variables. These attributes can have values between one and four:

- 1 - measured (i.e. not missing)
- 2 - interpolated
- 3 - estimated from e.g. another meteorological station
- 4 - not available (no interpolation or estimation possible)

The status line refers to all the following lines, until a new status line replaces it.

Table 19. Excerpt from a CABO-format weather file (NL2.989) with missing values.

```
(...)
```

2	1989	63	6540.	5.1	10.8	0.940	4.2	0.6
2	1989	64	4860.	7.5	13.9	1.130	3.1	0.0
-999	1989	65	1	1	1	1	3	1
2	1989	65	7440.	6.5	17.6	0.510	3.5	0.0
2	1989	66	2360.	6.0	11.0	0.810	3.5	19.3
-999	1989	67	1	1	1	3	3	1
2	1989	67	4340.	0.0	7.4	0.730	4.5	5.9
-999	1989	68	1	1	1	1	3	1
2	1989	68	13000.	-0.3	10.3	0.360	4.0	6.0
-999	1989	69	1	1	1	1	1	1
2	1989	69	10030.	5.0	13.8	0.940	4.5	0.0
2	1989	70	7110.	3.7	10.9	0.970	2.7	0.6

```
(...)
```

6.4.3 Rainfall files

Note: The use of rainfall files is no longer supported!

Rainfall files contain daily rainfall data only. Rainfall data must be used in combination with a complete data set (either daily or monthly) of any available weather station.

The option to use separate rainfall files is of much practical value. Rainfall generally has more spatial variation than the other weather variables. Rainfall data are also usually available at much higher density than any of the other

weather variables (Van Keulen and van Heemst, 1986). Rainfall can also be used to simulate the effect of irrigation.

The rainfall files are stored in subdirectory \Wofost Control Centre\METEO\CLIMD. In the WCC you can choose the file by activating the button 'Rainfall data options' on the 'Weather' tab (see Section 3.4.3). When running WOFOST in the TERMINAL mode, supply the file name in the timer file (see Section 6.5). Syntax rules are given in Table 20. The filename is free; files that come with WOFOST have the name *.RRD. An example is provided in Table 21.

Table 20. Syntax of a rainfall file.

<p>line 1: the WCC-variable 'WCCDESCRIPTION' with the description of the rainfall station.</p> <p>line 2: the WCC-variable 'WCCFORMAT' with an indication for the weather format. WCCFORMAT=99 indicates rainfall station.</p> <p>line 3: the WCC-variable 'WCCYEARS' that gives the years. WCCYEARS will be one or series of years.</p> <p>(lines 1 to 3 are preceded with <**> indicating these are comment lines. Note the double asterisks that are obligated).</p> <p>The header ends with lines that start with a <*>; these lines may contain any information.</p> <p>First line after the header:</p> <p>line 1: number of years, available years.</p> <p>line 2-367: day of the year, daily precipitation (mm) for each year. When the year is not a leap year, the precipitation on day 366 is zero.</p> <p>The values should be separated by at least one space character. Missing values are not allowed.</p>

Table 21. Excerpt from a rainfall file (NIAMEY.RRD).

<pre> ** WCCDESCRIPTION=Niamey ** WCCFORMAT=99 ** WCCYEARS=1950-1952 * * Weather station: Niamey. * 3 1950 1951 1952 1 0.0 0.0 0.0 2 0.0 0.0 0.0 3 0.0 0.0 0.0 (...) 238 1.8 0.0 0.0 239 2.3 33.4 0.0 240 21.0 0.0 36.2 (...) 364 0.0 0.0 0.0 365 0.0 0.0 0.0 366 0.0 0.0 0.0 </pre>
--

6.5 Run files

For running WOFOST, so-called run files are used. There are four types of run files:

- the timer file (WCCTI.TIM) on weather and crop calendar related data (Section 6.5.1);

- the site file (WCCSI.SIT) on default values for soil (Section 6.5.2);
- the rerun file (WCCR.RER) on defining series of consecutive WOFOST-runs (Section 6.5.3)
- the run option file (WCC.WCC) on general information like file names etc. (Section 6.5.4).

These files are stored in subdirectory \Wofost Control Centre\RUNIO. Syntax rules for the run files are similar to those of the crop and soil files (Table 11). When running WCC, the variables in these run files are changed through the interface on the different tab pages. When running WOFOST in TERMINAL mode, all the variables can be changed in the specific run files.

6.5.1 Timer file

The timer file especially concerns those variables with a time-related unit (weather, crop calendar). The file WCCTI.TIM is presented (Table 22). A figure with some explanation on the variables is shown in

Table 23. Variables that occur in the timer file are discussed in more detail in the description of the WCC (Chapter 3).

Table 22. An example of the timer file (WCCTI.TIM).

```

** File      : ..\RUNIO\WCCTI.TIM
** Generated by: C:\Program files\Wofost Control Centre\EXEC\WCC.EXE
** Date     : 3/22/98 4:41:10 PM
RUNNAM  = 'WCC'
IWEATH  = 2
CLFILE  = 'NL1.'
ISYR    = 1987
INYEAR  = 3
IRNDAT  = 3
RAFILE  = '<none>'
ISYRR   = -999
INYRG   = 1
CRFILE  = 'WWH101.CAB'
ISTCHO  = 0
IDEM    = 1
IDSOW   = 1
IDESOW  = 100
IDLSON  = 140
IENCHO  = 2
IDAYEN  = 270
IDURMX  = 260
IBAL    = 1
PRDEL   = 50.000000
CRPNAM  = 'Winter wheat 101, N-U.K., Denmark'
SOLNAM  = 'ECL-coarse'
CLMNAM  = 'Netherlands, Wageningen'
RAINAM  = '<none>'
ISDAY   = 1

```

Table 23. Variables in the timer file: type (C = character string enclosed with '<>'; I = integer; R = real), their meaning and some additional information (see Fig. 40 and Annex B).

parameter	type	meaning and possible values
RUNNAM	C	Run name (max. 6 characters, between quotes).
IWEATH	I	Format of weather: 0 (WOFOST-monthly), 1 (WOFOST-climate), or 2 (CABO).

CLFILE	C	File name of weather station.
ISYR	I	First year for which crop growth is simulated.
INYEAR	I	Number of years to simulate crop growth.
IRNDAT	I	Option for the use/selection of rainfall data: 0 (generates statistics with varying total monthly rainfall and number of rainy days), 1 (distributes monthly rainfall over given number of days), 2 (reads rainfall data out of separate file) or 3 (rainfall as it occurs in weather file). See Chapter 4 about the input of rainfall to learn more about this option).
RAFILE	C	Name of rainfall station.
ISYRR	I	(First) Year of rainfall data to be used (if IRNDAT = 2). If IRNDAT \neq 2, then ISYRR = -999.
INYRG	I	Number of runs for which rainfall has to be generated (IRNDAT = 0), or distributed (IRNDAT = 1). If IRNDAT \neq 0 or 1, then INYRG = 1 (WOFOST does not accept 0!). This variable is also used for the number of rainfall years (IRNDAT = 2).
CRFILE	C	Name of crop file.
ISTCHO	I	Options for start simulation: 0 (fixed emergence day), 1 (fixed sowing day) and 2 (variable sowing day).
IDEM	I	Day of emergence (day of year). Used if ISTCHO = 0.
IDSOW	I	Day of sowing (day of year). Used if ISTCHO = 1.
IDESOW	I	Earliest possible day of sowing (day of year). Used if ISTCHO = 2.
IDLSOW	I	Ultimate sowing day (day of year). Used if ISTCHO = 2.
IENCHO	I	Option to determine end of simulation: 1 (fixed end day), 2 (maturity, but not to exceed maximum duration), or 3 (earliest of both days).
IDAYEN	I	Ultimate day of harvest (day of year). Used if IENCHO = 1 or 3.
IDURMX	I	Maximum number of days from emergence to end of simulation used if IENCHO = 2 or 3.
IBAL	I	Option for output summary water balance: 0 (no summary), 1 (for whole system), 2 (for root zone), or 3 (for whole system and root zone).
PRDEL	R	Output interval: one output line per time interval. Output lines for day of emergence, anthesis and the last day are always provided. If the output interval is longer than the growing period, the detailed output will be reduced to these three lines. No detailed output will be produced, if the interval is set at zero days.
CRPNAM	C	Description of crop.
SOLNAM	C	Description of soil.
CLMNAM	C	Description of weather station.
RAINAM	C	Description of rainfall station.
ISAY	I	Start date of the water balance (day of year).

6.5.2 Site file

Site file concerns the default values for soil characteristics that are not given in the soil file. The file WCCSI.SIT is presented in Table 24. In

Table 25 some explanation is provided. Variables that occur in the site file are discussed in more detail in the description of the WCC (Chapter 3).

Table 24. An example of the site file (WCCSI.SIT).


```

** File       : ..\RUNIO\WCCSI.SIT
** Generated by: C:\Program files\Wofost Control Centre\EXEC\WCC.EXE
** Date      : 3/22/98 4:41:10 PM
SOFILE = 'ECl.NEW'
IZT    = 0
IFUNRN = 0
IDRAIN = 0
SSMAX  = 0.000000
WAV    = 20.000000
ZTI    = 999.000000
DD     = 20.000000
RDMSOL = 120.000000
NOTINF = 0.000000
NBASE  = 60.000000
NREC   = 0.500000
PBASE  = 10.000000
PREC   = 0.100000
KBASE  = 60.000000
KREC   = 0.500000
SSI    = 0.000000
SMLIM  = 0.040000

```

Table 25. The variables in the site file: type (C = character string enclosed with <'>; I = integer; R = real), their meaning and some additional information (Annex B).

variable	type	meaning and possible values
SOFILE	C	Name of soil file.
IZT	I	Ground water influence: 0 (no) or 1 (yes).
IFUNRN	I	Non-infiltrating fraction of rain is function of storm size (1) or not (0).
IDRAIN	I	Presence (1) or absence (0) of drains.
SSMAX	R	Maximum surface storage capacity (cm water).
WAV	R	Initial amount of available soil water in the rootable soil (moisture content above permanent wilting point) (cm water).
ZTI	R	Initial depth of the ground water table (cm). The value 999 is maximum initial depth of the ground water table.
DD	R	Drainage depth (cm).
RDMSOL	R	Maximum rooting depth allowed by soil (cm). This is dictated by soil characteristics like profile depth and presence of ground water.
NOTINF	R	(Maximum) non-infiltrating fraction of rainfall. Range: 0 - 1.
NBASE	R	Basic supply of nitrogen by the unfertilized soil (N, kg•ha ⁻¹). Range: 0 - 100.
NREC	R	Apparent nitrogen recovery. Increase in uptake of N as fraction of applied N. Range: 0 - 1.
PBASE	R	Basic supply of phosphorus by the unfertilized soil (P, kg•ha ⁻¹). Range: 0 - 10.
PREC	R	Apparent phosphorus recovery. Increase in uptake of P as fraction of applied P. Range: 0 - 1.
KBASE	R	Basic supply of potassium by the unfertilized soil (K, kg•ha ⁻¹). Range: 0 - 100.
KREC	R	Apparent potassium recovery. Increase in uptake of K as fraction of applied K. Range: 0 - 1.
SSI	R	Initial surface storage (cm water).
SMLIM	R	Maximum moisture content in topsoil (cm water). This value should be between moisture content at wilting point and moisture content at saturation.

6.5.3 Rerun file

With the rerun file, a series of consecutive WOFOST-runs can be defined by providing a set of new values for one or more variables for each consecutive run. The variables that are not included in such a set keep their values as defined in the different input files.

In each set (run) within one rerun file, the same variables must appear, even if their values are identical to those in the previous set (run). The order of the variables should be the same in each set (run). A new set (run) starts when the

first variable is repeated. Further the syntax rules for the timer, site, crop and soil file apply. An example of a rerun file is given in Table 26.

Table 26. An example of the rerun file (WCCRR.RER).

```
** File      : ..\RUNIO\WCCRR.RER
** Generated by: C:\Program files\Wofost Control Centre\EXEC\WCC.EXE
** Date     : 3/22/98 4:41:10 PM
RUNNAM='WCC1';
TSUM1=1000.
RUNNAM='WCC2';
TSUM1=1050.
```

6.5.4 Run option file

The run option file stores all required run options. The file is stored in the directory "RUNIO". The file WCC.WCC is presented in Table 27 ; Table 28 shows some explanation on the variables. Before running WOFOST, the program WCC automatically copies WCC.WCC to the file RUNOPT.DAT. This is because WOFOST expects the filename RUNOPT.DAT. If WOFOST is to be run in TERMINAL mode, be sure to copy the file WCC.WCC to RUNOPT.DAT before executing WOFOST.

Table 27. An example of the run option file (WCC.WCC).

```
** File      : ..\RUNIO\RUNOPT.DAT
** Generated by: C:\Program files\Wofost Control Centre\EXEC\WCC.EXE
** Date     : 3/22/98 4:41:10 PM
IOPT2 = 4           ! Start/Stop options
IPRODL = 3         ! Production levels
IOXWL = 0          ! Type of water-limited crop growth
TIMFIL = 'WCCTI.TIM' ! Timer filename
SITFIL = 'WCCSI.SIT' ! Site filename
WOPFRER = 'WCCRR.RER' ! Rerun filename
WOFOUT = 'WCC.OUT' ! Filename detailed output
SERIES = 1         ! Final results for series of years
REPORT = 1        ! Report: one line per year and statist
FIXNAM = 'WCC'    ! Output filename (max 8, no ext.)
RQUIRD = 1        ! Long term means results
```

Table 28. The variables in the run option file: type (C = character string enclosed with <'>; I = integer; R = real), their meaning and some additional information (see Table 27 and Annex B).

variable	type	meaning and possible values
IOPT2	I	Start/Stop option: 2 (run WOFOST with default input from data files), 4 (run WOFOST from reruns file without default run) and 5 (run FSEOPT for calibration of WOFOST; only possible in TERMINAL mode and not available in WCC).
IPRODL	I	Production levels: 1 (simulation of potential crop growth), 2 (simulation of water limited crop growth), 3 (calculation of nutrient limited crop growth).
IOXWL	I	Type of water-limited crop growth: 0 (effects of drought only), 1 (effects of both drought and oxygen shortage).
TIMFIL	C	Timer filename.
SITFIL	C	Site filename.
WOPFRER	C	Rerun filename.
WOFOUT	C	Filename detailed output.
SERIES	I	Final results for series of years: 0 (no), 1 (yes). This option has meaning only when running WOFOST in TERMINAL mode. The WCC gives always output when the run covers more than 1 year.

REPORT	I	Report: 1 (one line per year and statistics). This is the only valid option also for running WOFOST in TERMINAL mode.
FIXNAM	C	Output filename for summary output of potential and water limited production (max 8 characters; no extension because WOFOST uses *.WPS and *.PPS as extension). This is only used when running WOFOST in TERMINAL mode; WCC uses its own filename.
RQUIRD	I	Long term means results. This is a summary file of the summary files of potential and water limited production: 0 (no), 1 (yes). In WCC, the summary is only shown when there are more than two years (because of calculating statistics) and the rerun option is used. File name of this summary file is FIXNAM and the extension *.SUM.

6.6 Output files

This section discusses the way WOFOST presents the simulation results. Simulation results are stored in output files. There are four different output file types (Table 29).

Table 29. The output files.

File name	Contents	Section
*.OUT	detailed output of simulation	5.6.1
*.PPS	summary output for potential growth	5.6.2
*.WPS	summary output for water limited growth	5.6.3
*.SUM	summary output	5.6.4

The detailed output of each simulation is always created (each run in WCC and TERMINAL mode).

The summary output for potential (*.PPS) and water limited growth (*.WPS) is only shown when WCC has been run for more than one year. Statistics are given for runs of three or more weather years (in case of water-limited also for more than two rainfall years). When running WOFOST in TERMINAL mode, you can choose, by editing the WCC.WCC file, for a summary output of potential and water limited growth even if it is only for one year. Statistics will only be given for runs of more than two years.

The summary output (one line per type of growth) is created in the WCC only when simulation is made for more than two weather years (in case of water-limited also for more than two rainfall years) and more than one run is used in the reruns. A summary output can always be chosen in the TERMINAL mode by editing the WCC.WCC file. However, no output will be shown (only a header) for runs with less than three years.

The simulation results are discussed briefly. See Annex B for explanation of the variable names. Van Keulen and Wolf (1986) provide an extensive discussion of most output variables. See Janssen et al. (1990) and Section 5.3.6 for the output on nutrient-limited production.

6.6.1 Detailed output

An example of a detailed output file for each production level is provided. Potential growth is presented in Table 30, water-limited growth in Table 31, the water balance in Table 32, and the nutrient requirements in Table 33. The default name of a detailed output file is WCC.OUT. In the WCC, you can change the name by using the session options (see Section 3.3.1). When running WOFOST in the TERMINAL mode, supply the filename in the run option file (see Section 6.5).

The first lines in a detailed output file provide general information on the simulation (Table 30). The run name (RUNNAM), the name of the output file (OUTPUT), and the name of the rerun file used, if any (RERUN) are given. WEATHER provides information on the weather format and the start year of the

simulation. If CABO format (one file per year) is used, the name of the weather file does not change when simulation is done for a series of years. The indicated start year, however, changes and provides the correct information. The rain option (RAIN), crop (file) (CROP), and soil type (SOIL) used for simulation are specified. START provides information on the start date of the water balance, the day of sowing, and emergence.

Table 30. Detailed output, potential growth

```

**WOFOST version 7.1.7, release February 2011
RUNNAM -> WCC
OUTPUT -> file: ..\output\wcc.out
RERUNS -> no reruns
WEATHER-> name: Netherlands, Wageningen
           file: ..\meteo\cabowe\nl1.   start year: 1987
RAIN    -> belonging to weather station
CROP    -> name: Winter wheat 101, N-U.K., Denmark
           file: ..\cropd\wwh101.cab
SOIL    -> name: EC1-coarse
           file: ..\soild\ec1.new
START   -> fixed emergence date IDEM = 1
           start waterbalance = -99   sowing date = -99   emergence date = 1
POTENTIAL CROP PRODUCTION
=====
DAY IDSEM DVS  TSUM  WLW  WST  WSO  TAGP  LAI  TRA  GASS  MRES  DMI
           degrd kg/ha  kg/ha  kg/ha  kg/ha m2/m2  mm/d CH2O CH2O kg/ha/d
  1  0  0.00   0.   68.   37.   0.   105.  0.14 0.02   1.4   1.1   0.2
 51 50  0.07   67.   70.   38.   0.   108.  0.15 0.04   0.0   0.0   0.0
101 100 0.27  268.  173.   85.   0.   258.  0.37 0.32  39.4   2.7  25.1
151 150 0.78  781. 2755. 4391.   0.  7170.  5.84 1.08 220.1  63.7 104.3
169 168 1.00 1004. 2774. 7274.  532. 10780.  5.88 2.77 495.6  84.0 291.7
201 200 1.56 1538. 2316. 6846. 7446. 17695.  4.91 2.23 357.0 147.5 148.6
229 228 2.00 1957.  112. 3889. 8894. 19143.  0.24 0.27  10.1  10.1   0.0
SUMMARY:
HALT  ANTH TWRT   TWLV   TWST   TWSO   TAGP HINDEX TRANSP TRC  GASST MREST
229 168  1231.  2974.  7274.  8894.  19143.  0.46  25.0 131. 39129.  9786.

```

The results of the simulation are provided under POTENTIAL CROP PRODUCTION. A line with variable names is given (DAY, IDSEM, DVS, etc. See Annex B and Section 3.5.1 for explanation). After a blank line follows a line with the units of the variables. The model output is provided with each line representing a specific day. The number of lines depends on the length of the simulation and on the requested output interval. In this example, the interval was 50 days. The day of anthesis (development stage, DVS = 1) and the last day of simulation are always included. The last three lines provide a summary of the simulation results.

If water-limited growth is simulated as well, the next part of the file provides the relevant output, as shown in the example in Table 31. The structure of this output is similar to the output for potential production. Additional variables (RESERV, AVAIL, RAIN etc.), describing hydrological and other field conditions are provided; other variables are left out like GASS, MRES (see Annex B and Section 3.5.2 for explanation).

The general information on the run name etc. is followed by a line with WATER (AND O2) LIMITED CROP PRODUCTION WITH/WITHOUT GROUNDWATER. Oxygen limitation refers to excessive supply of water in the rooting zone. With or without groundwater refers to the selected soil conditions. This line is followed by the variables defining field conditions. Finally, the daily model output and the summary are provided.

Table 31. Detailed output, water-limited growth.

```

**WOFOST version 7.1.7, release February 2011
RUNNAM -> WCC
OUTPUT -> file: ..\output\wcc.out
RERUNS -> no reruns
WEATHER-> name: Netherlands, Wageningen
           file: ..\meteo\cabowe\nl1.   start year: 1987
RAIN    -> belonging to weather station
CROP    -> name: Winter wheat 101, N-U.K., Denmark
           file: ..\cropd\wwh101.cab
SOIL    -> name: ECl-coarse
           file: ..\soild\ec1.new
START   -> fixed emergence date IDEM = 1
           start waterbalance = 1 (1987) sowing date = -99 emergence date = 1
WATER LIMITED CROP PRODUCTION WITHOUT GROUNDWATER
=====
fixed fraction      RDMso= 60.   NOTinf=0.00
SM0=0.390 SMFC=0.110 SMW=0.040 SMLIM=0.104   RDM= 60. WAV= 20.0 SSmax= 0.0
DAY  WLW  WST  WSO  TAGP  LAI  RD   SM  RESRV  AVAIL  RAIN  TRA  EVA  wet  dry
      kg/ha kg/ha kg/ha kg/ha m2/m2 cm vol.fr cm   cm   mm mm/d mm/d days
  1   68.  37.   0.  105.  0.14 10. 0.104 18.1 0.6   0. 0.02 0.09 0 0
 51   70.  38.   0.  108.  0.15 60. 0.110 4.2 4.2  51. 0.04 0.14 0 0
101  173.  85.   0.  258.  0.37 60. 0.112 4.3 4.3 174. 0.32 1.81 0 0
151 2755. 4391.   0. 7170.  5.84 60. 0.105 3.9 3.9 279. 1.08 0.09 0 0
169 2774. 7274.  532. 10780. 5.88 60. 0.096 3.3 3.3 346. 2.77 0.23 0 0
201 2069. 6846. 5112. 15360. 4.39 60. 0.123 5.0 5.0 433. 2.16 0.37 0 12
229  112. 3889. 6695. 16944. 0.24 60. 0.106 3.9 3.9 541. 0.27 0.69 0 0
SUMMARY :
                                stress days
HALT ANTH TWRT  TWLV  TWST  TWSO  TAGP HINDEX TRC  GASST  MREST wet dry
229 168 1231. 2974. 7274. 6695. 16944. 0.40 129.5 34966. 8725. 0 12

```

The lines on water-limited crop growth are followed by the water balance(s) (Table 32). The water balance can be for the whole soil system and/or for the

root zone only (this zone extends as roots grow). The water balance covers the period between emergence and the last day of simulation. The different components of the water balance are explained in Section 3.5.3.

Table 32. Detailed output, water balance

WATER BALANCE WHOLE SYSTEM (1 DIMENS. COLUMN ; cm)				
init max root zone	20.5	final max root zone	6.3	change: -14.2
init surf storage	0.0	final surf storage	0.0	change: 0.0
irrigation	0.0	evap water surface	0.0	
rainfall	54.1	evap soil surface	7.6	
		transpiration	21.9	to atmos: 29.5
		surface runoff	0.0	
		lost to deep soil	38.7	
TOTAL INIT + IN	74.6	TOTAL FINAL + OUT	74.6	checksum: -0.0 init

Following the water balance or the output on potential crop growth if water-limited crop growth is not simulated, the results of the subsequent years are provided and so on. If nutrient-limited production is simulated, the output on plant nutrients is given following the output for all years (Table 33). It first provides the calculated values for the basic supply of nutrients and their recoveries, followed by the results for potential, nutrient-limited, and water-limited production. The simulated yield of leaves, stems and storage organs (dry weight, $\text{kg}\cdot\text{ha}^{-1}$), the ratio (storage organ / (leaves + stems)) and the harvest index (storage organ / total above ground biomass) is provided. Subsequently, the amount of fertilizer that would be needed to obtain potential and water-limited production is given in element form ($\text{kg}\cdot\text{ha}^{-1}$).

Table 33. Detailed output, nutrient requirements.

SUMMARY CROP PRODUCTION AND NUTRIENT REQUIREMENTS				
Nbas = 85., Pbas = 14., Kbas = 85.				
Nrec = 0.50, Prec = 0.10, Krec = 0.50				
=====				
	Potential	Nutrient limited	Water limited	
	Crop production	Crop production	Crop production	
Leaves	1889.	795.	2035.	
Stems	5984.	2518.	5841.	
Storage organ	9948.	4035.	6462.	
Ratio SO/straw	1.26	1.22	0.84	
Harvest index	0.56	0.55	0.45	
Fertilizer N	354.9	-	208.5	
Fertilizer P	331.5	-	199.1	
Fertilizer K	215.8	-	177.5	

When reruns are defined (Section 6.5.3) the detailed output for potential, water-limited including water balances and nutrient requirements are repeated for each rerun.

6.6.2 Summary output

In the output files *.PPS (potential growth, Table 34) and *.WPS (water-limited growth, Table 35), the detailed output (Section 6.6.1) is summarized. One line is given for each growing season, similar to the summary lines in the file with detailed output.

Additional variables provided in *.PPS are FLWR (flowering date), LAIM (maximum leaf area index) and EVSOL (total evaporation soil surface) (see Annex B and Section 3.6.1 for explanation).

In the *.WPS file, some additional variables pertaining to the water balance are provided (LAIM, DELWAT, TRAT, EVSOL, LOSST, TSR, RYLD, RAGP) (see Annex B and Section 3.6.2 for explanation).

When the simulations cover three weather years or more (in case of water-limited production also three rainfall years or more), the mean, standard deviation and the coefficient of variation of some output variables over these years are given.

The default name of a *.PPS, a *.WPS file is WCC.* (WCC.PPS, etc.). This can be changed in the session functionality of the WCC (see Section 3.3.1). When running WOFOST in TERMINAL mode, the name can be changed in the run option file (see Section 6.5).

The output file *.SUM (Table 36), provides a summary of the *.PPS and *.WPS files. It gives the long-term average of some variables at one location. There is one line for potential production (PS=PP) and one line for water-limited production (PS=WP). *.SUM is only filled when WOFOST is run for more than two weather years (in case of water-limited crop growth also more than two rainfall years) and reruns is used. When running WOFOST in TERMINAL mode, the run option file can be edited to create this file (see Section 6.5).

Table 34. An example of a *.PPS file.

```

**WOFOST version 7.1.7, release February 2011
OUTPUT -> file: ..\output\wcc.pps
**
**
** RESULTS OF CROP GROWTH SIMULATION MODEL WOFOST: SUMMARY POTENTIAL PRODUCTION
WEATHER-> name: Netherlands, Wageningen
           file: ..\meteo\cabowe\nl1.   start year: 1987
RAIN  -> belonging to weather station
CROP  -> name: Winter wheat 101, N-U.K., Denmark
           file: ..\cropld\wwh101.cab
SOIL  -> name: EC1-coarse
           file: ..\soild\ec1.new
**
**
** SUMMARY POTENTIAL PRODUCTION
** YR RUNNAM SET SOW --> EM ANT FLWR DUR HALT  TWRT  TWLV  TWST  TWSO  TAGP  LAIM HINDEX TRC  GASST  MREST TRANSP EVSOL
1987 WCC      0 -99 0   1 168 169 228. 229.  1231.  2974.  7274.  8894. 19143.  6.01  0.46 131.  39129.  9786.  25.0  3.6
1988 WCC      0 -99 0   1 142 143 205. 206.   618.  1326.  4401.  8183. 13911.  2.81  0.59 126.  26543.  5832.  17.6  4.7
1989 WCC      0 -99 0   1 141 142 202. 203.   845.  1889.  5984.  9948. 17820.  4.00  0.56 144.  34944.  8207.  25.6  3.9
**
**
** MEANS over 3 years :
           212.           2063.  5886.  9008. 16958.  4.27  0.54 134.           22.74  4.1
** STANDARD DEVIATIONS :
           14.           838.  1439.  888.  2720.  1.61  0.06  9.1           4.49  0.6
** VARIATION COEFFICIENTS :
           6.7           40.60  24.44  9.86  16.04 37.77 12.01 6.78           19.73 14.11
** VARIATION COEFFICIENTS :
           6.5           37.39  18.36  13.26  13.43 32.22 12.69 6.87           18.07 13.46

```


Table 35. An example of a *.WPS file.

```

**WOFOST version 7.1.7, release February 2011
OUTPUT -> file: ..\output\wcc.wps
**
**
** RESULTS OF CROP GROWTH SIMULATION MODEL WOFOST: SUMMARY WATER-LIMITED PRODUCTION
WEATHER-> name: Netherlands, Wageningen
           file: ..\meteo\cabowe\nl1.   start year: 1987
RAIN  -> belonging to weather station
CROP  -> name: Winter wheat 101, N-U.K., Denmark
           file: ..\cropld\wwh101.cab
SOIL  -> name: EC1-coarse
           file: ..\soild\ec1.new

NO GROUNDWATER
**
**
** SUMMARY WATER-LIMITED PRODUCTION
** YEAR RUNNAM SET SOW EM  DUR   TWLV  TWST   TWSO   TAGP   LAIM HINDEX  TRC RAIN T DELWAT  TRAT EVSOL  LOSST  TSR  RYLD  RAGP
1987 WCC      0 -99  1  228.  2974.  7274.   6695.  16944.  6.01  0.40  130.  54.1 -14.2  21.9   7.6  38.7  0.0  75.3  88.5
1988 WCC      0 -99  1  205.  1319.  4000.   2477.   7795.  2.77  0.32  135.  48.0 -13.4  10.5  10.2  40.7  0.0  30.3  56.0
1989 WCC      0 -99  1  202.  1879.  5211.   3181.  10271.  3.95  0.31  142.  37.3 -16.2  14.6   7.3  31.6  0.0  32.0  57.6
MEANS over 3 years :      212.  2057.  5495.  4118.  11670.  4.24  0.34  136.  46.5 -14.6  15.7   8.3  37.0      45.8  67.4
STANDARD DEVIATIONS      :  14.   842.  1656.  2260.  4732.  1.64  0.05   6.   8.5  1.4  5.8  1.6  4.8      25.51  18.31
VARIATION COEFFICIENTS :  6.72  40.93  30.13  54.89  40.55 38.57 13.84  4.7  18.2  9.8  36.9  19.5  12.8

```

Table 36. An example of a *.SUM file.

```

** FILE: ..\output\wcc.sum
** WITH SUMMARY OF LONG TERM SIMULATED YIELD STATISTICS, POTENTIAL AND WATER-LIMITED PRODUCTION
** CALCULATED WITH **WOFOST version 7.1.7, release February 2011
**
**PS RUNNAM IZT SOW EM DUR TWLV TWST TWSO var% TAGP var% LAIM HINDEX RYLD RAGP TRC RDMSOL
PP WCC1 0 -99. 1. 212. 2063. 5886. 9008. 9.86 16958. 16.04 4.27 0.54
WP WCC1 0 -99. 1. 212. 2035. 5841. 6462. 30.94 14338. 27.98 4.22 0.45 72.59 84.01 136. 120.
PP WCC2 0 -99. 1. 215. 2340. 6598. 8928. 13.26 17866. 13.43 4.76 0.50
WP WCC2 0 -99. 1. 215. 2311. 6492. 5954. 32.41 14756. 26.82 4.70 0.40 68.20 82.16 138. 120.

```

6.7 Log-files

Different log-files are produced every time WOFOST is run. Log-files are output files that contain information on the last run(s) executed. There are three different log files:

- WCC.LOG (always produced);
- WOFOST.LOG (only produced when errors occur);
- WEATHER.LOG (only produced when CABO weather is used).

The WCC.LOG contains valuable information on the simulation run when a runtime error occurs. In most cases this will lead you to the cause (and solution) of the runtime error (see Section 3.3.3). It is put in the directory "RUNIO".

WOFOST.LOG contains information on the data and run files that have been used when a runtime error occurs. It is put in the directory "RUNIO".

WEATHER.LOG contains the file header and the warnings and errors that occurs, if any, during the processing of CABO-format weather. WEATHER.LOG is put in directory "RUNIO". The error messages in WEATHER.LOG also appear in WCC.LOG.

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Annex A Abbreviations

AB-DLO	DLO - Research Institute for Agrobiology and Soil fertility.
CABO-DLO	DLO - Centre for Agro-Biological Research (currently AB-DLO).
CEC	Commission of the European Communities.
CGMS	Crop Growth Monitoring System.
CWFS	Centre for World Food Studies.
DLO	Agricultural Research Department.
EC	European Community(ies).
FAO	Food and Agriculture Organization of the United Nations.
FSE	FORTRAN Simulation Environment (Van Kraalingen, 1991).
GIS	Geographic Information System.
IRRI	International Rice Research Institute, Los Baños, Philippines.
ISRIC	International Soil Reference and Information Centre.
JRC	Joint Research Centre of the Commission of the European Communities.
MARS	Monitoring Agro-ecological resources with Remote sensing and Simulation; Monitoring Agriculture with Remote Sensing.
NASREC	National Soil Reference Collection and Database.
QUEFTS	QUantitative Evaluation of the Fertility of Tropical Soils (Janssen et al., 1990).
SC-DLO	DLO Winand Staring Centre for Integrated Land, Soil and Water Research.
SYSNET	Systems Research Network for Eco-regional Land Use Planning in Tropical Asia.
WAU	Wageningen Agricultural University.
WAU-TPE	Wageningen Agricultural University, Department of Theoretical Production-Ecology.

Annex B Description of variables and parameters in WOFOST

Legend to Table 37:

variable type: C = character
 I = integer
 R = real

Input from or output to file:

iOF = input from run option file
 iRF = input from rerun file
 iTD = input from timer file
 iSD = input from site file
 iCF = input from crop data file
 iSF = input from soil data file
 oDR = output to file with detailed results per growing season
 oSY = output to file with results for series of years
 oLT = output to file with long term mean results

Table 37. Description of variables and parameters in WOFOST

<i>Variable or parameter</i>	<i>Type and I/O</i>	<i>Description</i>
AMAXTB	R iCF	Maximum leaf CO ₂ assimilation rate as a function of development stage of the crop (kg•ha ⁻¹ •hr ⁻¹ ; -).
ANT(H)	I oDR, oSY	Duration of pre-anthesis phase (d).
AVAIL	R oDR	Amount of water available in actual root zone (cm water).
AWC	R oDR, oSY, oLT	Available water capacity of soil (mm water per m soil depth).
CFET	R iCF	Correction factor for evapotranspiration in relation to the reference crop.
CONTAB	R iSF	10-log hydraulic conductivity as a function of pF (log(cm•d ⁻¹); log(cm)).
CLFFILE	C iTD	Filename of weather station.
CLMNAM	C iTD	Description of weather station.
CRAIRC	R iSF	Critical soil air content for aeration (cm ⁻³ •cm ⁻³).
CRFIL	C iTD	Filename of crop file.
CRPNAM	C iCF	Crop name.
CVL	R iCF	Conversion efficiency of assimilates into leaf (kg•kg ⁻¹).
CVO	R iCF	Conversion efficiency of assimilates into storage organ

			(kg•kg ⁻¹).
CVR	R	iCF	Conversion efficiency of assimilates into root (kg•kg ⁻¹).
CVS	R	iCF	Conversion efficiency of assimilates into stem (kg•kg ⁻¹).
DAY	I	oDR	Day number of calendar year.
DD	R	iSD	Depth of drainage (cm).
DEFLIM	R	iSF	Required moisture deficit for a deep seedbed (cm) (soil workability parameter).
DELWAT	R	oSY	Difference between final and initial available water in the root zone of (cm water).
DEPNR	R	iCF	Crop group number for soil water depletion.
DLC	R	iCF	Critical day length (photoperiod) (hr).
DLO	R	iCF	Optimum day length (photoperiod) (hr).
DMI	R	oDR	Rate of dry matter increase (kg•ha ⁻¹ •d ⁻¹).
DTSMTB	R	iCF	Daily increase in thermal time as function of average temperature (°C•d ⁻¹).
DUR	I	oSY, oLT	Duration of simulation period (d).
DVS	R	oDR	Development stage of crop (-).
DVSEND	R	iCF	Development stage at harvest.
DVSI	R	iCF	Initial development stage.
EFFTB	R	iCF	Initial light-use efficiency of CO ₂ assimilation of single leaves as function of daily temperature ((kg•ha ⁻¹ •hr ⁻¹)/(J•m ⁻² •s ⁻¹); °C).
EM	I	oSY, oLT	Emergence date, (day of the year).
EVA	R	oDR	Evaporation rate from soil or from water stored on soil surface (mm•d ⁻¹).
EVSOL	R	oSY	Total evaporation from soil surface (cm water).
FIXNAM	C	iOF	Output filename for summary output of potential and water limited production (max 8 characters, no extension). This is only used when running WOFOST in TERMINAL mode; WCC uses its own filename.
FLTB	R	iCF	Fraction of above ground dry matter increase partitioned to leaves as a function of development stage (kg•kg ⁻¹ ; -).
FLWR	I	oSY	Day of flowering (day in year).
FOTB	R	iCF	Fraction of above ground dry matter increase partitioned to storage organs as a function of development stage (kg•kg ⁻¹ ; -).
FRTB	R	iCF	Fraction of total dry matter increase partitioned to roots as a function of development stage (kg•kg ⁻¹ ; -).
FSTB	R	iCF	Fraction of above ground dry matter increase partitioned

			to stems as a function of development stage ($\text{kg}\cdot\text{kg}^{-1};-$).
GASS	R	oDR	Gross assimilation rate ($\text{kg}(\text{CH}_2\text{O})\cdot\text{ha}^{-1}\cdot\text{d}^{-1}$).
GASST	R	oDR, oSY	Total gross assimilation ($\text{kg}(\text{CH}_2\text{O})\cdot\text{ha}^{-1}$).
HALT	I	oDR, oSY	Day number at harvest (day of the year).
HINDEX	R	oDR, oSY, oLT	Harvest index: weight of storage organs / weight of total above ground crop.
IAIRDU	I	iCF	Presence of air ducts in roots (e.g. rice) (present (=1) or not (=0)).
IBAL	I	iTD	Option for output summary water balance: 0 (no summary), 1 (for whole system), 2 (for root zone), or 3 (for whole system and root zone).
IDAYEN	I	iTD	Ultimate date of harvest (day of the year).
IDEM	I	iTD, oDR	Day of emergence (day of the year).
IDESOW	I	iTD	Earliest date of sowing (day of the year).
IDLSOW	I	iTD	Ultimate date of sowing (day of the year).
IDRAIN	I	iSD	Presence (1) or absence (0) of drains.
IDSEM	I	oDR	Number of days since emergence (d).
IDSL	I	iCF	Factor on which development rate between development stage 0 and 1 depends (temperature (0), photo period (1) or both (2)).
IDSOW	I	iTD	Date of sowing (day of the year).
IDURMX	I	iTD	Maximum number of days from emergence to the end of the simulation.
IENCHO	I	iTD	Option to determine end of simulation (fixed end date (1), maturity but no to exceed maximum duration (2), earliest of the two dates (3)).
IFUNRN	I	iSD	Indicates whether non-infiltrating fraction of rain is a function of storm size (1) or not (0).
INYEAR	I	iTD	Number of years to simulate.
INYRG	I	iTD	Number of runs with manipulated rain / number of rain years.
IOPT2	I	iOF	Start/Stop option: 2 (run WOFOST with default input from data files), 4 (run WOFOST from reruns file without default run) and 5 (run FSEOPT for calibration of WOFOST; only possible in TERMINAL mode and not available in WCC).
IOXWL	I	iOF	Type of water-limited crop growth: 0 (effects of drought only), 1 (effects of both drought and oxygen shortage).
IPRODL	I	iOF	Production levels: 1 (simulation of potential crop growth), 2 (simulation of water limited crop growth), 3 (calculation of nutrient limited crop growth).

IRNDAT	I	iTD	Option for the use/selection of rainfall data: 0 (generates statistics with varying total monthly rainfall and number of rainy days), 1 (distributes monthly rainfall over given number of days), 2 (reads rainfall data out of separate file) or 3 (rainfall as it occurs in weather file).
ISDAY	I	iTD	Start date of water balance (day of the year).
ISTCHO	I	iTD	Options for the start of simulation (fixed emergence day (0), fixed sowing day (1) or variable sowing day (2)) (day of the year).
ISYR	I	iTD	First year of simulation (year)
ISYRR	I	iTD	First year of rainfall data (year)
IWEATH	I	iTD	Weather format: (WOFOST-monthly (0), WOFOST-climate (1), or CABO (2).
IZT	I	iSD, oLT	Influence of groundwater: 0 (no) or 1 (yes).
KBASE	R	iSD	Basic supply of potassium by the unfertilized soil for one growing season of 120 days ($\text{kg}\cdot\text{ha}^{-1}$).
Kbas	R	oDR	Basic supply of potassium by the unfertilized soil in the actual growing season of the crop ($\text{kg}\cdot\text{ha}^{-1}$).
KDIFTB	R	iCF	Extinction coefficient for diffuse visible light as function of development stage.
KMAXSO	R	iCF	Maximum concentration of K in storage organs ($\text{kg}\cdot\text{kg}^{-1}$).
KMAXVE	R	iCF	Maximum concentration of K in vegetative organs ($\text{kg}\cdot\text{kg}^{-1}$).
KMINSO	R	iCF	Minimum concentration of K in storage organs ($\text{kg}\cdot\text{kg}^{-1}$).
KMINVE	R	iCF	Minimum concentration of K in vegetative organs ($\text{kg}\cdot\text{kg}^{-1}$).
KREC	R	iSD	Apparent recovery of K fertilizer.
Krec	R	oDR	Idem.
KSUB	R	iSF	Maximum percolation rate of water to subsoil ($\text{cm}\cdot\text{d}^{-1}$).
K0	R	iSF	Hydraulic conductivity of saturated soil ($\text{cm}\cdot\text{d}^{-1}$).
LAI	R	oDR	Leaf area index: (leaf area)/(soil area) ($\text{ha}\cdot\text{ha}^{-1}$).
LAIEM	R	iCF	Leaf area index at emergence ($\text{ha}\cdot\text{ha}^{-1}$).
LAIM	R	oSY, oLT	Maximum leaf area index ($\text{ha}\cdot\text{ha}^{-1}$).
LOSST	R	oSY	Total water percolated to deep soil, not available for plant growth (cm water).
MRES	R	oDR	Maintenance respiration rate ($\text{kg}(\text{CH}_2\text{O})\cdot\text{ha}^{-1}\cdot\text{d}^{-1}$).
MREST	R	oDR, oSY	Total maintenance respiration ($\text{kg}(\text{CH}_2\text{O})\cdot\text{ha}^{-1}$).
NBASE	R	iSD	Basic supply of nitrogen by the unfertilized soil for one growing season of 120 days ($\text{kg}\cdot\text{ha}^{-1}$).

Nbas	R	oDR	Basic supply of nitrogen by the unfertilized soil in the actual growing season of the crop ($\text{kg}\cdot\text{ha}^{-1}$).
NFIX	R	iCF	Fraction of N uptake that originates from biological fixation ($\text{kg}\cdot\text{kg}^{-1}$).
NMAXSO	R	iCF	Maximum concentration of N in storage organs ($\text{kg}\cdot\text{kg}^{-1}$).
NMAXVE	R	iCF	Maximum concentration of N in vegetative organs ($\text{kg}\cdot\text{kg}^{-1}$).
NMINSO	R	iCF	Minimum concentration of N in storage organs ($\text{kg}\cdot\text{kg}^{-1}$).
NMINVE	R	iCF	Minimum concentration of N in vegetative organs ($\text{kg}\cdot\text{kg}^{-1}$).
NOTINF	R	iSD, oDR	Maximum fraction of rain not-infiltrating into the soil.
NREC	R	iSD	Apparent recovery of N fertilizer.
Nrec	R	oDR	Idem.
PBASE	R	iSD	Basic supply of phosphorus by the unfertilized soil for one growing season of 120 days ($\text{kg}\cdot\text{ha}^{-1}$).
Pbas	R	oDR	Basic supply of phosphorus by the unfertilized soil in the actual growing season of the crop ($\text{kg}\cdot\text{ha}^{-1}$).
PERDL	R	iCF	Maximum relative death rate of leaves due to water stress (-; $\text{kg}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$).
PMAXSO	R	iCF	Maximum concentration of P in storage organs ($\text{kg}\cdot\text{kg}^{-1}$).
PMAXVE	R	iCF	Maximum concentration of P in vegetative organs ($\text{kg}\cdot\text{kg}^{-1}$).
PMINSO	R	iCF	Minimum concentration of P in storage organs ($\text{kg}\cdot\text{kg}^{-1}$).
PMINVE	R	iCF	Minimum concentration of P in vegetative organs ($\text{kg}\cdot\text{kg}^{-1}$).
PRDEL	I	iTD	Number of time steps between output lines (days).
PREC	R	iSD	Apparent recovery of P fertilizer.
Prec	R	oDR	Idem.
PS	C	oLT	Production level (production situation) (PP = potential; WP = water-limited).
Q10	R	iCF	Relative change in respiration rate per 10 °C temperature change.
RAFILE	C	iTD	Filename of rainfall station.
RAGP	R	oSY, oLT	Relative total above ground production: (water-limited production) / (potential production).
RAIN	R	oDR	Total rainfall in the simulation period (mm water).
RAINAM	C	iTD	Description of rainfall station.
RAINT	R	oSY	Total rainfall in the simulation period (cm water).

RD	R	oDR	Depth of actual root zone (cm).
RDI	R	iCF	Initial rooting depth (cm).
RDM	R	oDR	Actual rooting depth (cm).
RDMCR	R	iCF	Maximum rooting depth of mature crop (plant characteristic) (cm).
RDM SOL	R	iSD, oLT	Maximum rooting depth allowed by soil (cm).
RDMso	R	oDR	Maximum rooting depth allowed by soil (cm).
RDRRTB	R	iCF	Relative death rate of roots as a function of development stage ($\text{kg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}; -$).
RDRSTB	R	iCF	Relative death rate of stems as a function of development stage ($\text{kg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}; -$).
REPORT	I	iOF	Report: 1 (one line per year and statistics). This is the only valid option also for running WOFOST in TERMINAL mode.
RESRV	R	oDR	Available soil water in potential root zone (in and below actual root zone) (cm water).
RFSETB	R	iCF	Reduction factor for senescence as function of development stage.
RGRLAI	R	iCF	Maximum relative increase in LAI ($\text{ha} \cdot \text{ha}^{-1} \cdot \text{d}^{-1}$).
RML	R	iCF	Relative maintenance respiration rate leaves ($\text{kg} (\text{CH}_2\text{O}) \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$).
RMO	R	iCF	Relative maintenance respiration rate storage organs ($\text{kg} (\text{CH}_2\text{O}) \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$).
RMR	R	iCF	Relative maintenance respiration rate roots ($\text{kg} (\text{CH}_2\text{O}) \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$).
RMS	R	iCF	Relative maintenance respiration rate stems ($\text{kg} (\text{CH}_2\text{O}) \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$).
RQUIRD	I	iOF	Long term means results. This is a summary file of the summary files of potential and water limited production: 0 (no), 1 (yes). In WCC the summary is only shown when there are more than two years (because of calculating statistics) and the rerun option is used.
RRI	R	iCF	Maximum daily increase in rooting depth ($\text{cm} \cdot \text{d}^{-1}$).
RUNNAM	C	iTD, iRF, oDR, oSY, oLT	Characterization of the simulation runs.
RYLD	R	oSY, oLT	Relative yield: (water-limited yield/potential yield).
SERIES	I	iOF	Final results for series of years: 0 (no), 1 (yes). This option has only meaning when running WOFOST in TERMINAL mode. The WCC gives always output when the run covers more than 1 year.
SITFIL	C	iOF	Site filename.

SLATB	R	iCF	Specific leaf area as a function of development stage ($\text{ha}\cdot\text{kg}^{-1}$; -).
SM	R	oDR	Soil moisture content ($\text{cm}^3\cdot\text{cm}^{-3}$).
SMFCF	R	iSF, oDR	Soil moisture content at field capacity ($\text{cm}^3\cdot\text{cm}^{-3}$).
SMLIM	R	iSD, oDR	Initial maximum moisture content in initial rooting depth (-).
SMTAB	R	iSF	Soil water retention; volumetric moisture content (second column) as function of pF (first column) ($\log(\text{cm})$; $\text{cm}^3\cdot\text{cm}^{-3}$).
SMW	R	iSF, oDR	Soil moisture content at wilting point ($\text{cm}^3\cdot\text{cm}^{-3}$).
SMO	R	iSF, oDR	Soil moisture content of saturated soil ($\text{cm}^3\cdot\text{cm}^{-3}$).
SOFILE	C	iSD	Filename of soil.
SOLNAM	C	iSF	Soil name.
SOPE	R	iSF	Maximum percolation rate root zone ($\text{cm}\cdot\text{d}^{-1}$).
SOW	I	oSY, oLT	Day of sowing (day of the year).
SPA	R	iCF	Specific pod area ($\text{ha}\cdot\text{kg}^{-1}$).
SPADS	R	iSF	1st topsoil seepage parameter deep seedbed (soil workability parameter).
SPAN	R	iCF	Life span of leaves growing at 35 °C (days).
SPASS	R	iSF	1st topsoil seepage parameter shallow seedbed (soil workability parameter).
SPODS	R	iSF	2nd topsoil seepage parameter deep seedbed (soil workability parameter).
SPOSS	R	iSF	2nd topsoil seepage parameter shallow seedbed (soil workability parameter).
SSATB	R	iCF	Specific stem area as function of development stage ($\text{ha}\cdot\text{kg}^{-1}$; -).
SSI	R	iSD	Initial surface storage (cm water).
SSMAX	R	iSD, oDR	Maximum surface storage capacity (cm water)
TAGP	R	oDR, oSY, oLT	Total above ground production (dead and living plant organs) ($\text{kg}\cdot\text{ha}^{-1}$) (for potato and beet: TAGP= total above ground production + storage organ).
TBASE	R	iCF	Lower threshold temperature for ageing of leaves (°C).
TBASEM	R	iCF	Lower threshold temperature for emergence (°C).
TDWI	R	iCF	Initial total crop dry weight ($\text{kg}\cdot\text{ha}^{-1}$).
TEFFMX	R	iCF	Maximum effective temperature for emergence (°C).
TIMFIL	C	iOF	Timer filename.
TMNFTB	R	iCF	Reduction factor of gross assimilation rate as function of

			low minimum temperature (-; °C).
TMPFTB	R	iCF	Reduction factor of AMAX as function of average temperature (°C).
TRA	R	oDR	Transpiration rate (mm•d ⁻¹).
TRANSP	R	oDR, oSY	Total transpiration (cm water).
TRAT	R	oSY	Total transpiration (cm water).
TRC	R	oDR, oSY, oLT	Transpiration coefficient (kg water per kg dry matter).
TSR	R	oSY	Total surface runoff during simulation run (cm water).
TSUM	R	oDR	Thermal time (temperature sum) (°C•d ⁻¹).
TSUMEM	R	iCF	Thermal time from sowing to emergence (°C•d ⁻¹).
TSUM1	R	iCF	Thermal time from emergence to anthesis (°C•d ⁻¹).
TSUM2	R	iCF	Thermal time from anthesis to maturity (°C•d ⁻¹).
TWLV	R	oDR, oSY, oLT	Total dry weight of leaves (dead and living) (kg•ha ⁻¹).
TWRT	R	oDR, oSY	Total dry weight of roots (dead and living) (kg•ha ⁻¹).
TWSO	R	oDR, oSY, oLT	Total dry weight of storage organs (dead and living) (kg•ha ⁻¹).
TWST	R	oDR, oSY, oLT	Total dry weight of stems (dead and living) (kg•ha ⁻¹).
var%	R	oLT	Coefficient of variation.
WAV	R	iSD, oDR	Initial amount of available water in total rootable soil (moisture content above wilting point) (cm water).
WLV	R	oDR	Dry weight of living leaves (kg•ha ⁻¹).
WOFOUT	C	iOF	Filename detailed output.
WOFRER	C	iOF	Rerun filename.
WSO	R	oDR	Dry weight of living storage organs (kg•ha ⁻¹).
WST	R	oDR	Dry weight of living stems (kg•ha ⁻¹).
YEAR	I	oSY	Year (water limited).
YR	I	oSY	Year (potential production).
YZERO	R	iCF	Maximum amount of vegetative organs at zero yield (kg•ha ⁻¹) (to calculate nutrient uptake).
ZTI	R	iSD	Initial depth of groundwater table (cm).
wet	I	oDR	total number of days characterized by reduced crop growth due to oxygen shortage (d).
dry	I	oDR	total number of days characterized by reduced crop growth due to water shortage

(d).

Annex C Troubleshooting

C.1 Problems with WCC

In this section some examples of problems that might happen are collected. Of course you can avoid many problems by first consulting the digital help file (see Section 3.3.7) of the WCC and underlying technical document. Possible problems:

- extraordinary value (fixed sowing data of 400)

```
Value out of range: 400
Allowed range: 1 - 366
```

Solution: you can change the variable into a more plausible value or in case you really want to enter an extraordinary value (e.g. relatively high TSUM etc.) you can exit WCC and change the lower and upper limit of the variable in the file `..\EXEC\WCC_VAR.DBF`.

- wrong directory name (`..\RUNIO1` instead of `..\RUNIO`)

```
The message 'File not found: ..\RUNIO\RUNOPT.DAT' appears followed by the normal WCC window. But if you run WOFOST the WCC replies with the message 'I/O error 103' and you are not able to run WOFOST.
```

Solution: You can either rename the directory or change the contents in the file "WOFOST Control Centre\DIRECT.INI" according to the new directory name.

- missing file (WOFOST.EXE)

```
'<path to WCC>\WOFOST.EXE' not found!
```

Solution: Search for WOFOST.EXE on your system and place this file under the main WOFOST Control Centre directory or reinstall WOFOST/WCC.

- crop input tab is empty

Solution: There are no crop files in directory `.\CROPD\`, so transfer crop files to this directory, or reinstall WOFOST/WCC or create crop files according to the guidelines in Section 6.2.

C.2 Problems with WOFOST

C.2.1 Introduction

When you run WOFOST version 7.1, a Command Box window appears with the message '**Running the simulation. Please wait...**'. After this message, three things can happen:

- the message '**Press any key to continue**' appears. Press any key and close the Command box. A window with the message '**Simulation successful**' appears. You can now look at the results.
- the message '**Press any key to continue**' appears. Press any key and close the Command box. A window with the message '**Runtime error while running the simulation. Show log-file?**' appears. In this case, you can have a look at the WCC.LOG that contains information on the

simulation run. The log-file should lead you to the cause of the runtime error. Sometimes you may get a runtime error message in the MS DOS-box.

- no message appears and the simulation seems to be taking longer than expected. Stop the simulation by pressing **Enter**. The message **Press any key to continue** appears. Press any key and close the Command box. A window with the message **Runtime error while running the simulation. Show log-file?** appears. Have a look at the WCC.LOG that contains information on the simulation run. The log-file should lead you to the cause of the runtime error.

The WCC.LOG contains error messages. The error messages you can expect are probably due to erroneous input data. The most common error messages are selected and presented.

C.2.2 Error messages related errors in crop and soil files

- Variable is missing (TSUM1)

```
Routine RDDATA, called by RDSREA, attempts to read
a single value from file ..\CROPD\WWH101.CAB
into REAL variable TSUM1
ERROR in RDDATA: Variable name not in data file
```

- Value of variable is missing (second value of AMAXTB)

```
Error(s) while reading from ..\croprd\wwh101.cab

Line Error text                               Somewhere here
==== =====
58 There must be another value                 [AMAXTB = 0.00, ,]
```

- Wrong variable type (TSUM1 is a real instead of integer)

```
Routine RDDATA, called by RDSREA, attempts to read
a single value from file ..\CROPD\WWH101.CAB
into REAL variable TSUM1
ERROR in RDDATA: On data file this variable is INTEGER
```

- Wrong character in number ('o' instead of '0')

```
Error(s) while reading from ..\croprd\wwh101.cab

Line Error text                               Somewhere here
==== =====
30 Illegal after INTEGER value                 [TSUM1 =10o0. ]
```

- The equal sign is missing

```
Error(s) while reading from ..\croprd\wwh101.cab

Line Error text                               Somewhere here
```



```
==== =====
30 Next variable name or = expected      [TSUM1      1050.      ]
```

- The ';' is missing between previous value and next variable

```
Error(s) while reading from ..\cropld\wwh101.cab

Line Error text                               Somewhere here
==== =====
140 After a value this is illegal             [ = 0.0110      NMINVE = ]
```

C.2.3 Error messages related to weather

- Missing value in weather file (WOFOST-format)

```
ERROR in CLIMRD: error while reading climate data
```

- Missing year in weather file (WOFOST-format)

```
1954
ERROR in CLIMRD: cannot find requested year
```

- Missing station name in weather file (WOFOST-format) (when you omit station name, WOFOST assumes that the next line with year number indicates the station name; the consequence is that WOFOST cannot find the year anymore)

```
1955
ERROR in CLIMRD: cannot find requested year
```

- No hard return after last data line in file (WOFOST-format)

```
ERROR in CLIMRD: error while reading climate data
```

- Comments after the last data line in file (CABO-format)

```
Error in STINFO: incorrect data file
Error in WEATHR: called after error from STINFO or STINFO not called
```

- Missing value (CABO-weather)

```
Error in WEATHR: missing data, in: PHL1.979 day: 1 attr.:-444444
```

- Missing comment leader ('*') in header. Now WOFOST wants to read first data line while this line contain comments.

```
Error in STINFO: incorrect geographical data line
Error in WEATHR: called after error from STINFO or STINFO not called
```


Annex D Julian day calendar

Perpetual

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1	32	60	91	121	152	182	213	244	274	305	335
2	2	33	61	92	122	153	183	214	245	275	306	336
3	3	34	62	93	123	154	184	215	246	276	307	337
4	4	35	63	94	124	155	185	216	247	277	308	338
5	5	36	64	95	125	156	186	217	248	278	309	339
6	6	37	65	96	126	157	187	218	249	279	310	340
7	7	38	66	97	127	158	188	219	250	280	311	341
8	8	39	67	98	128	159	189	220	251	281	312	342
9	9	40	68	99	129	160	190	221	252	282	313	343
10	10	41	69	100	130	161	191	222	253	283	314	344
11	11	42	70	101	131	162	192	223	254	284	315	345
12	12	43	71	102	132	163	193	224	255	285	316	346
13	13	44	72	103	133	164	194	225	256	286	317	347
14	14	45	73	104	134	165	195	226	257	287	318	348
15	15	46	74	105	135	166	196	227	258	288	319	349
16	16	47	75	106	136	167	197	228	259	289	320	350
17	17	48	76	107	137	168	198	229	260	290	321	351
18	18	49	77	108	138	169	199	230	261	291	322	352
19	19	50	78	109	139	170	200	231	262	292	323	353
20	20	51	79	110	140	171	201	232	263	293	324	354
21	21	52	80	111	141	172	202	233	264	294	325	355
22	22	53	81	112	142	173	203	234	265	295	326	356
23	23	54	82	113	143	174	204	235	266	296	327	357
24	24	55	83	114	144	175	205	236	267	297	328	358
25	25	56	84	115	145	176	206	237	268	298	329	359
26	26	57	85	116	146	177	207	238	269	299	330	360
27	27	58	86	117	147	178	208	239	270	300	331	361
28	28	59	87	118	148	179	209	240	271	301	332	362
29	29		88	119	149	180	210	241	272	302	333	363
30	30		89	120	150	181	211	242	273	303	334	364
31	31		90		151		212	243		304		365

For Leap Years Only

(Use in the year 2000, 2004, 2008, 2012, etc.)

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1	32	61	92	122	153	183	214	245	275	306	336
2	2	33	62	93	123	154	184	215	246	276	307	337
3	3	34	63	94	124	155	185	216	247	277	308	338
4	4	35	64	95	125	156	186	217	248	278	309	339
5	5	36	65	96	126	157	187	218	249	279	310	340
6	6	37	66	97	127	158	188	219	250	280	311	341
7	7	38	67	98	128	159	189	220	251	281	312	342
8	8	39	68	99	129	160	190	221	252	282	313	343
9	9	40	69	100	130	161	191	222	253	283	314	344
10	10	41	70	101	131	162	192	223	254	284	315	345
11	11	42	71	102	132	163	193	224	255	285	316	346
12	12	43	72	103	133	164	194	225	256	286	317	347
13	13	44	73	104	134	165	195	226	257	287	318	348
14	14	45	74	105	135	166	196	227	258	288	319	349
15	15	46	75	106	136	167	197	228	259	289	320	350
16	16	47	76	107	137	168	198	229	260	290	321	351
17	17	48	77	108	138	169	199	230	261	291	322	352
18	18	49	78	109	139	170	200	231	262	292	323	353
19	19	50	79	110	140	171	201	232	263	293	324	354
20	20	51	80	111	141	172	202	233	264	294	325	355
21	21	52	81	112	142	173	203	234	265	295	326	356
22	22	53	82	113	143	174	204	235	266	296	327	357
23	23	54	83	114	144	175	205	236	267	297	328	358
24	24	55	84	115	145	176	206	237	268	298	329	359
25	25	56	85	116	146	177	207	238	269	299	330	360
26	26	57	86	117	147	178	208	239	270	300	331	361
27	27	58	87	118	148	179	209	240	271	301	332	362
28	28	59	88	119	149	180	210	241	272	302	333	363
29	29	60	89	120	150	181	211	242	273	303	334	364
30	30		90	121	151	182	212	243	274	304	335	365
31	31		91		152		213	244		305		366

Annex E Upper and lower limits of parameters

The upper and lower limits described in Table 38 should be used with care. Some of the limits given are hard boundary values that should not be crossed. Others are suggestions for a reasonable range of the parameter but not an absolute boundary. Moreover, often the valid range of a particular parameter is depending on the type of crop while the ranges given in Table 38 are basically covering the full range over all crop types. Therefore, it is generally a poor idea to use the ranges provided for analysis of sensitivity. Instead a crop/cultivar specific interpretation of the parameter ranges should be made in order to obtain meaningful results.

Table 38. Upper and lower limits for parameters in the WOFOST model.

PARAMETER	LOWER	UPPER
AMXTB	1.00000	70.00000
CFET	0.80000	1.20000
CONTAB	-8.00000	2.00000
CRAIRC	0.04000	0.10000
CVL	0.60000	0.76000
CVO	0.45000	0.85000
CVR	0.65000	0.76000
CVS	0.63000	0.76000
DD	20.00000	300.00000
DEFLIM	-0.30000	0.00000
DEPNR	1.00000	5.00000
DLC	6.00000	18.00000
DLO	6.00000	18.00000
DTSMTB	0.00000	38.00000
DVSI	0.00000	0.50000
DVSEND	1.00000	2.50000
EFFTB	0.40000	0.50000
FLTB	0.00000	1.00000
FOTB	0.00000	1.00000
FRTB	0.00000	1.00000
FSTB	0.00000	1.00000
IAIRDU	0.00000	1.00000
IBAL	0.00000	3.00000

IDAYEN	1.00000	366.00000
IDEM	1.00000	366.00000
IDESOW	1.00000	366.00000
IDL SOW	1.00000	366.00000
IDRAIN	0.00000	1.00000
IDSL	0.00000	1.00000
IDSOW	1.00000	366.00000
IDURMX	1.00000	366.00000
IENCHO	1.00000	3.00000
IFUNRN	0.00000	1.00000
INYEAR	1.00000	1000.00000
INYRG	1.00000	1000.00000
IRNDAT	0.00000	3.00000
ISTCHO	0.00000	2.00000
ISYR	1.00000	4000.00000
ISYRR	1.00000	4000.00000
IWEATH	0.00000	2.00000
IZT	0.00000	1.00000
KBASE	0.00000	100.00000
KDIFTB	0.44000	1.00000
KMAXSO	0.00500	0.05000
KMAXVE	0.00500	0.05000
KMINSO	0.00200	0.01800
KMINVE	0.00200	0.01800
KREC	0.00000	1.00000
KSUB	0.10000	100.00000
K0	0.10000	100.00000
LAIEM	0.00070	0.30000
NBASE	0.00000	100.00000
NFIX	0.00000	0.75000
NMAXSO	0.00900	0.05600
NMAXVE	0.00900	0.04600
NMINSO	0.00220	0.03500
NMINVE	0.00220	0.01800
NOTINF	0.00000	1.00000

NREC	0.00000	1.00000
PBASE	0.00000	100.00000
PERDL	0.00000	0.10000
PMAXSO	0.00160	0.01000
PMAXVE	0.00160	0.01000
PMINSO	0.00070	0.04000
PMINVE	0.00030	0.00200
PRDEL	1.00000	366.00000
PREC	0.00000	1.00000
Q10	1.50000	2.00000
RDI	10.00000	50.00000
RDMCR	50.00000	400.00000
RDMSOL	10.00000	150.00000
RDRRTB	0.00000	0.02000
RDRSTB	0.00000	0.04000
RFSETB	0.25000	1.00000
RGRLAI	0.00700	0.50000
RML	0.02700	0.03000
RMO	0.00300	0.01700
RMR	0.01000	0.01500
RMS	0.01500	0.02000
RR1	0.00000	3.00000
SLATB	0.00070	0.00420
SMFCF	0.05000	0.74000
SMLIM	0.01000	0.90000
SMTAB	0.01000	0.90000
SMW	0.01000	0.35000
SM0	0.30000	0.90000
SOPE	0.10000	100.00000
SPA	0.00080	0.00300
SPADS	0.02000	0.80000
SPAN	17.00000	50.00000
SPASS	0.05000	0.90000
SPODS	0.02000	0.04000
SPOSS	0.03000	0.07000

SSATB	0.00030	0.00030
SSI	0.00000	20.00000
SSMAX	0.00000	20.00000
TBASE	-10.00000	10.00000
TBASEM	-10.00000	8.00000
TDWI	0.50000	300.00000
TEFFMX	18.00000	32.00000
TMNFTB	0.00000	1.00000
TMPFTB	0.00000	1.00000
TSUMEM	0.00000	170.00000
TSUM1	150.00000	1050.00000
TSUM2	600.00000	1550.00000
WAV	0.00000	45.00000
YZERO	0.00000	400.00000
ZTI	0.00000	999.00000
ISDAY	1.00000	366.00000

Annex F Description of subroutines

AFGEN*	This function allows linear interpolation in table TABLE for a given value of the independent variable X.
ASSIM	This routine calculates the gross CO ₂ assimilation rate of the whole crop, FGROS, by performing a Gaussian integration over depth in the crop canopy. At three different depths in the canopy, i.e. for different values of LAI, the assimilation rate is computed for given fluxes of photosynthetically active radiation, where after integration over depth takes place. The input variables SINB, PARDIR and PARDIF are calculated in routine TOTASS.
ASTRO	This subroutine calculates astronomic day length, diurnal radiation characteristics such as the atmospheric transmission, diffuse radiation etc.
CLIMRD	Reads weather data from WOFOST format files including the generation of rainfall. The routine searches the file for the requested year and reads weather data, latitude and altitude of the site. Years with weather data must be in consecutive order on file.
CONVR2	Converts weather data from 'repaired DBMETEO' files to appropriate units, and vice versa. The data type is converted from integer to real, or back, depending on the ACTION required. The method by which data are stored in the repaired weather files is with INTEGER*2 variables to reduce file size. The routine can undertake two different actions 1) convert 'repaired DBMETEO' INTEGER*2 values to REAL values needed after reading a record (ACTION='DECODE_REPAIRED'); 2) convert REAL values to INTEGER*2 values, needed before writing a record in the 'repaired DBMETEO' file (ACTION='CODE_REPAIRED').
CROPNO*	This subroutine is called to assign the right values to EVWMX, EVSMX, TRA and RD during the simulation of the water balance before emergence. After emergence these values are calculated in CROPSI.
CROPSI	In this routine the simulation of the potential or the water-limited crop growth is performed. Called by WOFSIM to perform a specific task. Four different tasks are distinguished: ITASK = 1, initialization; ITASK = 2, rate calculation; ITASK = 3, integration; ITASK = 4, finish section.
DATES	Converts either a year and day number to a month number and a day number within that month (ACTION='TO_MONTHS') or the inverse, from a day number in a certain month to a day number within the year (ACTION='TO_YEAR'). Leap years are recognized.
EVTRA	This routine calculates for a given crop cover the maximum evaporation rate from a shaded wet soil surface and from a shaded water surface, and the maximum and actual crop transpiration rate.
GAMMA2	This function calculates gamma-distributed numbers for the specified gamma distribution parameters BETA and ALFA.
METEO	Provides the calling program with weather data (including rainfall) and evapotranspiration values. Different file formats can be used depending on the value of IWEATH. Random rainfall generation or distribution takes place depending on IWEATH. Depending on the value of IWEATH, different variables are used to define the data file to be used.

NUTRIE This routine calculates nutrient requirements and nutrient-limited yields according to the QUEFTS-system (Janssen et al., 1990) and generates output.

PAUZE Waits for <RETURN> key from keyboard.

PENMAN This routine calculates the potential evapo(transpi)ration rates from a free water surface (E0), a bare soil surface (ES0), and a crop canopy (ET0) in mm/d. For these calculations the analysis by Penman is followed (Frère and Popov, 1979; Penman, 1956).

PRHEAD Write headers to output file.

PRIJRC Output format, used for specific purpose of JRC, Ispra, Italy.

PRIWFD Prints on unit IUOUT part of WOFOST.OUT (standard output table showing variables of crop growth and water balance at interval of PRDEL days) relative to water-limited production calculated on the basis of soil water balance routine WATFD (free drainage).

PRIWGW Prints on unit IUOUT part of WOFOST.OUT (standard output table showing variables of crop growth and water balance at interval of PRDEL days) relative to water-limited production calculated on the basis of soil water balance routine WATGW.

PRIWPP Prints part of WOFOST.OUT (standard output table for single run) on potential production.

RANDOM This function generates pseudo-random numbers uniformly distributed between 0 and 1.

RDMINF Reads in METEO.INF file and returns stations names, latitudes and altitudes.

REPRD Reads weather data from 'repaired DBMETEO' files. This routine automatically detects changes in input data such as weather station, year etc.

RNDIS This routine calculates the daily rainfall (RSERIE) by distributing the given monthly rainfall (RAINTB) over a defined number of randomly chosen rainy days. Monthly rain and number of rainy days equal the given values. Revision includes a minor modification in the random number call and modification to distribute rain in leap years.

RNGEN This routine generates one year of daily rainfall data (RSERIE) on the basis of the given long term average monthly rainfall (RAINTB) and number of rainy days (RAIND) (wet is >0. or > .1 mm). The method follows the proposal of Geng et al. (1986). The procedure is a combination of a Markov chain and a gamma distribution function.

RNREAL Reads rainfall data from an external file called RAFILE. The file should contain the rainfall data for the requested year.

ROOTD In this routine the depth of the root zone is calculated for each day of the crop cycle.
Called by WOFOST: ITASK = 1, initialization; ITASK = 2, rate calculation; ITASK = 3, integration; ITASK = 4, finish section.

STATPP Statistics of potential production. Subroutine for statistical treatment of yield variables, simulated in a series of simulation runs with WOFOST.

STATWP Statistics of production, limited by availability of water. Subroutine for statistical treatment of yield variables, simulated in a series of simulation runs with WOFOST, using the soil water balance model WATFD (free drainage).

STDAY Determines sowing date.

- SUBSOL This routine calculates the rate of capillary flow or percolation between groundwater table and root zone.
- SWEAF The fraction of easily available soil water between field capacity and wilting point is a function of the potential evapotranspiration rate (for a closed canopy) in $\text{cm}\cdot\text{day}^{-1}$, ET_0 , and the crop group number, CGNR (from 1 (=drought-sensitive) to 5 (=drought-resistant)). The function SWEAF describes this relationship given in tabular form by Doorenbos and Kassam (1979) and by Van Keulen and Wolf (1986; p.108, table 20).
- TOTASS This routine calculates the daily total gross CO_2 assimilation by performing a Gaussian integration over time. At three different times of the day, irradiance is computed and used to calculate the instantaneous canopy assimilation, where after integration takes place. Goudriaan and Van Laar (1994) give more information.
- WATFD In routine WATFD the simulation of the soil water balance is performed for FREELY DRAINING soils in the water-limited production situation.
- WATGW In routine WATGW the simulation of the soil water balance is performed for soils influenced by the presence of groundwater. Two situations are distinguished: with or without artificial drainage. The soil water balance is calculated for a cropped field in the water-limited production situation.
- WATPP In this routine the variables of the soil water balance in the potential production situation are calculated. The purpose is to quantify the crop water requirements for continuous growth without drought stress. It is assumed that the soil is permanently at field capacity.
- W70MAIN This subroutine is the main driver routine. It reads the directories and opens and closes input, output and log files. The subroutine reads the run files (run options, timer and site file). Further it controls the reruns, the different weather years and the different randomized rainfall years in different loops. Within the hart of these loops it calls the subroutines WOFSIM (two times: for potential and water limited) and NUTRIE (for nutrient limited) and PRHEAD, STATPP and STATWP for writing headers and summarize output and statistics.
- WOFOST7 *This file has been removed from the source distribution, note that the figure on the following page still shows this file.*
- WOFSIM This routine organizes the simulation of crop growth and of soil water conditions, the generation of weather data and the writing of reports by successive calls to the relevant weather, crop, soil water and printing subroutines, in that order.

*Not taken-up in diagram model structure

