Calibration of WOFOST crop growth simulation model for use within CGMS

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http://www.wofost.wur.nl

Contents

1. Introduction

The WOFOST model is a generic crop growth model which can be applied for simulating the growth of many crop species under a wide range of environmental conditions. For each crop species, a separate input data file with specific data is used in WOFOST For the main environmental conditions in an area, representative climate and soil data files are used. In this way, WOFOST can easily be applied for assessments at regional or national scales of the yield potential of a large number of annual crops.

WOFOST is, for example, applied within the Crop Growth Monitoring System (CGMS). The output from WOFOST is used as a basis for monitoring the quality of the agricultural season over the whole territory of the EU and for yield forecasting per administrative region in the EU. For that purpose, WOFOST is fully linked to a geographical information system and to a relational data base management system in CGMS (Boogaard et al., 2002). Besides, WOFOST is available as a stand alone crop model which can be applied for analysing experiments, for predicting crop yields at the regional and national scale and for estimating yield changes due to changed conditions. Such changes may be climate change, application of irrigation water, change in crop variety or rotation, or change in growth period.

A brief description of the WOFOST model can be obtained from http://www.wofost.wur.nl which also provides downloads for several implementations of the WOFOST model. Detailed information on the modelling system and the main described processes in WOFOST is given by Supit et al. (1994) and can be found on the internet: http://www.supit.net (Supit & Van der Goot, 2002). A short description of WOFOST and an overview of the input files and the output files is given in the user’s guide of WOFOST (Boogaard et al., 1998). This last report describes the required input data, the options to run WOFOST, and the resulting model output.

To apply the WOFOST model for a specific crop species and for specific conditions with respect to climate and soil conditions, a model calibration is often required. WOFOST was developed as a generic model, however, it appears to achieve better crop growth simulation results if the model variables are calibrated for site-specific conditions. A procedure to calibrate WOFOST for specific conditions was not yet given in the reports about WOFOST, mentioned above. In a model calibration, the number of model variables that can be varied, is enormous. Hence, the model calibration should be done in certain order.

A calibration procedure for the different parts of WOFOST is described in Section 2. In this section, also a number of exercises in calibrating WOFOST are mentioned, which are described in Annex A. The answers to these exercises are given in Annex B. In Section 3, the required experimental information for the calibration of WOFOST is given.

2.Calibration procedure

2.1 Introduction

The model calibration is done first for a potential production situation. This requires information from crop experiments under potential production conditions. This means that the crop growth is not limited by water excess or shortage or by nutrient shortage, yield losses by weed competition, pest and disease infestation are practically nil and growth reduction due to other factors (poor soil structure, salinity or acidity) are also prevented. This requires optimum crop management and nutrient supply, irrigation and drainage, crop protection etc. which in general is found only in well-kept trials.

Next, the model calibration is done for the water-limited production situation. This requires information from crop experiments under water-limited conditions. This means that the crop growth may be limited by water excess or shortage, as no irrigation water is applied and possibly drainage may be limited. However, crop management, nutrient supply and crop protection should be optimum in these experiments too.

The model calibration is done for first the potential (aspects no. 1, 2 and 3 of WOFOST) and next the water-limited production situation (aspects no. 4, 5 and 6) in the following order: 1. length of growth period and phenology; 2. light interception and potential biomass production; 3. assimilate distribution between crop organs; 4. water availability; 5. evapotranspiration; 6. water-limited production. For each aspect of WOFOST, exercises are given in the following sections for calibrating WOFOST. The exercises are described in Annex A.

2.2 Length of growth period and phenology

The length of the growth period is the period between crop emergence and the date of crop maturity or senescence (yellowing of leaves). The total biomass production is equal to the mean daily biomass production times the total growth duration, hence this growth duration should be simulated well for a reliable biomass and yield prediction.

The date of sowing or crop emergence is important management input for WOFOST. If the sowing date is used as input, then the emergence date is calculated based on a temperature sum from sowing to emergence (TSUMEM in crop data file (Boogaard et al., 1998)). In that case, TSUMEM should be calibrated on observed sowing and emergence dates from field experiments with the same crop variety.

The date of crop maturity in WOFOST is calculated on the basis of two parameters describing the required temperature sum: TSUM1 describes the temperature sum from emergence to anthesis (flowering) and TSUM2 from anthesis to maturity. The daily increase in temperature sum is generally equal to the mean daily temperature minus a base temperature (e.g. 0 ^{0}C for wheat). The crop phenology is expressed as a development stage (variable 'DVS') which is the ratio between the accumulated temperature sum and the TSUM1 and TSUM2 parameters. DVS reaches 1 at anthesis and 2 at maturity.

A crop produces not only biomass but goes through a number of phenological development stages. In dependence of the phenological stage (i.e. DVS), WOFOST allocates the produced biomass to the different crop organs. This is described below in more detail (Section 2.4). For example, if DVS >1, all assimilates produced by a wheat crop are allocated to the grains. This indicates the importance of, for example, simulating well the date of anthesis. An anthesis date that is simulated too late, results in a too high green biomass and a low grain yield.

As an example, a WOFOST growth simulation is done for wheat in the Netherlands (Exercise 1, see Annex A). This is done for a potential production situation where water supply, nutrient supply and crop protection and management are all optimum. In this case, soil information is not used. The date of crop emergence is set at a fixed date in spring. The simulated dates of anthesis and maturity can be compared with the observed dates. As the simulated dates differ from the observed ones, the temperature sums for phenological development needed to be changed. For this, the rerun facility in WOFOST is applied. Four runs are done for four stepwise lowered values for TSUM1 and TSUM2 (Exercise 2). These simulated dates for anthesis and maturity are compared with the observed day numbers. In the following series of reruns, the TSUM1 and TSUM 2 values are fine-tuned, for optimum correspondence between simulated and observed anthesis and maturity dates.

Assuming that in Exercise 2 the WOFOST model was fine-tuned for a new wheat variety, a new crop data file for this wheat variety can be made (Exercise 3). This was done by copying the old crop data file and by entering new values for TSUM1 and TSUM2 in the new file.

2.3 Light interception and potential biomass production

The daily biomass production in a potential production situation mainly depends on the intercepted amount of irradiation. For most crops, the canopy during the main growth period is completely closed and almost all irradiation is intercepted. As on a weekly (or longer) basis the variation in irradiation is generally limited, the biomass production per week is often quite constant during the main part of the growth period. This results in a linear increase in biomass with time during the main growth period. The time course of total biomass production for most crops can be described by three phases:

a. exponential growth phase with small plants during first growth period, incomplete (but exponentially increasing) light interception and hence low but rapidly increasing biomass production;
b. linear, main growth phase with almost complete light interception and large production of biomass;
c. decreasing growth phase with dying leaves and rapidly decreasing biomass production until final death of canopy.

The total biomass production can be roughly estimated from the mean daily biomass production during the linear growth phase times the length of linear growth phase plus one fourth of the lengths of both exponential and decreasing growth phases. This indicates the strong relationship between the attainable biomass production and thus yield level, and the length of the linear growth phase. Rapid canopy establishment due to optimum growing conditions and high sowing rate on the one hand and an optimum control of pest and diseases which delays leaf senescence and damage on the other hand, results in the longest linear growth phase and the highest biomass production.

The WOFOST simulation of the potential production of wheat in Wageningen shows the time course of green leaf mass, the resulting leaf area index (LAI) and hence the fraction of irradiation that is intercepted (Fint) by the canopy, and the time course of total above-ground biomass production (Exercise 4). The length of the linear growth phase can be derived from these time courses and can be used for a first rough biomass production estimate for wheat in Wageningen. It is shown that at the end of the growth period the daily rate of biomass production decreases by both the decrease in photosynthesis rate and by the decrease in Fint.

If the simulated LAI or the fraction of light intercepted is too high but the amount of leaf biomass is simulated well, LAI can be lowered by entering a lower specific leaf area (SLATB, ha leaf area/kg leaf mass) in the crop data file (Exercise 5). If the LAI becomes lower, the simulated values for light interception and hence biomass production become lower too. Assuming that the simulated total above-ground production is now too low compared to the observed biomass production at harvest, Exercise 5 shows how the calibration of the biomass production can be done. The biomass production is mainly determined by the daily photosynthesis rate. This rate is calculated with a photosynthesis-light response curve, of which the initial angle (EFFTB) is mostly constant and of which the maximum (AMAXTB, in crop data file) may be changed (this maximum is often crop variety specific and decreases in case of nutrient shortage and canopy ageing due to a decrease in chlorophyll content).

The simulated time course of LAI and light interception at the beginning and at the end of the growth period may also be calibrated in a different way from that described above. WOFOST calculates LAI during the initial phase of crop establishment from a LAI at emergence (LAIEM) and from a maximum (sink or leaf growth limited) relative increase in LAI (RGRLAI, in crop data file). These two parameters strongly affect the initial increase in LAI and hence the duration till the linear growth phase with complete light interception. The simulated time course of LAI during the final growth period is strongly affected by the life span of leaves (SPAN in crop data file). A higher value for SPAN results in a longer time period that the leaves stay green and productive and hence, results in a higher LAI and thus biomass production near crop maturity. The effects of changes in these three parameters are not described in the exercises.

2.4 Assimilate distribution between crop organs

A crop produces not only biomass but goes through a number of phenological stages. For example, wheat has periods of establishment and first growth, a period of vegetative growth (tillering and head development), a period of flowering (anthesis) and a period of grain filling and ripening. The lengths of these periods can be calculated on the basis of temperature sums (Section 2.2). WOFOST does not really describe the organ formation of the crop but it allocates the produced assimilates to the different crop organs in dependence of the phenological development stage of the crop. For this allocation, WOFOST uses partitioning factors (in crop data file) in dependence of DVS. For example for wheat, as long as DVS<0.3, the main part of assimilates is allocated to roots and leaves and when DVS >1, all assimilates are allocated to the grains.

In this way, different crop species and varieties can be described in the WOFOST simulations. For example, a wheat variety with a relatively long period till anthesis (high TSUM1) and a relatively short period from anthesis till maturity date (low TSUM2) results in a large green biomass, a low grain yield, and thus a relatively low harvest index. For a higher wheat grain production, the variety should produce less green biomass and should produce and fill grains during a longer period, resulting in a higher ratio of grain yield over total biomass (e.g. harvest index – HI). This requires a variety with lowered TSUM1 and increased TSUM2.

The allocation of produced assimilates to the different crop organs in the WOFOST simulation is important for mainly two reasons: first it determines the leaf mass and thus the LAI and light interception; second it determines the allocation to the economical products (grains, roots, etc.) and thus the yield level and the harvest index. In Exercise 6, the effects of changes in variety characteristics are calculated. This is done for varieties with respectively earlier anthesis, earlier anthesis plus longer grain filling period, and longer growth duration with longer grain filling period. The earlier anthesis date is shown to result in a lower leaf mass and LAI and thus in a lower total biomass production. Simultaneously, the earlier anthesis date results in a higher harvest index, and also a higher yield. The longest growth duration results in the highest total biomass production, but not in the highest yield. The highest yield corresponds with the longest grain filling period, if the total biomass production is not too high (i.e. high assimilate losses by maintenance respiration in case of a too large canopy).

In a situation where the simulated allocation of assimilates to the different crop organs is clearly different from the observed allocation of assimilates and the dates for the main phenological stages (i.e. emergence, anthesis, maturity) are simulated well, the partitioning factors in the crop data file need to be changed. These partitioning factors determine the allocation of assimilates to the different crop organs in dependence of DVS. For example in Exercise 7, the simulated harvest index (wheat grain yield / total above-ground biomass) was much lower than the observed value. Hence, the partitioning factors were changed to reproduce well the observed harvest index.

2.5 Water availability

The following sections (2.5 up to 2.7) describe the calibration of the WOFOST model for water-limited conditions. In this section the water availability is discussed and in the next sections the water use by evapotranspiration and the resulting water-limited production.

The water availability is determined by first the soil physical characteristics and second the water balance. The water balance in the rooted zone during the growth period is equal to the difference between the water supply from precipitation and irrigation and the water losses by crop transpiration, soil evaporation and percolation to deeper soil layers. The soil physical characteristics determine the amount of water that can be stored at maximum in the soil and that can be supplied to the crop.

At a few locations, the groundwater level is shallow and capillary rise from groundwater may result in considerable additional water supply. This requires additional location-specific information that is often not available, such as the relationship between hydraulic conductivity and soil capillary rise, the time course of groundwater level, and the degree of artificial drainage. As these areas with shallow groundwater (low-lying river basins and river delta's) do not occur very often, this contribution of groundwater to the water availability is not treated in the following. However, note that this groundwater effect on water availability can be handled in a simplified way in WOFOST.

The maximum soil-water holding capacity in a free drainage situation is determined by the maximum crop's rooting depth and by the maximum available moisture fraction in the soil. This last variable is equal to the difference between soil moisture content at field capacity (i.e. moisture content after one or two days of free drainage of a wetted soil) and soil moisture content at wilting point (pF=4.2 which is about soil suction at which plants irreversibly die). The maximum rooting depth (RDMCR) is dependent on the type of crop species and is given for each crop in the crop data file. For wheat RDMCR is 125 cm. However, many wheat roots may go deeper than 125 cm. However, this means that from a wet soil this maximum amount of available water (i.e. 125 cm * maximum available moisture fraction) can be used by a wheat crop. For soils which are shallow or have unfavourable soil structures or layers, a more shallow rooting depth due to soil limitation (RDMSOL) may be entered into WOFOST from screen. Hence if RDMSOL < RDMCR, the maximum rooting depth is equal to RDMSOL.

The values for the soil moisture contents at field capacity and wilting point are specified in data files for a number of different soil types which mainly differ with respect to soil texture class. For the CGMS applications of WOFOST (Boogaard et al., 2002), the maximum soil-limited rooting depth and the maximum available moisture fraction are derived with pedotransfer functions from common soil characteristics. However, for reliable water-limited production simulations with WOFOST, it is preferred to measure the moisture contents at field capacity and wilting point (i.e. mean value for the maximum rooting depth) for each soil type for which simulations are done.

The initial water availability at crop emergence depends on the water supply by precipitation and irrigation and the water use by crop transpiration and soil evaporation during the months before crop emergence. For growth simulations with WOFOST, the initial water availability is generally not known. In that case it is often assumed that initially the maximum rooting depth is at field capacity. In humid areas with rainfall exceeding evapotranspiration during the winter, this assumption works well for the crop growth starting in spring. However, in areas with dry periods (e.g. semi-arid areas) preceding crop emergence, the initial water availability may be largely overestimated. This may result in a strongly overestimated water supply during the growth period in the WOFOST simulation. This indicates the need for measuring the initial water availability at crop emergence.

The WOFOST simulation of the water-limited production of wheat in Wageningen (Exercise 8) shows the time courses of biomass production and grain yield which can be compared with those for potential (i.e. irrigated) production. The periods when drought limits growth of the water-limited crop, resulting in a lower yield, are shown. For additional information, the time courses of the soil moisture content in the actual root zone, the rooting depth and the total available soil moisture for crop uptake in the root zone are studied in this exercise. Finally, WOFOST gives the balance of water inputs (from precipitation and from addition of water to root zone by root growth) and water losses (by crop transpiration and soil evaporation and percolation to deep soil layers), which gives a complete picture of the water availability and water use in this production system. This simulated water balance can, in addition to the mentioned time course of soil moisture in the root zone, be used for checking and calibrating the simulated water-limited production system.

The initial water conditions in the root zone are determined in a WOFOST simulation by two variables. First, the variable SMLIM which specifies the initial soil moisture content in the initial root zone (0-10 cm depth). Second, the variable WAV which specifies the initially available (above moisture content at wilting point) amount of soil moisture in the maximum root zone. The sensitivity of the water-limited production to these initial water conditions is analysed in Exercise 9, and appears to be quite strong. As discussed above, the initially available amount of water may be considerably overestimated in situations with dry periods preceding crop emergence. In that case, the water availability during the growth period and the water-limited production may be considerably overestimated too.

The water-limited production is also determined by the maximum soil-water holding capacity of the soil. This capacity is determined by first the maximum rooting depth (RDMSOL), as discussed above, and the available soil moisture fraction (i.e. soil moisture content at field capacity minus that at wilting point). The water-limited production from WOFOST changes if the available soil moisture fraction or RDMSOL changes. Exercise 10 shows the sensitivity of water-limited production to changes in the soil moisture content at field capacity (soils from coarse to fine). Highest water-limited production is calculated for the medium soils. This indicates the need for measuring the soil moisture contents at field capacity and wilting point and the actual rooting depth for the main soil types, for which WOFOST simulations are done. Such new soil data can be entered in a new soil data file (Exercise 11).

2.6 Evapotranspiration

The potential evapotranspiration from a bare soil surface, a water surface and a crop surface are all calculated with the Penman approach (Frère & Popov, 1979; Supit et al., 1994). This approach is universal and in general works well in most situations. However, some possibilities for calibration of the actual evapotranspiration are given in the following.

In WOFOST, the actual crop transpiration is equal to the potential evapotranspiration times correction factors for the degree of light interception, the degree of water stress, and for the crop in general. This last factor, variable CFET in crop data file, is in general 1.0. However, its value may be increased to e.g. 1.15 if the WOFOST simulation underestimates the actual transpiration due to the relatively great height and thus large transpiration of, for example, a maize crop. The reason is that the Penman approach is mainly developed for a short crop like grass. In (semi-)arid areas with advection, simulated transpiration may also be too low compared to observations and may need a correction.

The degree of drought stress and the resulting reduction in transpiration rate, and proportionally in photosynthesis too, are determined by the soil moisture content in the root zone. If the soil moisture content becomes lower than the critical moisture content, the water-stress correction factor is gradually reduced from 1.0 to 0.0 at a moisture content equal that at wilting point. However, the critical soil moisture content is not a constant value. It differs between crop species and varieties but also depends upon the evapotranspiration itself. The latter is caused by plants being more prone to drought stress when the atmospheric evaporative demand is high and thus the potential plant evapotranspiration is high. In WOFOST, crop sensitivity to drought stress is indicated by variable DEPNR with higher values indicating a less drought sensitive crop (e.g. 4.5 for wheat and 3.0 for potato). Differences in drought sensitivities between crop varieties may be included by changing DEPNR. For more information about this drought stress approach, see Supit et al. (1994).

Soil moisture content may become too high for crop growth too, in general in soils where drainage is limited. If the air content becomes less than the value for the variable CRAIRC (in soil data file), both transpiration and photosynthesis are reduced due to oxygen shortage. Hence, in wet growing conditions, this variable CRAIRC may need more precise calibration. In free draining soils, oxygen shortage in general does not occur.

2.7 Water-limited production

The model calibration is done first for a potential production situation. If this is done well, the model should next be calibrated on the basis of information from crop experiments under water-limited conditions. The water-limited production is determined by the water availability and the water use during the crop growth period. The water use is mainly determined by crop transpiration and soil evaporation, and sometimes percolation to deep soil layers. This water use is in general calculated well by the model. As described in Section 2.6, crop transpiration may need some calibration in particular in (semi)-arid conditions.

The water availability during the growth period is determined by both the initial water availability, the maximum soil-water holding capacity as dependent on rooting depth and the available soil moisture fraction, and the balance of water inputs (mainly precipitation) and use (see above) during the growth period. The initial soil water availability in the maximum rooting depth should be based on measurement of soil moisture content at crop emergence or should be based on calculation of the water balance during the months before crop emergence. Often only a rough estimate for the initial soil water availability is available for the WOFOST simulation, however, the sensitivity of water-limited production to this initial soil water availability was shown to be quite strong (see Section 2.5).

The maximum soil-water holding capacity is determined by the maximum rooting depth (of full-grown crop) and the available soil moisture fraction (moisture content at field capacity minus that at wilting point). For these three variables reliable values should be available for each soil type for which WOFOST simulations are done, to achieve precise water-limited crop production analyses (as discussed in Section 2.5). However, for regional-scale studies, often regional-mean values (based on pedotransfer functions) are only available for these variables that determine the maximum soil-water holding capacity.

In many studies on crop production and yield prediction at the regional, national or continental scale, the information on initial soil water availability and on the maximum soil-water holding capacity is missing. In that case, it is important to calibrate WOFOST on the basis of the limited information from representative field experiments under water-limited conditions. Assuming that mainly biomass production or grain yield data are available from such field experiment, it is shown in Exercise 12 how a first estimate for the initial soil water availability and/or the maximum soil-water holding capacity can be made. For this, WOFOST simulations are done varying the values for the initial soil water availability and the maximum soil-water holding capacity.

The resulting model output for biomass production, grain yield, components of the water balance, etc. can be compared with observed data, as described in Exercise 12. The maximum soil-water holding capacity depends on the maximum rooting depth and the available soil moisture fraction, which is equal to soil moisture content at field capacity minus that at wilting point. To prevent too much complexity in this analysis, one of these three variables is varied in Exercise 12 at the time.

3. Required experimental data for WOFOST calibration

3.1 Crop data

From experiments which are representative for the studied region, crop data are required, i.e. for

- the main crops
- under the main range of environmental conditions (main soil types, climates, hydrological, etc. conditions)
- with representative types of management (optimal nutrient supply and crop protection both with and without irrigation (i.e. potential and water-limited production))

The following information from experiments is needed:
- Crop information, initial: a. weight of seed or planting material; b. sowing density; c. sowing/planting date;
- Crop information during the growth period: a. phenological development or dates of sowing, emergence, anthesis and maturity; b. leaf area index or light interception; c. plant density;
- Crop information from intermediate and final harvests: a. total biomass; b. distribution of biomass over plant organs; c. living and dead leaf weight; d. crop composition at final harvest: e.g. plants/m^2, ears/plant, grains/ear and grain weight;
- Other crop information such as, for example: a. leaf damage; b. yield losses by pest and disease infestation and/or weed competition; c. yield losses by nutrient shortage.

3.2 Soil data

From experiments which are representative for the main crops and environmental conditions in the studied region, the following soil information is needed:

1. Soil information, initial: a. soil physical characteristics (pF curve or soil moisture contents at field capacity and wilting point and soil porosity); b. soil-limited rootable depth; c. possibly, hydraulic conductivity; d. for paddy rice, surface water storage (bund height);

2. Soil information during the growth period: a. soil moisture content in rooted soil; b. ground water level;

3. Special soil and landscape characteristics (if applicable and of importance for crop growth and/or water availability): a. hydrology; b. salinity; c. sodicity; d. special soil layers or structure; e. slope and degree of surface runoff.

3.3 Weather data

To simulate with WOFOST the observed crop growth at experimental locations and to use this experimental information (see Sections 3.1 and 3.2) for the model calibration, also weather information from these locations is needed. This weather information is described in the following. For use of WOFOST for regional-scale studies of, for example, the yield potential, the same weather information from representative meteorological stations in that region is needed.

Required weather information (in CABO-format for daily weather data for WOFOST, see Boogaard et al, 1998 (section 5.4.2)) during the growth period (daily values):

a. minimum temperature (^{0}C);
b. maximum temperature(^{0}C);
c. daily global irradiation (kJ.m^{-2}.d^{-1});
d. precipitation (mm.d^{-1});
e. mean wind speed at 2 m above ground level (m.s^{-1});
f. vapour pressure (early morning, kPa).

3.4 Other additional information

1. applied inorganic fertiliser, animal and green manure;
2. crop management and protection;
3. crop rotation;
4. irrigation method and amount of applied irrigation water;
5. soil tillage method;
6. drainage system.

References

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Internet resources

- www.wofost.wur.nl
- www.supit.net

Annex A: Exercises

Exercise 1. Familiarizing with the WOFOST model

Aim: Familiarize yourself a bit with the WOFOST Control Centre by simulating growth of winter-wheat in The Netherlands.

WCC settings:	
General	• simulation of potential crop growth • output interval= 1 days
Crop	• winter wheat 102 • Start day: fixed emergence at day 100 • end day: maturity
Weather	• CABO format • weather : Netherlands, Wageningen, 1973 • 1 year
Soil	Not applicable (not used for potential production)
Reruns	Don't use reruns

Run the WOFOST model with the settings above and visualize the different output variables under "Detailed output - Potential".

Q1.1 Find out the days at which the model reaches emergence, anthesis and maturity.

Exercise 2. Calibration of phenology of wheat variety

Aim of this exercise: Find values for TSUM1 and TSUM2 parameters in order to reproduce the observed anthesis and maturity dates.

WCC settings:	
General	• simulation of potential crop growth • output interval = 1 days
Crop	• winter wheat 102 • Start day: fixed emergence at day 100 • end day: maturity
Weather	• CABO format • weather : Netherlands, Wageningen, 1973 • 1 year
Soil	Not applicable (not used for potential production)
Reruns	• Add reruns, select crop variables TSUM1 and TSUM2 for four reruns (WCC1 → WCC4) with TSUM1= 1050, 1000, 950 and 900 TSUM2= 1000, 950, 900, and 850; • Indicate: use reruns.

Run the WOFOST model with the settings above and visualize the development stage (DVS) under "detailed output - Potential". The different values for TSUM1 and TSUM2 that were simulated with the rerun facility demonstrate that this has an impact on the phenological development in the model.

Experimental data shows that the wheat crop in Wageningen reaches Anthesis and maturity at June 29 and August 18 in 1973.

Q 2.1 Determine the optimum values of TSUM1 and TSUM2 in order to simulated the observed Anthesis and Maturity dates. Use Rerun to adjust the TSUM1 and TSUM2 values iteratively

<u>Tip:</u> A Julian day calendar is available in Annex C of this document.

Exercise 3. Create a new crop data file for wheat

Carry out these steps:

1. Copy `WWH102.cab` to `WWHnew.cab` in folder `..\WOFOST Control Center\CROPD\`
2. Edit `WWHnew.cab` using notepad. Change:

```
CRPNAM='Wheat new for the Netherlands'
TSUM1= <selected value in exercise 2>
TSUM2= <selected value in exercise 2>
```

3. Restart WOFOST
4. Run (again for Wageningen 1973 for new wheat variety)
5. Are the simulated dates for anthesis and maturity okay?

Exercise 4. Light interception and potential biomass production

Aim: Understand the concepts of light interception and biomass accumulation in WOFOST and some important model parameters.

WCC settings:	
General	• simulation of potential crop growth • output interval= 1 days
Crop	• New crop variety from Exercise 3 • Start day: fixed emergence at day 100 • end day: maturity
Weather	• CABO format • weather : Netherlands, Wageningen, 1973 • 1 year
Soil	Not applicable (not used for potential production)
Reruns	Don't use reruns

Run the WOFOST model with the settings above and visualize the graphs of WLV (living leaves) and LAI under "detailed output - Potential". The fraction of light intercepted (Fint) can be calculated for wheat with: (1 - exp (- 0.6* LAI)).

Q2.1. At which LAI, the light interception is 25%, 50%, 85%?

<u>Tip</u>: Export WOFOST simulation results to Microsoft Excel to carry out this analysis.

The analysis above showed that the light interception quickly saturates at LAI>3. Therefore, one way of estimating the period of linear growth is by counting the number of days where LAI>3.

Q2.2. Estimate the period of linear growth (nr of days) based on the LAI graph?

The period of linear growth can also be derived from the graph showing the Total AboveGround Production (TAGP), because the TAGP increases linearly during this period.

Q2.3. Estimate the period of linear growth from TAGP graph?

In practice you will find that the actual period of linear growth based on the TAGP graph is shorter then you would expect on the basis of the LAI graph. The crop data file WWHnew.cab contains the variable AMAXTB, which gives the photosynthesis rate at high light conditions as dependent on the development stage (DVS).

Q2.4. Explain the shorter period of linear growth derived from TAGP, given the functional shape of AMAXTB.

Exercise 5. Change in LAI and calibration of potential biomass production

Aim: calibrate leaf area index to reproduce the observed value, next calibrate the potential biomass level.

<u>Calibrate the leaf area index</u>
Measurements of maximum LAI during field experiments in Wageningen have shown that the maximum LAI reached is around 5. However, the total biomass is predicted well by the model. Thus, the LAI simulated by the model is too high while total biomass should remain similar. Therefore, write down the maximum LAI and total biomass at harvest from exercise 4.

WCC settings:	
General	• simulation of potential crop growth • output interval = 1 days
Crop	• New crop variety from Exercise 3 • Start day: fixed emergence at day 100 • end day: maturity
Weather	• CABO format • weather : Netherlands, Wageningen, 1973 • 1 year

Soil	Not applicable (not used for potential production)
Reruns	• Add reruns, select crop variable SLATB for four reruns (WCC1 → WCC4) with SLATB = 0.00211, 0.0020, 0.0019, 0.0018 (*right click in the edit cell to adjust a table parameter!*) • Indicate: use reruns.

As the simulated LAI is too high compared to the observed LAI (e.g. maximum LAI of 5) we need to adjust the SLATB (specific leaf area) which converts leaf mass in leaf area using the rerun facility in WOFOST.

Q5.1 Find the appropriate value for SLATB using the rerun facility

Calibrate the total crop biomass (TAGP)
A change in leaf area due to a change in SLATB will also impact the total crop biomass. The observed TAGP at harvest in the previous exercise was about 17800 kg/ha, and thus the simulated TAGP is too low in the WOFOST run with calibrated SLATB. In order to obtain the same amount of total biomass with lower LAI values, we need to increase the assimilation rate which is set by the parameter AMAXTB.

WCC settings:	
General	• simulation of potential crop growth • output interval = 1 days
Crop	• winter wheat variety from previous exercise • Start day: fixed emergence at day 100 • end day: maturity
Weather	• CABO format • weather : Netherlands, Wageningen, 1973 • 1 year
Soil	Not applicable (not used for potential production)
Reruns	• Add reruns, select variable SLATB and AMAXTB for four reruns (WCC1 → WCC4) with SLATB = <value found in previous exercise> AMAXTB = 35.83, 38, 40, 42 (only value at DVS=2.0 is not changed) • Indicate: use reruns.

Q5.2 Iteratively determine which value for AMAXTB is needed to increase the production towards the observed levels?

Note that with increasing AMAXTB, also the maximum LAI increases again due to increased amount of leaf biomass. In fact such calibrations should be tackled by calibrating SLATB and AMAXTB simultaneously. For the moment we will neglect this effect.

Q5.3 Change the values for SLATB and AMAXTB in the crop data file WWHnew.cab. Run WOFOST again with the new crop data file (with reruns disabled) and check if the value for TAGP is identical to the one found previously.

Exercise 7. Change in assimilate distribution

We now have a new wheat variety which has been calibrated in such a way that the simulated anthesis and maturity days match the observed ones, the maximum LAI is reproduced satisfactory and the total biomass is close to the observed values.
An important aspect of the simulation is the ratio of harvested products over the total crop biomass (the Harvest Index). The HI is important because a crop variety which a large HI is commercially interesting and provides a high grain yield. The wheat variety that we have calibrated so far produces a harvest index of 0.44, while the observed values in Wageningen are 0.5. We have seen that the simulated dates of anthesis and maturity correspond with the observed dates. Hence, the partitioning fractions in the crop data file should be changed in order to partition more assimilates to the storage organs and less to the stems and leaves.
The model parameters that govern the partitioning are the FSTB (fraction stems), FOTB (fraction organs) and FLTB (fraction leaves) which all describe the fraction as a function of the development stage. The sum of FOTB, FLTB and FSTB at any point during the development stage of the crop needs to be one (1). Figure 1 gives an overview of the partitioning factors for wheat.
It is clear that between DVS 0.95 and 1, a strong change in partitioning takes place where all assimilates are partitioned to the storage organs. We can change the assimilate distribution by slightly adjusting this point, so instead of starting the partitioning to organs at DVS 0.95, we can change it to 0.9 or 0.85. Therefore we will experiment with shifting the partitioning factors using the rerun facility.

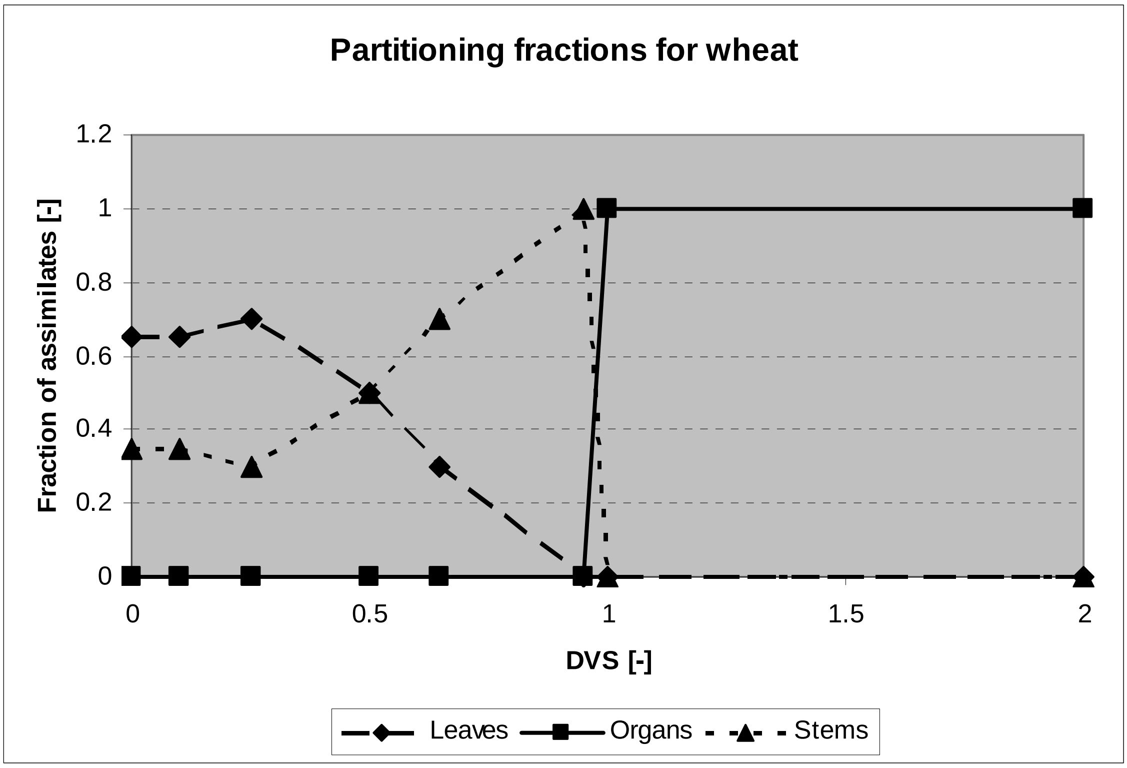

Figure 1. Partitioning fractions for winter-wheat in WOFOST.

WCC settings:	
General	• simulation of potential crop growth • output interval = 1 days
Crop	• winter wheat variety from previous exercises. • Start day: fixed emergence at day 100 • end day: maturity
Weather	• CABO format • weather : Netherlands, Wageningen, 1973 • 1 year
Soil	Not applicable (not used for potential production)
Reruns	• Add reruns, select variables FOTB, FSTB, FLTB for five reruns (WCC1 → WCC5) with changes in DVS to partitioning: 0.95, 0.85, 0.75 • Indicate: use reruns.

Q7.1 What is the optimum value for the DVS at which the partitioning to storage organs starts in order to reach a HI of 0.5? Moreover, what effect does it have on the total biomass production, the leaf area index?

Q7.2 Is it realistic that partitioning to storage organs starts before anthesis (grain formation)?

Exercise 8. Water availability

Aim: Understand the water balance implemented in WOFOST.

WCC settings:	
General	• And simulation of water-limited crop growth • output interval = 1 day • **<u>start date water balance=100</u>** • effects of both drought and oxygen shortage • Whole system and root zone
Crop	• winter wheat 102 • Start day: fixed emergence at day 100 • end day: maturity
Weather	• CABO format • weather : Netherlands, Wageningen, 1973 • 1 year
Soil	• soil type: EC2-medium (texture) • initial and maximum surface storage: both set to zero (storage from day to day, mainly of importance in flooded rice fields) • groundwater: not selected • maximum rooting depth of soil: 120 cm • initial available water (WAV): 10 cm • initial moisture content in initial rooting depth (SMLIM): 0.25 cm3/cm3 • non infiltration fraction: fixed and set to zero
Reruns	No reruns

Open “Results detailed – Water-limited production”, compare the water limited yield (WSO) and total above-ground Biomass (TAGP) with those for potential production?

Q8.1 The critical soil moisture level for winter-wheat is about 0.15. When do the drought periods occur according to the graph of soil moisture? Does this match up with graph of “Days of stress conditions (too dry)”.
Q8.2 How can you explain that not all days during this period are indicates as a day with stress conditions.

Write down the values for SM (soil moisture content in actual root zone), RD (actual rooting depth), RESRV (available water in maximum rooting zone) and AVAIL (available water in actual rooting zone) at emergence day 100 and at maturity day 244.

Q8.3 How these values are related at both dates? See also Graph for these four variables.

Q8.4 How are the values mentioned at previous point, related to the values for water stock in the water balance output of this run?

Exercise 9. Sensitivity to initial soil water conditions

Aim: Determine impact of initial soil moisture conditions as provided by variables SMLIM (available water in initial root zone) and WAV (initial water total root zone).

WCC settings:	
General	See exercise 8
Crop	See exercise 8
Weather	See exercise 8
Soil	See exercise 8
Reruns	• Add reruns, select variable SMLIM for five reruns (WCC1 → WCC5) with changes in value ranging from 0.10, 0.15, 0.20, 0.25, 0.30, which varies from wilting point to field capacity. • Indicate: use reruns.

Run WOFOST, open "Results detailed – Water-limited production" and compare the results for the five runs for the following variables: soil moisture content (SM), available water in actual root zone (AVAIL), total above-ground biomass (TAGP) and days with stress (dry).

Q9.1 Has the crop more drought stress during initial growth in run WCC1 with the lowest value for SMLIM ? Does the stress result in a lower yield?

WCC settings:	
General	See exercise 8
Crop	See exercise 8
Weather	See exercise 8
Soil	See exercise 8
Reruns	• Add reruns, select variable WAV for five reruns (WCC1 → WCC4) with changes in value ranging from 5, 10, 15, 20 cm. • Indicate: use reruns.

Run WOFOST, open "Results detailed – Water-limited production" and compare the results for the five runs for the following variables: soil moisture content (SM), available water in actual root zone (AVAIL), total above-ground biomass (TAGP) and days with stress (dry).

Create a table containing for all five treatments the following variables: Potential yield (WSO), water-limited yield (WSO), rainfall, initial soil water ("init max root zone"), transpiration and evaporation ("evap soil surface"). The last four variables can be retrieved from the tab "water balance".

Q9.2 What is mainly explaining the increase in yield from the WCC1 to WCC5 runs?

WCC settings:	
General	See exercise 8, but • **start date water balance=1**
Crop	See exercise 8
Weather	See exercise 8
Soil	See exercise 8
Reruns	• Add reruns, select variable WAV for five reruns (WCC1 → WCC5) with changes in value ranging from 0, 5, 10, 15, 20 cm. • Indicate: use reruns.

Run WOFOST, open "Results detailed – Water-limited production" and compare the results for the five runs for the following variables: soil moisture content (SM), available water in actual root zone (AVAIL), total above-ground biomass (TAGP) and days with stress (dry).

Q9.3 What do you conclude about the necessity to start the water balance before the crop simulation in order to reduce initialization errors?

Exercise 10. Sensitivity to maximum soil-water holding capacity

Aim: determine sensitivity to soil parameters, particularly the maximum water holding capacity at field capacity as specified by variable SMFCF.

WCC settings:	
General	See exercise 8
Crop	See exercise 8
Weather	See exercise 8
Soil	See exercise 8
Reruns	• Add reruns, select variable SMFCF for four reruns (WCC1 → WCC4). With SMFCF ranging from 0.15, 0.20, 0.25, 0.30, which results in 0.051 to 0.201 cm^3/cm^3 available moisture fraction above wilting point (i.e. coarse, medium, fine and very fine soil texture). • Indicate: use reruns.

Note that maximum soil-water holding capacity also strongly depends on the maximum rooting depth which may be limited by e.g. impermeable soil layers or shallow soil profile. This effect of rooting depth is not included in this exercise but may be analysed too (i.e. variation in site-variable RDMSOL in a new set of reruns).

Run WOFOST, open "Results detailed – Water-limited production" and compare the results for the four runs for the following variables: soil moisture content (SM), available water in actual root zone (AVAIL), transpiration (TRA) and total above-ground biomass (TAGP). Create a table of the main inputs (rainfall and initial soil moisture) of the water balance for the whole system (0-120 cm) and the main outputs (transpiration, evaporation, percolation) for the four reruns.

Q10.1 What is mainly explaining the low yield in the WCC1 run, which run has the highest yield and why?

Exercise 11. New soil data file

Based on measurements of soil moisture content at field capacity and at wilting point, the values in soil data files for WOFOST simulations should be set to location-specific values.
Therefore we create a new soil data file with the following steps:

1. copy `EC2.new` to `EC9.new` in folder "`..\WOFOST Control Center\SOILD\`"
2. Edit EC9.new with notepad:

   ```
   SOLNAM= 'EC9-medium new'
   SMW= 0.099
   SMFCF= 0.20
   ```

3. Restart WOFOST
4. Run WOFOST and check if the results are the same as the corresponding WCC run in the previous exercise.

Exercise 12: Calibration of water-limited production

Aim: calibrate drought sensitivity of winter-wheat in WOFOST using observed values of water-limited total biomass.

We assume that WOFOST is calibrated well for the potential production situation. For the water-limited production, however, the experimental information is limited to estimates of final total biomass which show that the that the total biomass in 1973 under water-limited conditions was between 15000 and 16000 kg/ha over different parts of the field.

We assume that the soil characteristics are roughly known, being those in soil data file EC2.new. Next, based on sensitivity analyses with WOFOST and on observed yield data, we try to calibrate WOFOST for a water-limited production situation by varying the maximum crop rooting depth (RMDCR) and the crop drought sensitivity index (DEPNR).

WCC settings:	
General	See exercise 8, but **start date water balance=1**
Crop	See exercise 8
Weather	See exercise 8
Soil	See exercise 8
Reruns	• Add reruns, select variables RDMCR and DEPNR with RDMCR ranging 75, 100, 125 and DEPNR ranging 3.5, 4, 4.5 which results in 9 unique combinations. • Indicate: use reruns.

Run WOFOST, open "Results detailed – Water-limited production" and display the chart "Soil Moisture Content (SM)". Compare the results for the nine runs.

Q12.1 For which run is the soil moisture depleted most and explain why this is the case.

Q12.2 Which combination(s) of WOFOST parameters seems to best reproduce the observed total crop biomass?

WCC settings:	
General	See exercise 8, but **start date water balance=1**
Crop	See exercise 8
Weather	See exercise 8
Soil	See exercise 8
Reruns	• Add reruns, select variables RDMCR and DEPNR with RDMCR a constant value of 80 and DEPNR ranging 3.5, 4, 4.5 which results in 3 unique combinations. • Indicate: use reruns.

Measurements during the field campaign in 1973 demonstrated that the maximum crop rooting depth was 80 cm. A second field trial was held in 1976 with the same variety. As 1976 was a drought year, crop yields were strongly impacted by drought and the water-limited yield was measured to be between 2500 and 3000 kg/ha over the field.

Run WOFOST, open "Results detailed – Water-limited production" and display the chart TAGP, compare the results for the nine runs.

Q12.3 Which is the most likely value for the DEPNR according to the 1976 simulation results?

Annex B: Answers to exercises

Exercise 1:

Q1.1: Crop emergence, DVS= 0.0, Day=100; Anthesis, DVS= 1.0, Day= 186; Maturity, DVS=2.0, Day= 244.

Exercise 2:

Q2.1: TSUM1= 945 (0C.d), TSUM2= 880 (0C.d)

Exercise 4:

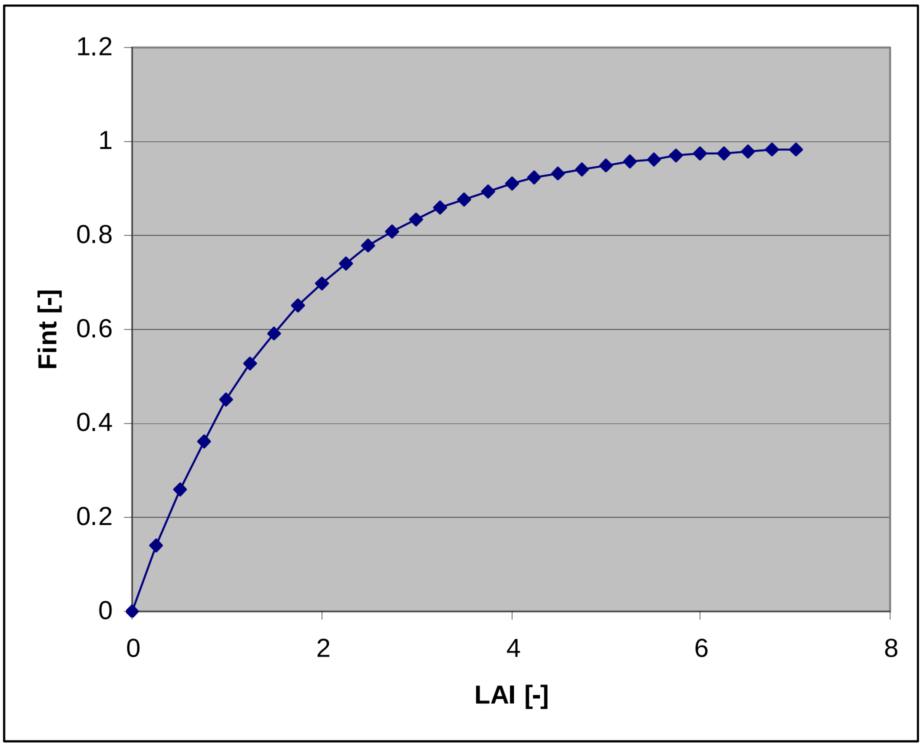

Figure 2. Light interception with increasing Leaf Area Index.

Q2.1 Fint=0.25 at LAI=0.5, Fint=0.5 at LAI=1.2, Fint=0.85 at LAI=3.2
Q2.2 Period of linear growth: day 150 to day 220 for LAI >3
Q2.3 Period of linear growth: day 152 to day 200 based on TAGP
Q2.4 Photosynthesis rate at high light conditions (AMAXTB in crop data file) decreases from DVS 1.3 (=day 193). Hence, the decrease in dry matter increase starts earlier than the decrease in Fint. Photosynthesis and thus biomass production is determined by both the initial angle (EFFTB in crop data file) and the maximum of the photosynthesis-light response curve (AMAXTB), of which EFFTB is mostly constant and AMAXTB decreases with ageing of the canopy. This last ageing-effect is caused by a decrease in chlorophyll content in the leaves.

Exercise 5:

The maximum LAI= 6.29 and TAGP (at harvest)= 17772 kg/ha from exercise 4.

Q5.1. The SLATB value that best reproduces the observations is 0.0018 m^2/kg with a maximum LAI of 4.9 and a TAGP at harvest of 16336 kg/ha.
Q5.2. the AMAXTB should be increased to 41.5 which results in a TAGP (at harvest)= 17785 kg/ha

Exercise 7:

Q7.1 The best fitting value for the swap in partitioning from stems/leaves to organs is at DVS 0.77.
Q7.2. Biophysically, it is not very realistic since the organs needed for storage of these assimilates have not yet formed. However, in WOFOST the produced assimilates are allocated to the final destination (i.e. crop organ). This means that in wheat where in reality a large amount of assimilates can be temporarily stored in the stems, this amount of stem reserves is finally redistributed to the grains. As these stem reserves are not considered in WOFOST, it is possible and necessary to allocate assimilates to the grains before anthesis.

Exercise 8:

Q8.1 Main periods with drought stress are at the end of the growing season where soil moisture drops below 0.15. Many of those days are also marked as days with water stress.
Q8.2 The amount of water-stress is not only depending on the critical soil moisture level, which in turn depends on crop type and actual evapotranspiration. The days not marked as days with drought stress are probably relatively cool days with little solar radiation and therefore a low reference evapotranspiration.

Day 100: SM= 0.250 cm^3/cm^3 ; RD= 10 cm; RESRV= 10 cm; AVAIL= 1.5 cm
Day 244: SM= 0.134 cm^3/cm^3 ; RD= 120 cm; RESRV= 4.2 cm; AVAIL= 4.2 cm

Q8.3 The initially (day 100) available amount of soil water (AVAIL) in the initial root zone (10 cm depth) is 1.51 cm and the total initially available amount (RESRV) of soil water in the maximum root zone is entered to be 10 cm (in 0-120 cm layer). RD is initially always 10 cm. The initial soil moisture content, SM, in the initial root zone is 0.250 cm^3/cm^3.

At maturity, the actual rooting depth is equal to the maximum value (RD= 120 cm). Hence, the available amount of soil water in the actual root zone is equal to the available amount in the maximum root zone (both 4.2 cm). If the available moisture fraction (4.2 / 120 (RD)) is 0.035 cm^3/cm^3, the soil moisture content is 0.099 (wilting point) + 0.035= 0.134 cm^3/cm^3.

Q8.4 The water balance output is given in the output file for both the root zone (which depth increases from 10 cm at emergence to 120 cm at maturity) and the whole system (continuously 120 cm depth). This last water balance gives as output the total amount of water in the 120 cm top layer at crop maturity which is 16.1 cm (=0.134 * 120 cm depth; 4.2 cm available for crop), and the cumulative water losses by crop transpiration and soil evaporation (21.7 + 5.8 cm). The water input is equal to the amount of rainfall during the growth period (21.8 cm) and the initial amount of water in the maximum root zone (21.9 cm, i.e. 120 * 0.099 cm^3/cm^3 (wilting point) + 10 (entered value for initially available soil water)).

The water balance for the root zone gives as output the same values as the water balance for the whole system, because the depth of both systems at maturity is identical (i.e. 120 cm). The input of the root zone-balance gives the initial water stock for an initial root zone of 10 cm, for which the initial soil moisture content was entered to be 0.25 cm^3/cm^3. In addition to precipitation (21.8 cm), water is added to the root zone by root growth. This last amount is equal to the amount of water in the layer between 10 and 120 cm depth at wilting point plus the initially available amount (see above) in this layer. In total, this amount is (110 * 0.099 + 8.49 cm=) 19.4 cm.

Exercise 9:

Q9.1 The initially available amount of water (AVAIL; in initial root zone of 10 cm) is nil in run WCC1 and much higher in the other runs. However, root growth results in run WCC1 in a rapid increase in available soil moisture from the deeper soil. Hence, also in this run the initial drought effect is very small (see graph with drought days). The difference in total biomass production (see graph) is nil between the five runs, which is mainly caused by the fact that the total initially available water (WAV) in the maximum root zone (0-120 cm) is identical in the five runs.

Q9.2
Grain yield = 7318 kg/ha for potential production.
Grain yield = 3458, 4801, 6362, 7217 kg/ha for the four different water-limited production runs (WCC1 → WCC4).

Inputs and outputs of the water balance for the whole system for runs WCC1, WCC2, WCC3 and WCC4:

	Input (cm)		Output (cm)		
	Rainfall	Soil initial	Transpi-ration	Evapo-ration	Soil final
WCC1	21.8	16.9	15.8	6.7	16.2
WCC2	21.8	21.9	21.7	5.8	16.1
WCC3	21.8	26.9	26.5	5.6	16.5
WCC4	21.8	31.9	28.3	5.6	18.3

The relationship between the yield level for the four runs and the total transpiration during the growth period is strong. If the soil water supply limits the crop transpiration, the yield decreases almost proportionally. The initially available amount of soil water in the maximum root zone (120 cm depth) varied between 5 cm (11.9 cm not available, as below moisture content at wilting point) and 20 cm. This difference completely determined the water availability and thus the crop transpiration and yield. However, this initially available amount of soil water is often not known, but appears to have a strong impact on the simulated water use and crop yield.

Q9.3 Sensitivity of simulation results on initial conditions of the water balance can be strongly decreased if the water balance is started prior to initialization.

Exercise 10:

Q10.1 The highest transpiration and hence the highest total above-ground biomass production (TAGP) is shown in the graphs for the WCC2 run with the medium soil type.

Grain yield = 7318 kg/ha for potential production.
Grain yield = 4526, 5128, 4968, 4820 kg/ha for the four different water-limited production runs (WCC1 → WCC4).

Inputs and outputs for the water balance of the whole system for runs WCC1, WCC2, WCC3 and WCC4:

	Input [cm]		Output [cm]			
	Rainfall	Soil initial	Trans-piration	Perco-lation	Evapo-ration	Soil final
WCC1	21.8	21.9	16.9	6	6.6	14.1
WCC2	21.8	21.9	23.2	0	5.7	14.7
WCC3	21.8	21.9	22.3	0	5.7	15.7
WCC4	21.8	21.9	21.1	0	5.8	16.7

This water balance shows that in the WCC1 run the maximum water holding capacity of the coarse soil is so low that the initial amount of available water (10 cm) is largely lost by percolation. This reduces the available water inputs and results in the lowest transpiration and grain yield for the coarse soil. The highest transpiration and crop yield is calculated for the medium soil, which is against expectations. The reason is that in the fine and very fine soils the maximum amount of available soil moisture (between field capacity and wilting point) is higher but also the critical soil moisture content. This critical soil moisture content is the moisture content below which the transpiration rate, and thus also the photosynthesis rate, is reduced by water shortage (Supit et al., 1994). Hence, transpiration, biomass production and crop yield were reduced more strongly in the fine and very fine soils. The graphs of transpiration and TAGP show the same differences between the four soil types and runs.

Exercise 11:

Water-limited grain yield and water balance results for soil data file EC9.new should be identical to those of run WCC2 in exercise 10.

Exercise 12 :

Q12.1 Soil moisture is depleted strongest for the run with the shallowest roots (75cm) because these roots are not able to tap water from deeper soil layers. Moreover, the run with the largest DEPNR (4.5) represents the most drought insensitive crop. This variety can therefore continue with drawing water from the soil down to lower soil moisture levels.

Q12.2 Based on the simulated TAGP values, all three varieties with RDMCR of 75cm show a simulated value between 15000 and 16000 kg/ha and therefore the current experiment does not provide an answer with regard to the final value that DEPNR should take.

Q12.3 The variety with DEPNR 4.5 provides a grain yield of 1714 kg/ha and is the best estimate of DEPNR.

Annex C: 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, 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