



Food and Agriculture Organization
of the United Nations

Chapter 2

Users guide

AquaCrop
Version 6.0 – 6.1

Reference manual

May 2018

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By Dirk RAES, Pasquale STEDUTO, Theodore C. HSIAO and Elias FERERES with the contribution of the AquaCrop Network

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Chapter 1. AquaCrop – FAO crop-water productivity model to simulate yield response to water

Chapter 2. Users guide

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Chapter 3. Calculation procedures

Chapter 4. Calibration guidance

Chapter 5. Training videos

Annexes

I. Crop parameters

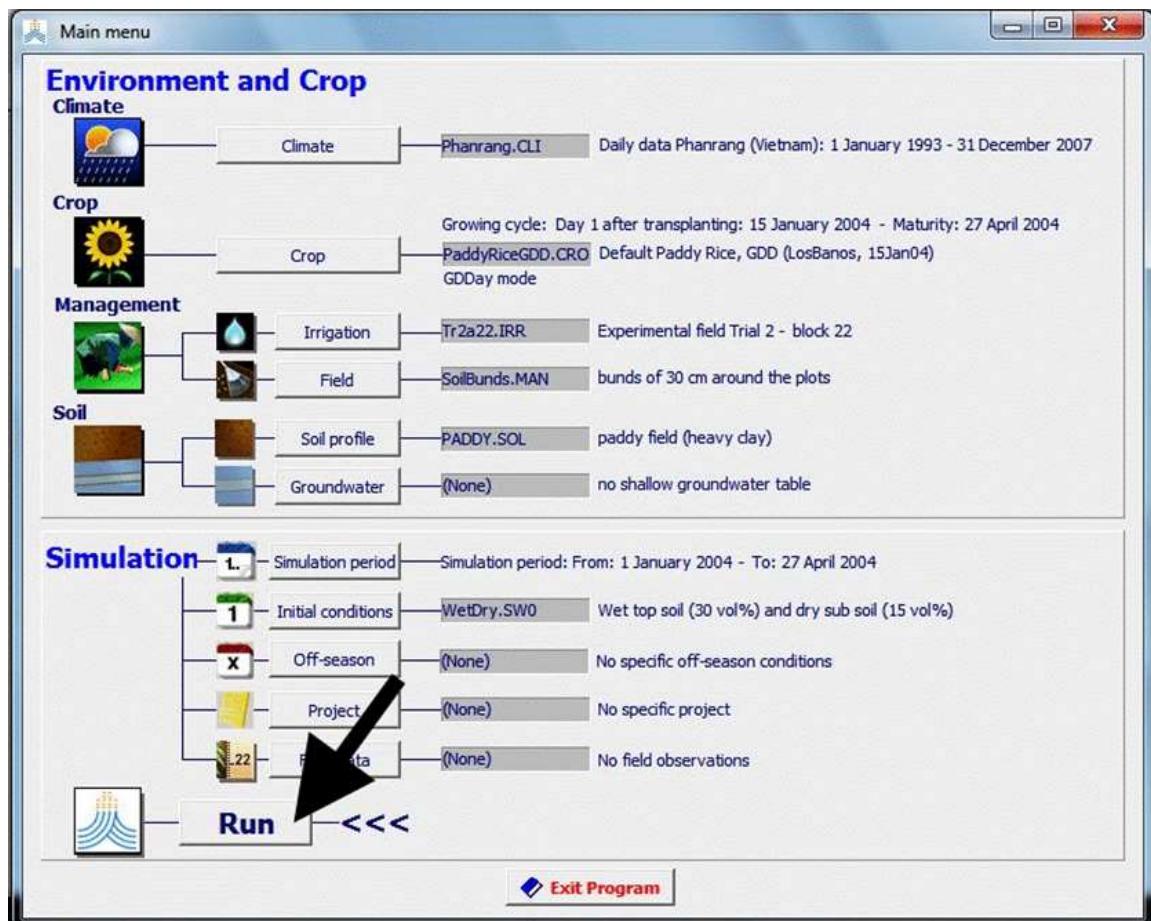
II. Indicative values for lengths of crop development stages

III. Indicative values for soil salinity tolerance for some agriculture crops

IV. ETo calculation procedure

Chapter 2. Users guide

Running AquaCrop



2.1 The AquaCrop environment

AquaCrop is a menu-driven program with a well-developed user interface. Windows (called menus) are the interface between the user and the program. Multiple graphs and schematic displays in the menus help the user to discern the consequences of input changes and to analyze the simulation results.

From the **Main menu** the user has access to a whole set of menus where input data is displayed and can be updated. Input consists of weather data, crop, irrigation and field management, soil and groundwater characteristics that define the environment in which the crop will develop. Also the sowing or planting day, the simulation period and conditions at the start of the simulation period are input. If the simulation period does not fully coincide with the growing cycle of the crop, off-season conditions valid outside the growing period, can be specified as well as input.

Before running a simulation, the user specifies in the **Main menu** the sowing date, the simulation period and the appropriate environmental, initial and off-season conditions. Input can be retrieved from input files. In the absence of input files, default settings are assumed (see 2.3 Default settings at start). The user can also select a project file containing all the required information for that run, and a field data file with measurements to assess simulation results.

When running a simulation the user can in the **Simulation run** menu track changes in soil water and salt content, and the corresponding changes in crop development, soil evaporation and transpiration rate, biomass production, yield development and water productivity. Simulation results are stored in output files and the data can be retrieved in spread sheet programs for further processing and analysis.

Program settings allow the user switching off calculation procedures, or altering default settings in AquaCrop. With the <Reset> command in the **Program Settings** menus, settings can be reset to their default.

2.2 Main menu

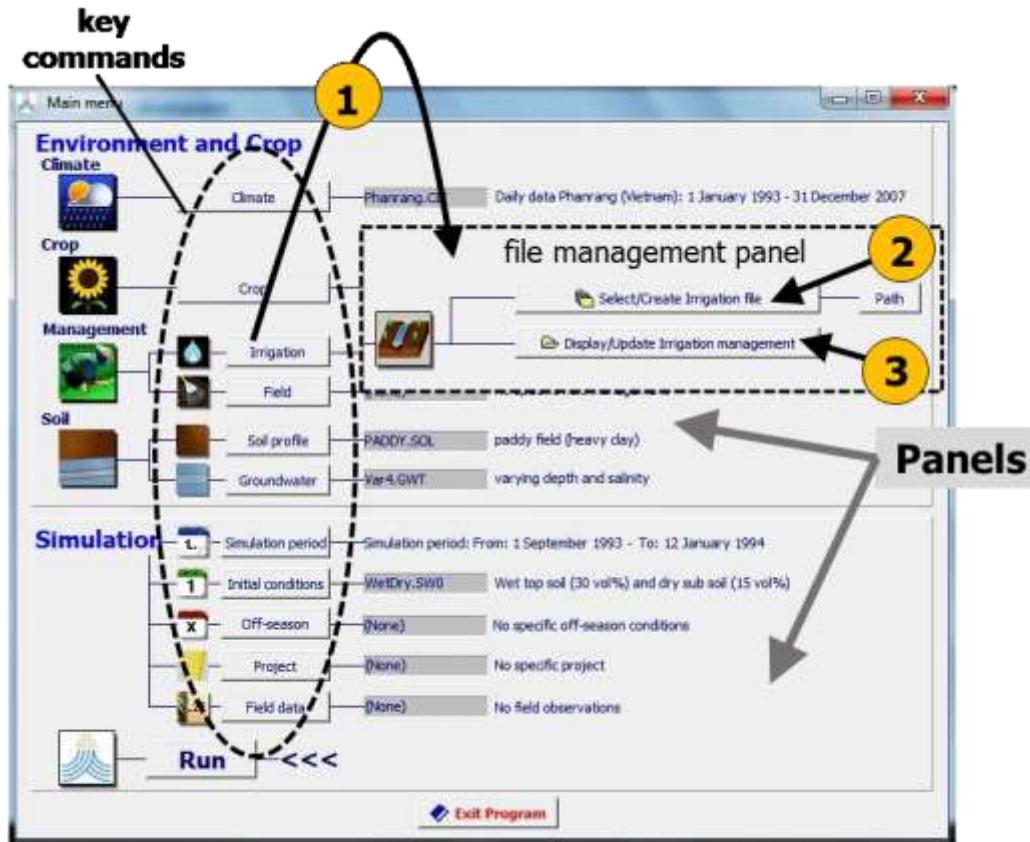


Figure 2.2 – *Main menu* of AquaCrop. By selecting (1) one of the key commands, the user gets access to the file management panel from which (2) files can be selected or created and (3) the input characteristics can be displayed and updated.

The **Main Menu** consists of 2 panels where the names and descriptions of the selected input files are displayed (Fig. 2.2):

- Environment and Crop panel:** where the user:
 - selects or creates **Climate**, **Crop**, **Irrigation** and **Field** management, **Soil profile** and **Groundwater** table files and displays or updates the corresponding characteristics;
 - specifies the start of the **growing cycle**;
- Simulation panel:** where the user:
 - specifies the **Simulation period**;
 - selects or creates **Initial conditions**, **Off-season** conditions, **Project** and **Field data** files, and displays or updates the corresponding characteristics;
 - **Run** a simulation for the specified environment, crop and simulation settings.

2.3 Default settings at start

2.3.1 Selected input

When AquaCrop is launched it selects a default crop and soil file. No other files (files are '(None)') are selected. In the absence of climate, irrigation management, field management, groundwater, initial and off-season conditions, and field data files, the default settings are assumed (Tab. 2.3).

Table 2.3. Default settings assumed at the start of AquaCrop or after undoing the selection of a project

| Environment | File | Remarks |
|--------------------------------|-------------|---|
| Climate | (None) | A default minimum and maximum air temperature (see Climate), an ETo of 5 mm/day, no rainfall and an average atmospheric CO ₂ concentration of 369.47 ppm are assumed throughout the growing cycle. When running a simulation without a climate file, the user has still the option to specify other than the default ETo and rainfall data. This climatic data can be specified for each day of the simulation period in the Input panel of the Simulation run menu |
| Crop | Default | Generic crop data |
| Irrigation management | (None) | Rainfed cropping is assumed. When running a simulation in this mode, irrigation can still be applied. The quality of the irrigation water and the irrigation application amount can be specified for each day of the simulation period in the Input panel of the Simulation run menu |
| Field management | (None) | No specific field management conditions are considered. It is assumed that soil fertility is unlimited, and that field surface practices does not affect soil evaporation or surface run-off |
| Soil | Default | Characteristics of a deep loamy soil |
| Groundwater | (None) | Absence of a shallow groundwater table |
| Simulation | File | Remarks |
| Period | | The simulation period covers the growing cycle completely |
| Initial conditions | (None) | At the start of the simulation it is assumed that in the soil profile (i) the soil water content is at field capacity and (ii) salts are absent |
| Off-season conditions | (None) | No specific field management conditions are considered outside the growing period. When running a simulation there are no irrigation events and mulches does not cover the field surface in the off-season |
| Project/ Field data | File | Remarks |
| Project | (None) | |
| Field data | (None) | |

The default input can be altered by selecting input files (see 2.4), by updating the default settings in the corresponding menus or by altering the characteristics retrieved from the input files (see 2.5), or by creating input files (see 2.6).

2.3.2 Program settings

2.4 Selecting input files and undoing the selection

By means of the <Select/Create> commands in the **Main menu** the user has access to data bases where the input files are stored (Fig. 2.4). The default data base is the DATA subdirectory of the AquaCrop folder. With the <Path> command the user can specify other directories.

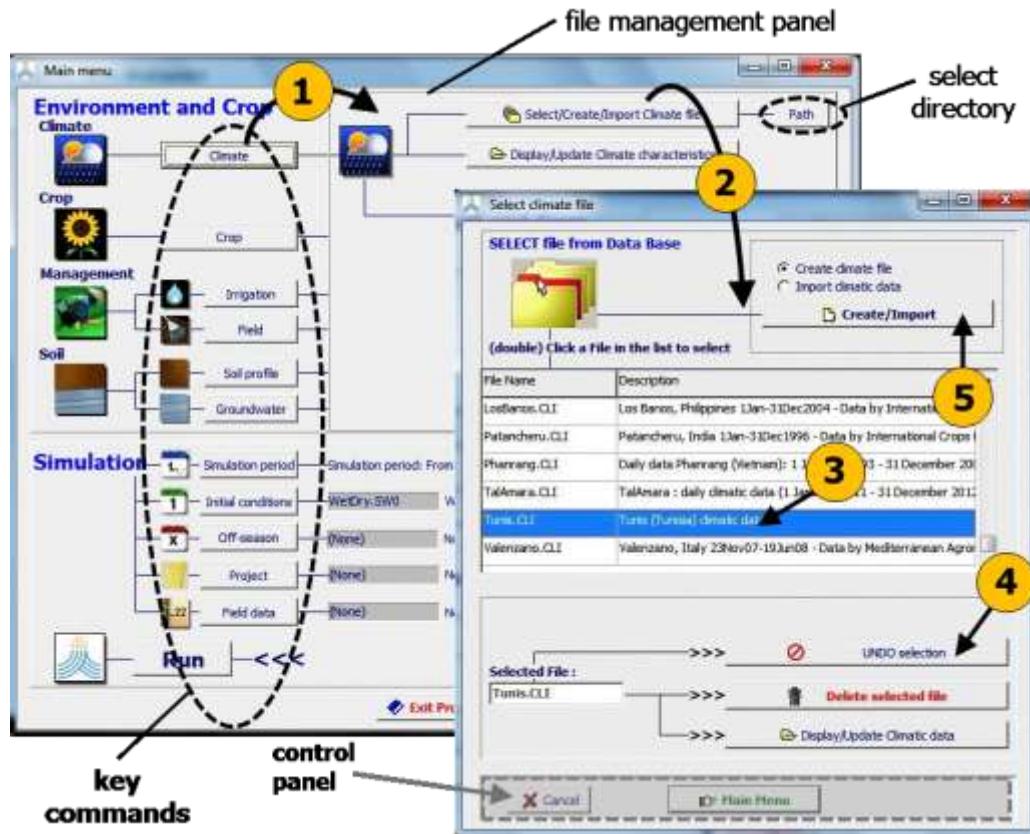


Figure 2.4 – By selecting (1) one of the key commands and subsequently (2) the corresponding <Select/Create> command in the file management panel in the **Main menu**, the user gets access to the *Select file* menus in which (3) one of the available files can be selected, (4) the selection can be undone, and (5) new files can be created.

2.4.1 Selecting a file

By clicking on the <Select> command in the **Main menu**, a list of the relevant input files available in the selected directory is displayed in one of the *Select file* menus (Fig. 2.4). An input file is selected by (double) clicking on its name in the list.

2.4.2 Undo the selection

When a climate, irrigation, field management, groundwater, initial conditions, off-season conditions, field data, or a project file has been selected, an option is available to undo the

selection and to return to the default settings (see 2.3). This is achieved by clicking on the <UNDO selection> command in the *Select file* menu (Fig. 2.4).

2.5 Displaying and updating input characteristics

2.5.1 Displaying input data

From the *Main menu* the user has access to a whole set of menus where input data are displayed (Fig. 2.5a). This is done by clicking on the file name or the corresponding icon in the *Main menu*.

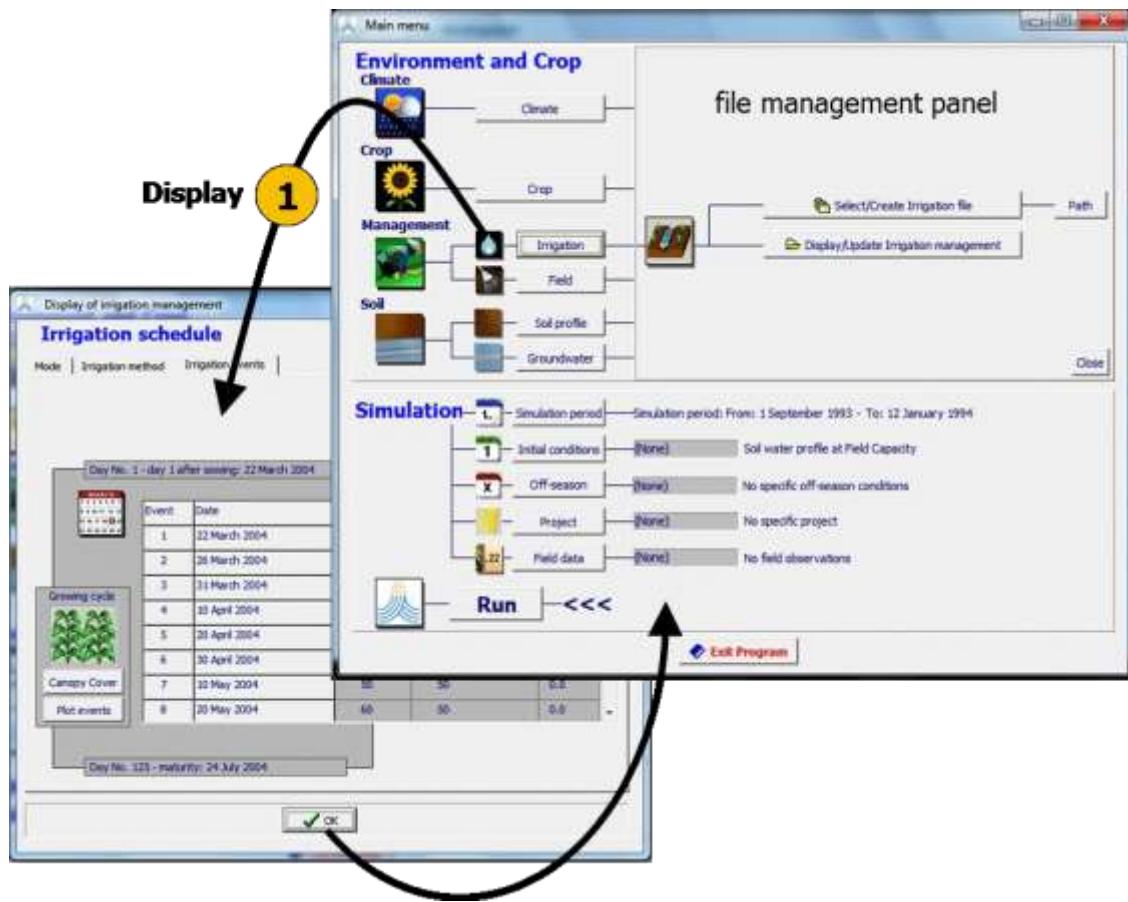


Figure 2.5a - By clicking on the Icons (or file names) in the *Main menu* the specified input data is displayed in a set of *Display* menus

2.5.2 Updating input data

From the **Main menu** the user has access to a set of menus where input data can be updated (Fig. 2.5b). This is done by first opening the access to the data base (click on the appropriate command in the **Main menu**) and by subsequently selecting the **<Display/Update characteristics>** command. In the menus the data can be updated and saved as default settings or in input files when returning to the **Main menu** (see 2.7 to exit and close a menu).

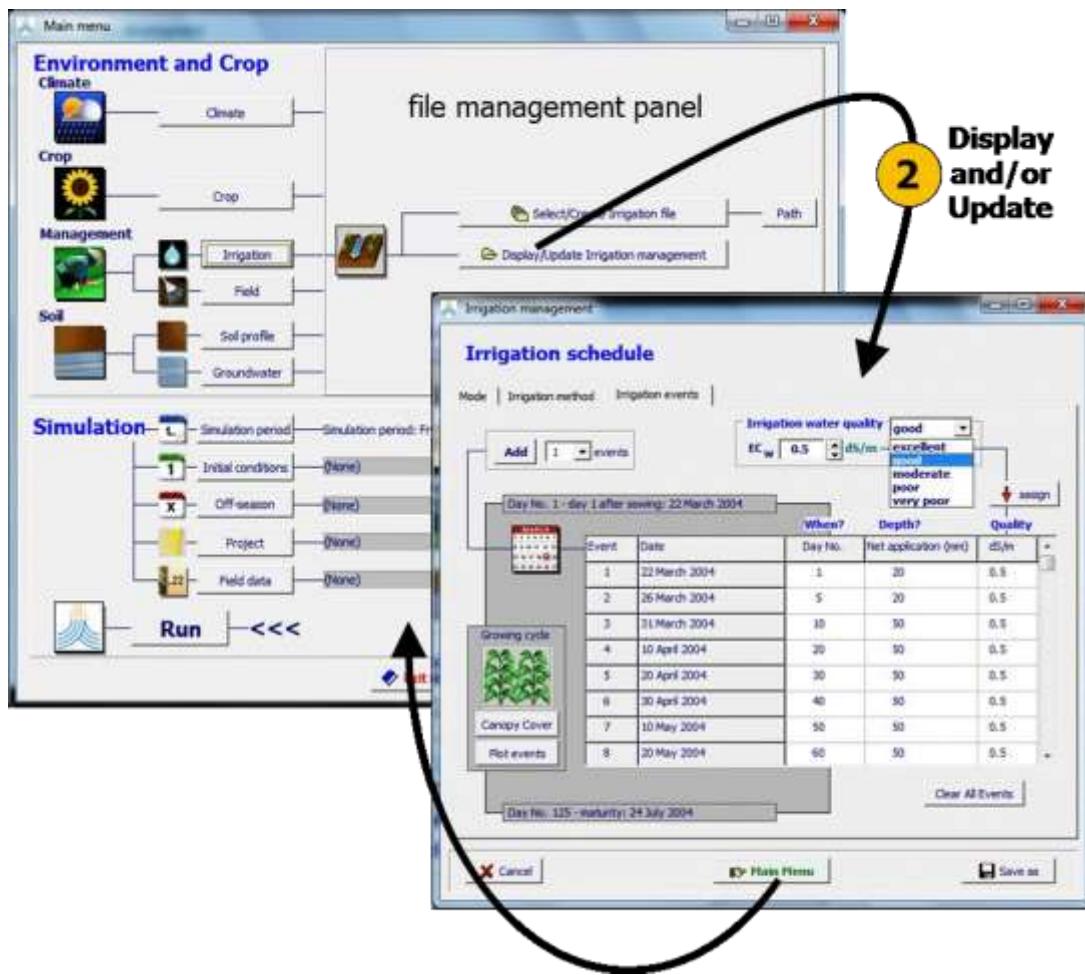


Figure 2.5b – Access to the *Irrigation management* menu where the displayed input data can be updated

In the Menu reference of this Chapter the Display/Update menus are described (sections 2.8 to 2.22).

2.6 Creating input files

2.6.1 The save on disk command

After updating the characteristics in one of the menus (see 2.5.2), an input file (if not yet available) is created by selecting the <Save on disk> command (Figure 2.6a).

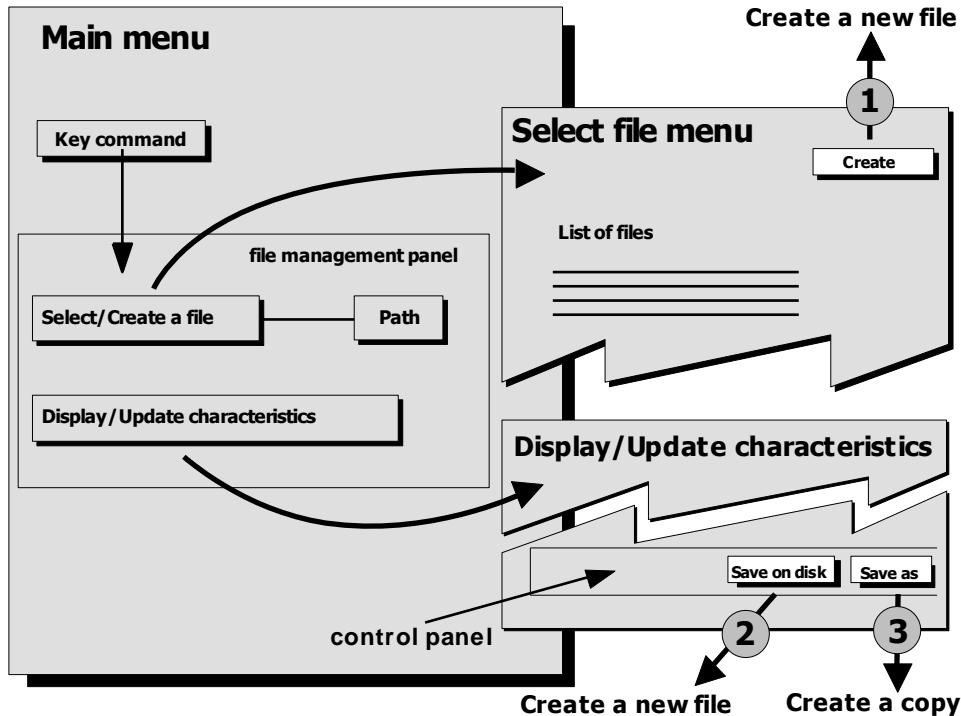


Figure 2.6a – Options to create a new file by selecting (1) the <Create> command at the top of the *Select file* menu, and (2) the <Save on disk> command (if the characteristics were not retrieved from a file) or (3) the <Save as> command (if the characteristics were retrieved from a file), in the control panel at the bottom of the *Display/Update* menu.

2.6.2 The save as command

If the displayed data in the characteristic menu was retrieved from an input file (Fig. 2.5b), a copy of the file will be created by clicking on the <Save as> command. This option allows the user to create various copies of a dataset which may differ only in one particular setting. This might be useful for the analysis of one or another effect on crop development or water productivity.

2.6.3 Create file

Create file menus are available to create input files for new climate, crop, irrigation and field management, soil profile, groundwater, initial conditions, field data or project data. The **Create file** menus becomes available by selecting the <Create file> command in the **Select file** menu (Fig. 2.6a).

- **Create climate file**

Creating a climate file consists in selecting or creating a Temperature file, ETo file, Rain file and CO₂ file (Fig. 2.6b)

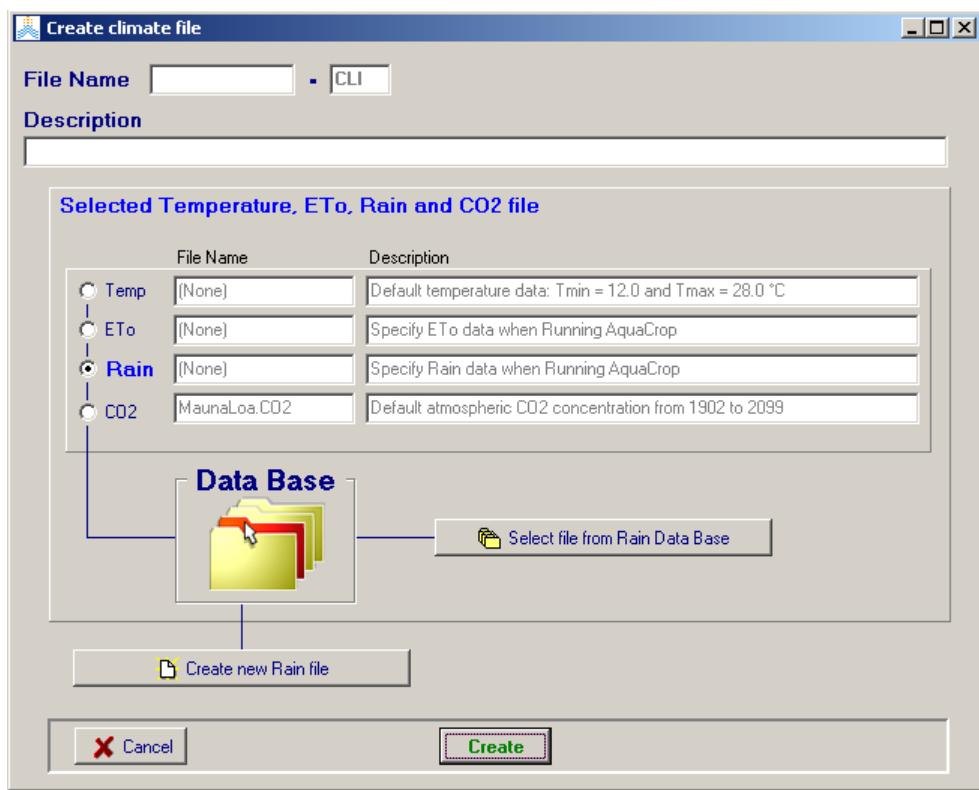


Figure 2.6b – *Create climate file* menu

- **Create/Import ETo, Rain or Temperature file**

When creating an ETo, Rain or Temperature file, the user has to specify the type of data (daily, 10-daily or monthly data), the time range and the data. Existing climatic data can be also pasted in an ETo, Rain, or Temperature file as long as the structure of the file is respected (see 2.23.2 Temperature, ETo and Rainfall files).

Air temperature data, rainfall data and/or other climatic data with which ETo can be calculated, can also be imported in AquaCrop. After importing the data, AquaCrop will create the corresponding files containing the climatic data (see section 2.9 Climatic data).

- **Create crop file**

When creating a crop file the users selects the crop type, indicates the planting method, and specifies a first indicative value for the cropping period and the length of the growing cycle (Fig. 2.6c). Subsequently AquaCrop generates the complete set of required crop parameters for the selected crop type. The crop type, which is fixed at the creation of the file, cannot be changed. The planting method, length of growing cycle, cropping period and all generated crop parameters can be adjusted in the *Crop characteristics* menu.

AquaCrop considers various crop types. Distinction is made between:

- Annuals:
 - Fruit/Grain producing crops (with a flowering period);
 - Leafy vegetable crops (flowering not considered);
 - Roots and tubers (with a root/tuber formation period);
- Perennials (Forage crops):
 - no dormancy
 - with dormancy

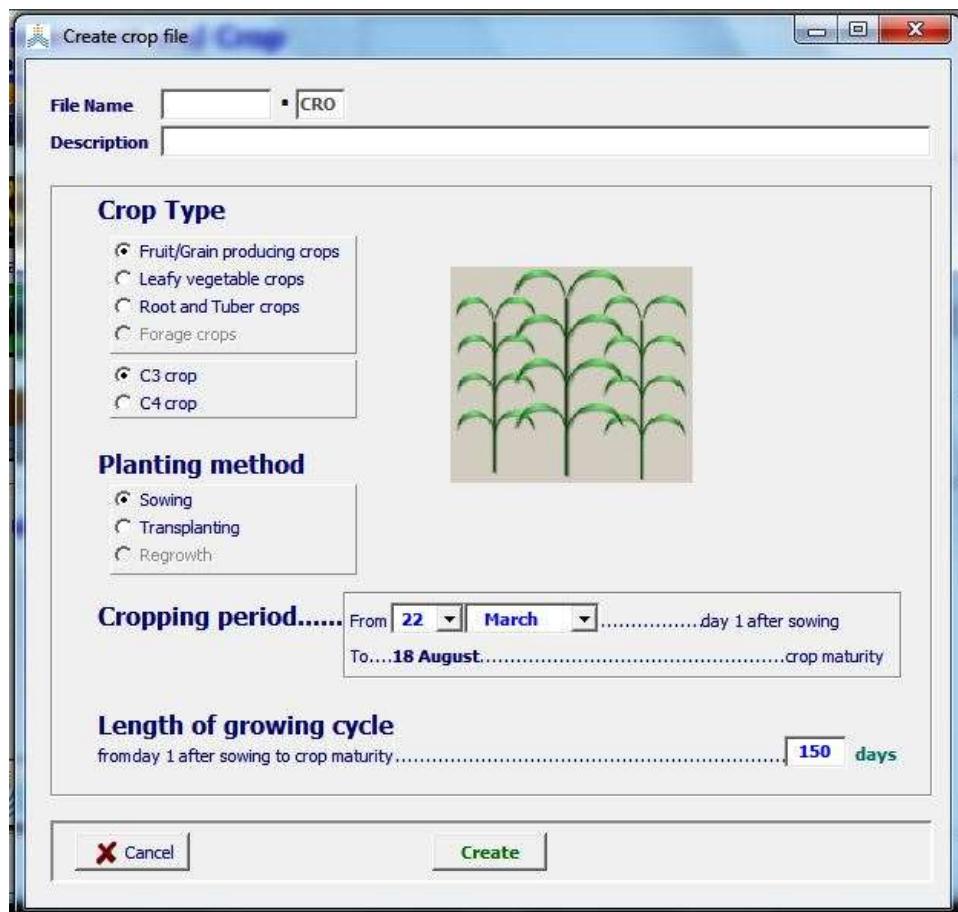


Figure 2.6c – Create crop file menu

- **Create irrigation file**

When creating an irrigation file, the type of file has first to be selected (Fig. 2.6d):

1. Net irrigation water requirement;
2. Irrigation schedule; or
3. Generation of irrigation schedule.



Figure 2.6d – Selection of the type of irrigation file that needs to be created

Subsequently the user specifies in the ***Create irrigation file*** the required information:

1. the allowable depletion when determining the net irrigation requirement;
2. the time, application depth and the irrigation water quality of the successive irrigation events of the irrigation schedule; or
3. the irrigation water quality, and the time and depth criteria to generate irrigation events.

The characteristics can be updated in the ***Irrigation management*** menu (see 2.12 Irrigation management).

- **Create field management file**

When creating a field management file, the user has to specify the degree of soil fertility, the presence of mulches, and field surface practices affecting surface runoff (Fig. 2.6e). With the help of this information AquaCrop generates the complete set of field management parameters. The parameters are displayed and the values can be adjusted in the ***Field management*** menu (see 2.13 Field management).

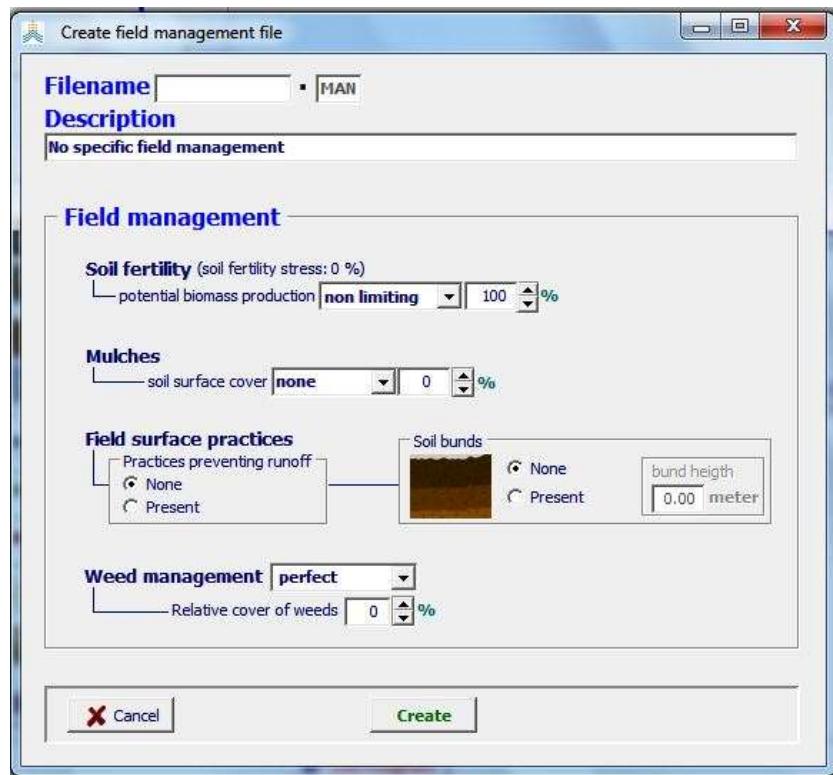


Figure 2.6e – Create field management menu

- **Create soil profile file**

When creating a soil profile file, the user has to specify only a few characteristics (Fig. 2.6f). With the help of this information AquaCrop generates the complete set of soil profile parameters. The parameters are displayed and the values can be adjusted in the ***Soil profile characteristics*** menu (see 2.14 Soil profile characteristics).

- **Create groundwater file**

When creating a groundwater file, the type of file has first to be selected (Fig. 2.6g):

1. Constant depth and water quality; or
2. Variable depth or water quality.

Subsequently the user specifies the depth and quality of the groundwater table for various moments (if variable) in the season in the ***Groundwater table characteristics*** menu (see 2.15 Groundwater table characteristics).

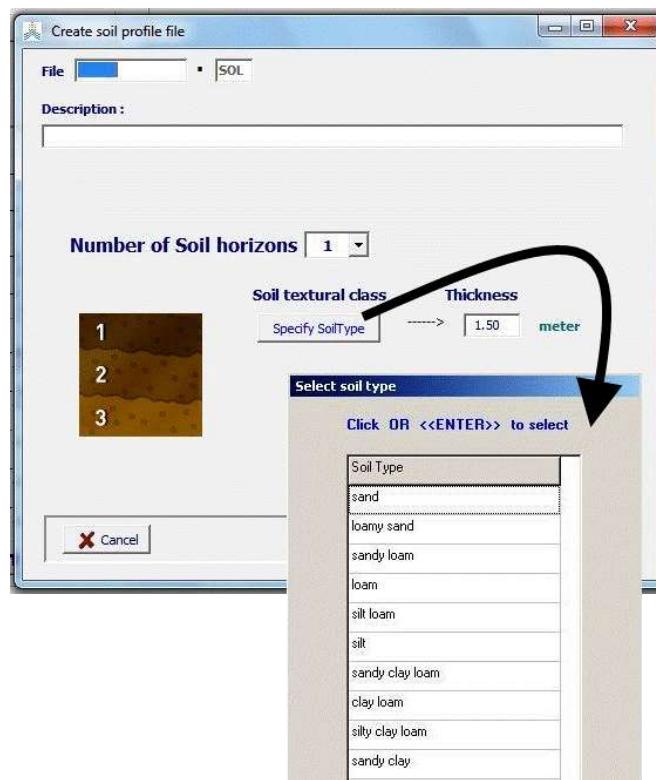


Figure 2.6f – *Create soil profile file* menu



Figure 2.6g – Selection of the type of groundwater file that needs to be created

- **Create initial conditions file**

When creating an initial conditions file, the user has to specify the soil water and salinity content, and the crop development and production at the first day of the selected simulation period. The parameters are displayed and the values can be adjusted in the ***Initial conditions*** menu (see 2.17 Initial conditions).

- **Create field data file**

When creating a field data file, the user specifies the experimental determined green canopy cover (CC), and/or the dry above-ground biomass (B), and/or the soil water content (SWC) observed in the field at particular dates in the ***Field Data*** menu (see 2.20 Field data).

- **Create project file**

When creating a project file, the type of file has first to be selected (see 2.19):

1. Single simulation run;
2. Successive years (multiple runs); or
3. Crop rotation (multiple runs).

Subsequently the user specifies the climate file, crop(s) file, irrigation and field management file, soil file, and selects the sowing or planting date(s), the simulation period and the corresponding initial and off-season conditions (see 2.19.3 Selecting and creating a project). The characteristics can be updated in the ***Project Characteristics*** menu (see 2.19.5 Updating project characteristics).

2.7 To exit and close a menu

Commands to exit a menu are available in the control panel at the bottom of each menu (Fig. 2.7). On exit, the window will be closed and the control is returned to the **Main menu**. The exit mode is determined by the selected command. The following options to exit a menu are generally available:

- **<Cancel>** All changes made to the input displayed in the menu are disregarded when returning to the **Main menu**;
- **<Return to Main menu>** Before returning to the **Main menu**, the program checks if data was changed or settings were altered in the menu. The changes will be saved if the user confirms to save the changes;
- **<Save on disk>** When data was not retrieved from an input file but consists of an update of the default settings, the user can select this option to save the data on disk before returning to the **Main menu**;
- **<Save as>** When data was retrieved from an input file, the user can select this option to save the data in a different file from which it was retrieved before returning to the **Main menu**.

By clicking on the “X” symbol at the upper right corner of a menu, the window is closed as well. This option is however not recommended since the exit mode cannot be specified.

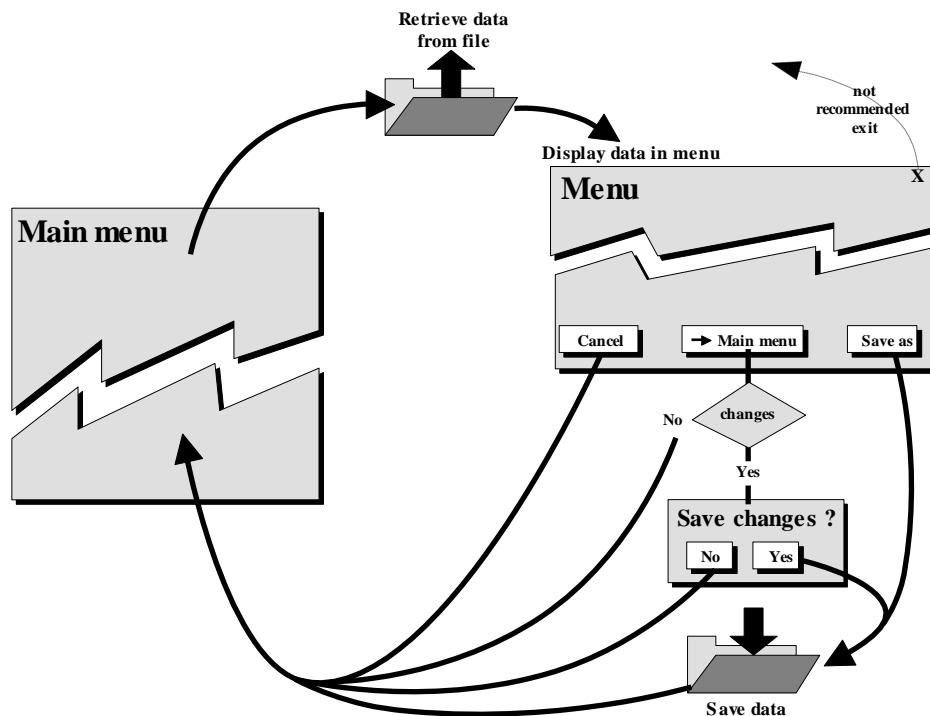


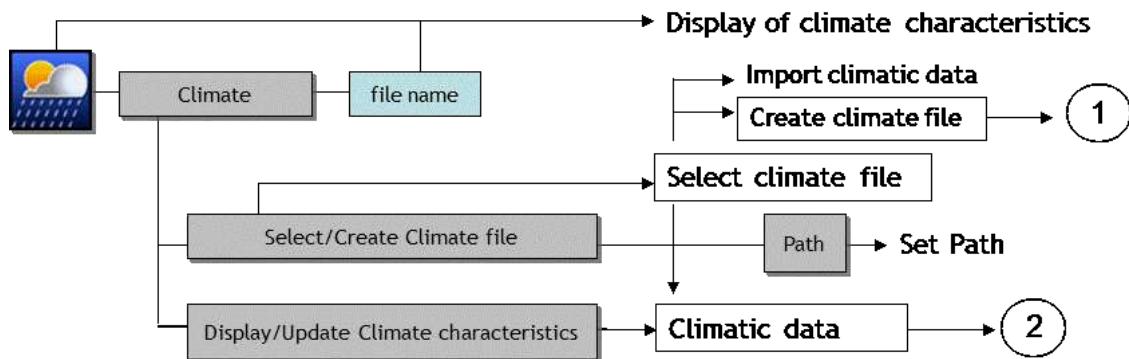
Figure 2.7 – Options to exit and close a menu

Menu reference

2.8 Hierarchical structure of the menus

2.8.1 Environment and Crop panel (Main menu)

▪ Climate



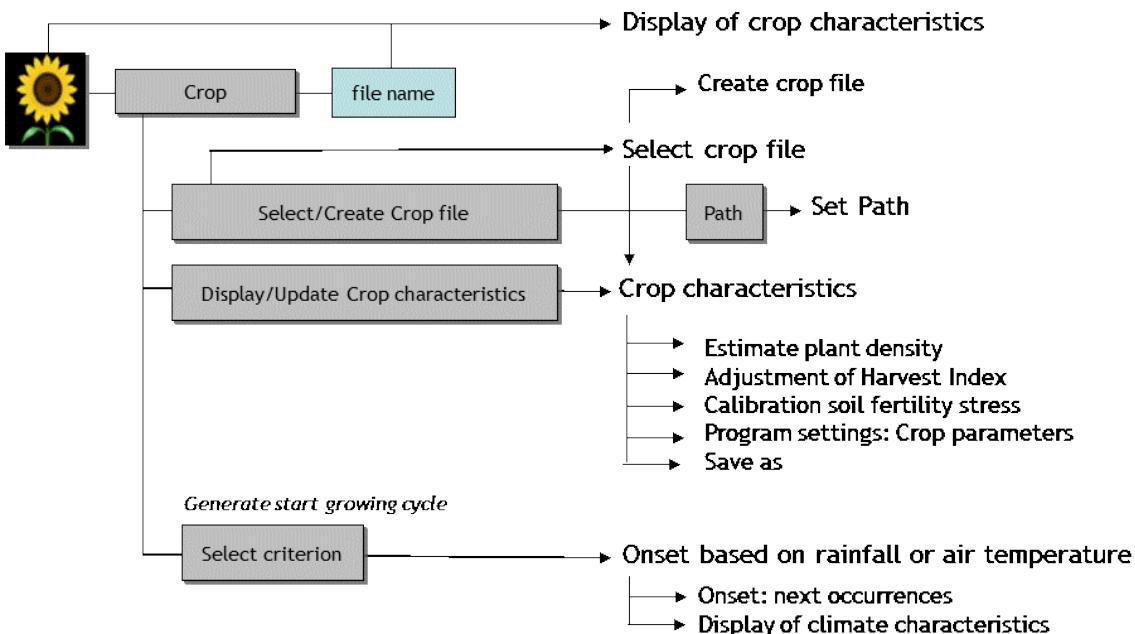
- 1) from the **Create climate file** menu the user gets access to:

- **Select temperature file** menu
- **Create temperature file** menu
- **Select ETo file** menu
- **Create ETo file** menu
- **Select rain file** menu
- **Create rain file** menu
- **Select CO2 file** menu

- 2) from the **Climatic data** menu the user gets access to:

- **Select rain file** menu
- **Display/update Rainfall data** menu
 - **Plot rain data** menu
- **Program settings: 10day or Monthly rainfall** menu
- **Select ETo file** menu
- **Display/update ETo data** menu
 - **Plot ETo data** menu
- **Select temperature file** menu
- **Display/update temperature data** menu
 - **Plot temperature data** menu
- **Program settings: Temperature parameters** menu
- **Select CO2 file** menu
- **Export aggregated climatic data** menu
- **Save as** menu

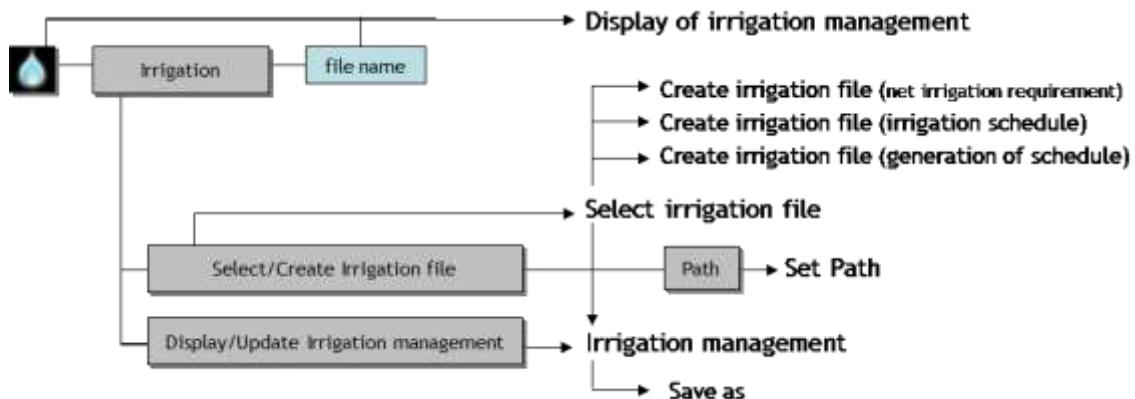
■ Crop



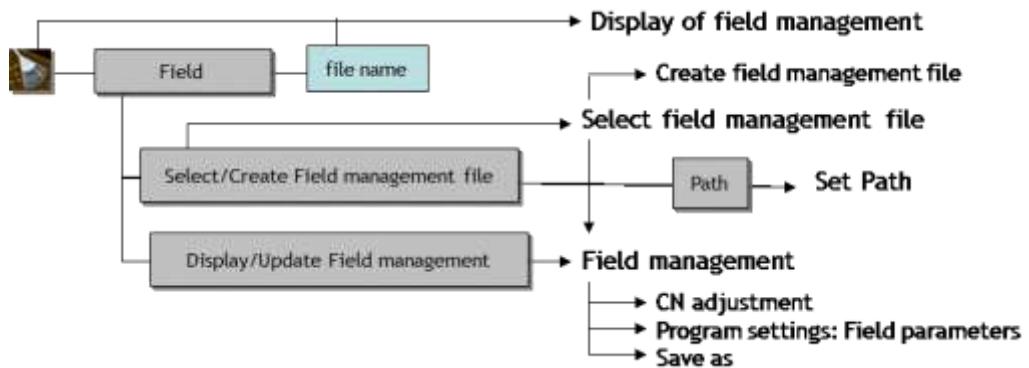
■ Management



- irrigation management



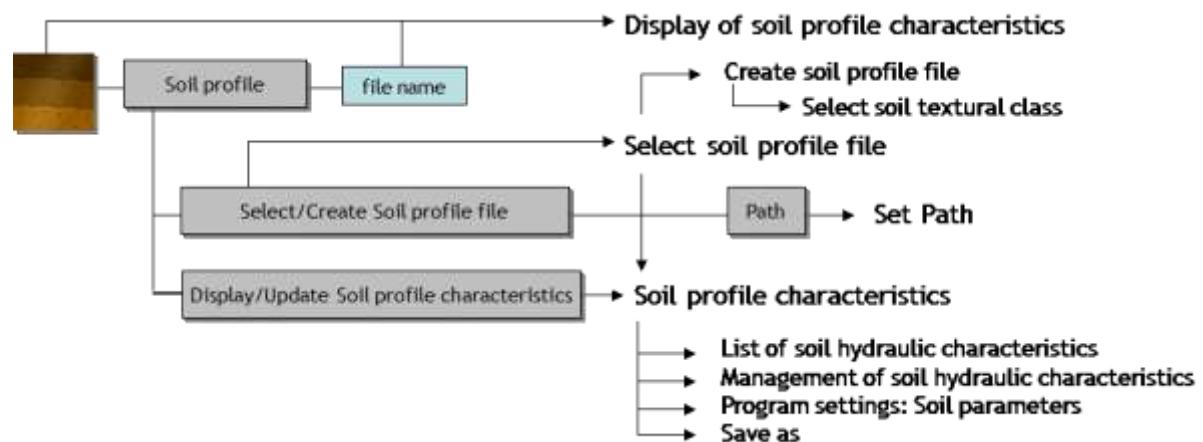
- field management



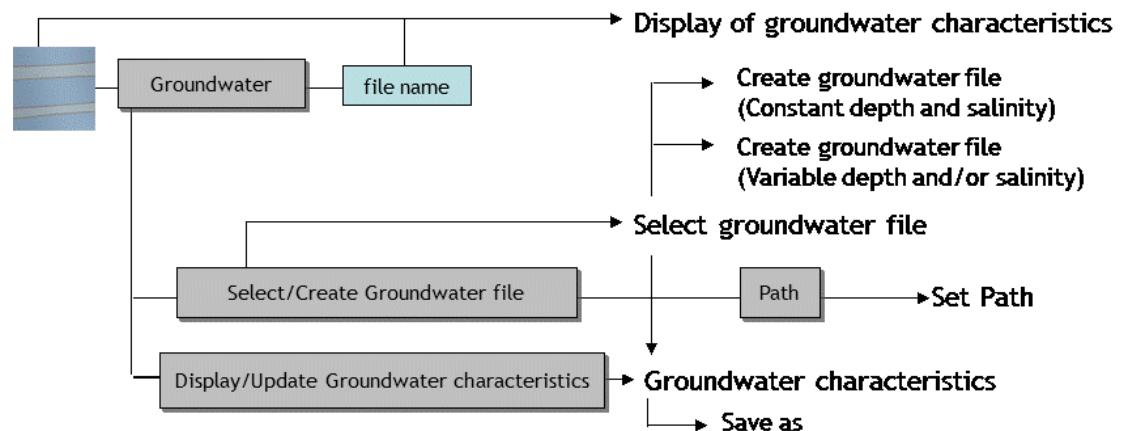
■ Soil



- soil profile

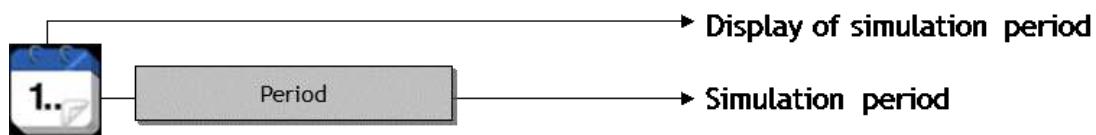


- groundwater

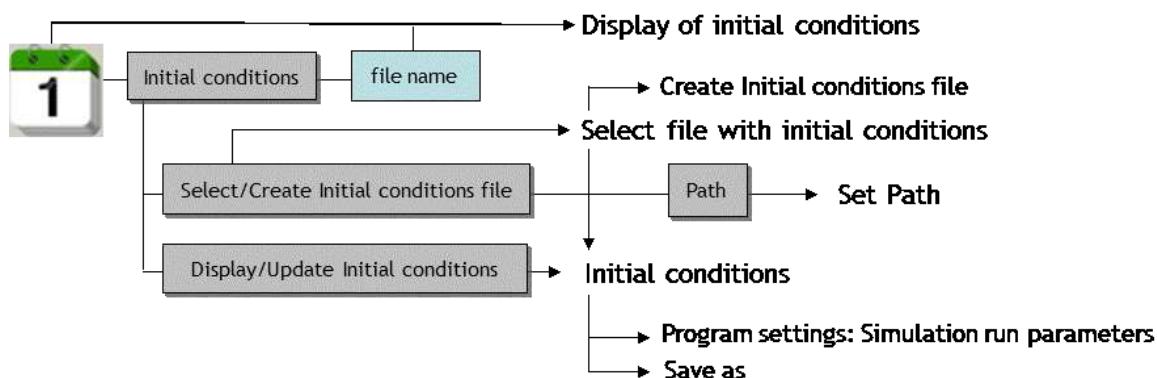


2.8.2 Simulation panel (Main menu)

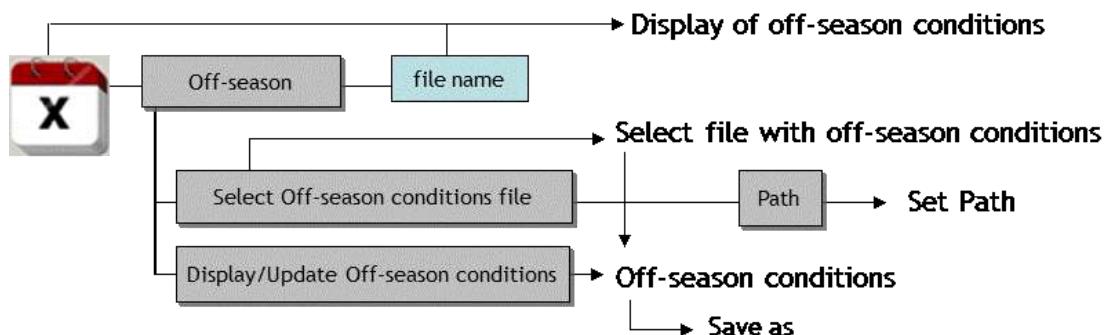
- **Simulation period**



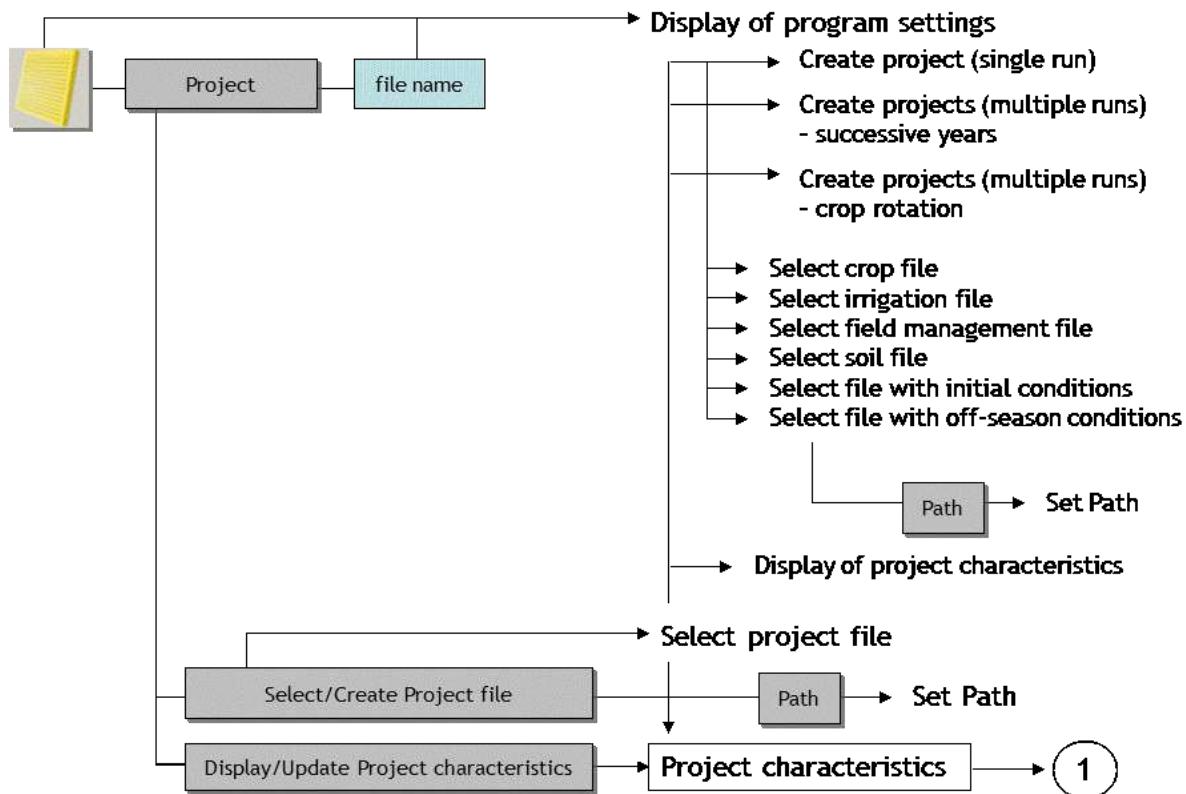
- **Initial conditions**



- **Off-season conditions**

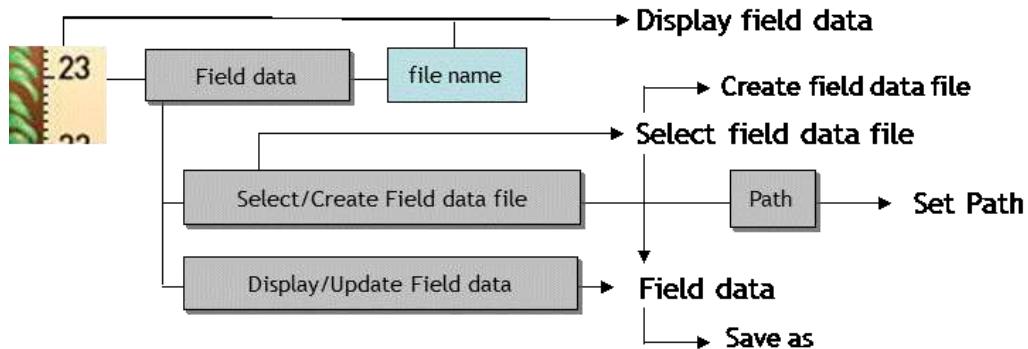


▪ **Project**

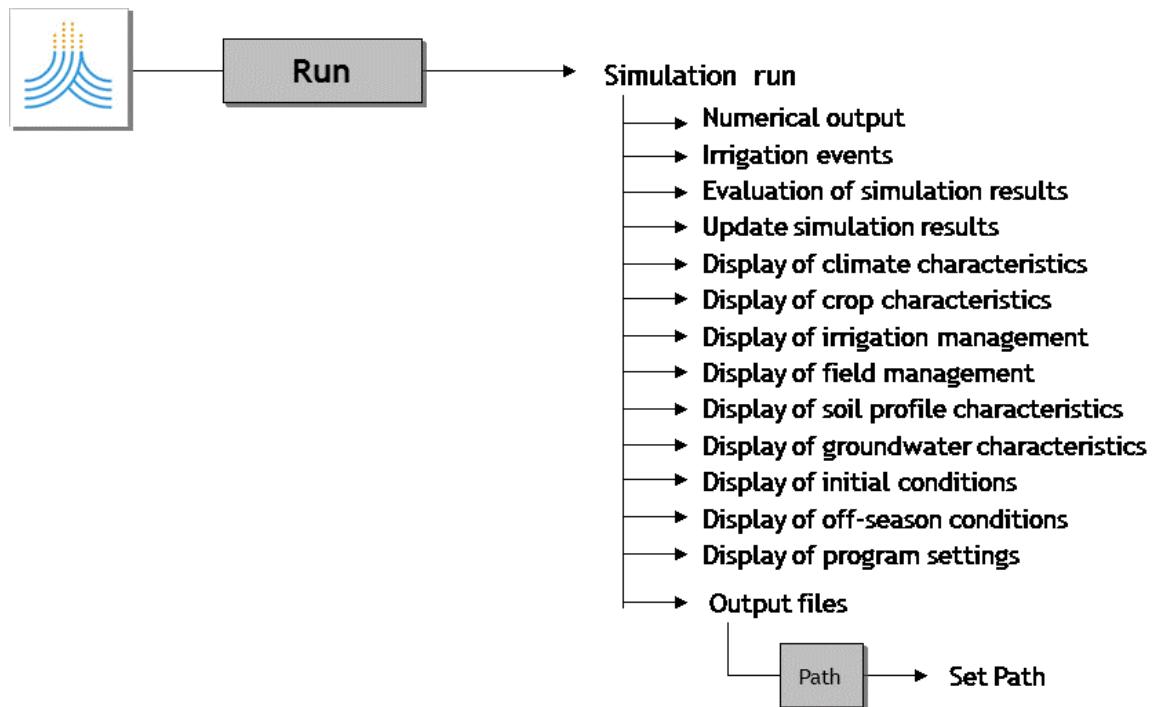


- 1) from the ***Project characteristics*** menu the user gets access to:
 - ***Display of climate characteristics*** menu
 - ***Display of crop characteristics*** menu
 - ***Select crop file*** menu
 - ***Display of irrigation characteristics*** menu
 - ***Select irrigation file*** menu
 - ***Display of field characteristics*** menu
 - ***Select field management file*** menu
 - ***Display of soil profile characteristics*** menu
 - ***Select soil file*** menu
 - ***Display of simulation period*** menu
 - ***Display of initial conditions*** menu
 - ***Select file with initial conditions*** menu
 - ***Display of off-season conditions*** menu
 - ***Select file with off-season conditions*** menu
 - ***Program settings: Crop parameters*** menu
 - ***Program settings: Field parameters*** menu
 - ***Program settings: Soil parameters*** menu
 - ***Program settings: Temperature parameters*** menu
 - ***Save as*** menu

▪ **Field data**



▪ **Run**



2.9 Climatic data

2.9.1 Climatic data required by AquaCrop

For each day of the simulation period, AquaCrop requires:

- the minimum (T_n) and maximum (T_x) air temperature,
- the reference evapotranspiration (ETo),
- the rainfall data, and
- the mean annual atmospheric CO_2 concentration.

The required climatic data are stored and retrieved from files:

- temperature files (files with extension ‘.Tnx’),
- ETo files (files with extension ‘.ETo’),
- rainfall files (files with extension ‘.PLU’) and
- CO_2 files (files with extension ‘.CO2’).

▪ Minimum and maximum air temperature

Temperature data are used to calculate growing degree day, which determines crop development and phenology (see 2.10), and also for making adjustment in crop transpiration during cold periods (see 2.10). In the absence of daily data, the input may also consists of 10-day or monthly data and the program uses an interpolation procedure to obtain daily temperature from the 10-day or monthly means.

The daily minimum air temperature (T_n) and the daily maximum air temperature (T_x) are, respectively the minimum and maximum air temperature observed during the 24-hour period, beginning at midnight. T_n and T_x for 10-day’s or months are the average of the daily values.

▪ Reference evapotranspiration (ETo)

The reference evapotranspiration, denoted as ETo , is used in AquaCrop as a measure of evaporative demand of the atmosphere. It is the evapotranspiration rate from a reference surface, not short of water. A large uniform grass (or alfalfa) field is considered worldwide as the reference surface. The reference crop completely covers the soil, is kept short, well watered and is actively growing under optimal agronomic conditions.

ETo can be derived from weather station data by means of the FAO Penman-Monteith equation, and an ETo calculator is integrated for that purpose in AquaCrop (see 2.9.2). The data from a weather station can be specified in a wide variety of units. The meteorological data can be imported, and procedures are available to estimate missing climatic data.

In the absence of daily data, the input may also consists of 10-day or monthly data and the program uses an interpolation procedure to obtain daily ETo from the 10-day or monthly means.

▪ Rainfall

The rainfall is the amount of water collected in rain gauges installed on the field or recorded at a nearby weather station. For rainfall, with its extremely heterogeneous distribution over time, the use of long-term mean data is not recommended. In case no daily rainfall data is available, 10-day and monthly data can be used as input.

- **Mean annual atmospheric CO₂**

AquaCrop considers 369.47 parts per million by volume as the reference. It is the average atmospheric CO₂ concentration for the year 2000 measured at Mauna Loa Observatory in Hawaii. Other CO₂ concentrations will alter canopy expansion and crop water productivity (Chapter 3 of the Reference Manual). AquaCrop uses as default the data from the MaunaLoa.CO2 (stored in the SIMUL subdirectory) which contains the mean annual atmospheric CO₂ concentration measured at Mauna Loa Observatory for historical years and for future estimates an increase of 2.0 ppm is assumed (following Pieter Hans (NOAA) - personal communication, December 2007). Other CO₂ files, containing data from alternative sources, can be selected in AquaCrop. When creating CO₂ files it is important to respect the file structure (see 2.23).

- **Covering climate file**

A covering climate file (file with extension ‘.CLI’) contains the names of the Tnx, ETo, PLU and CO2 file (Fig. 2.9a). The climatic data itself is stored in the Tnx, ETo, PLU and CO2 files. The selected climatic data can be displayed in the *Display of climate characteristics* menu and updated in the *Climatic data* menu (see 2.9.5).

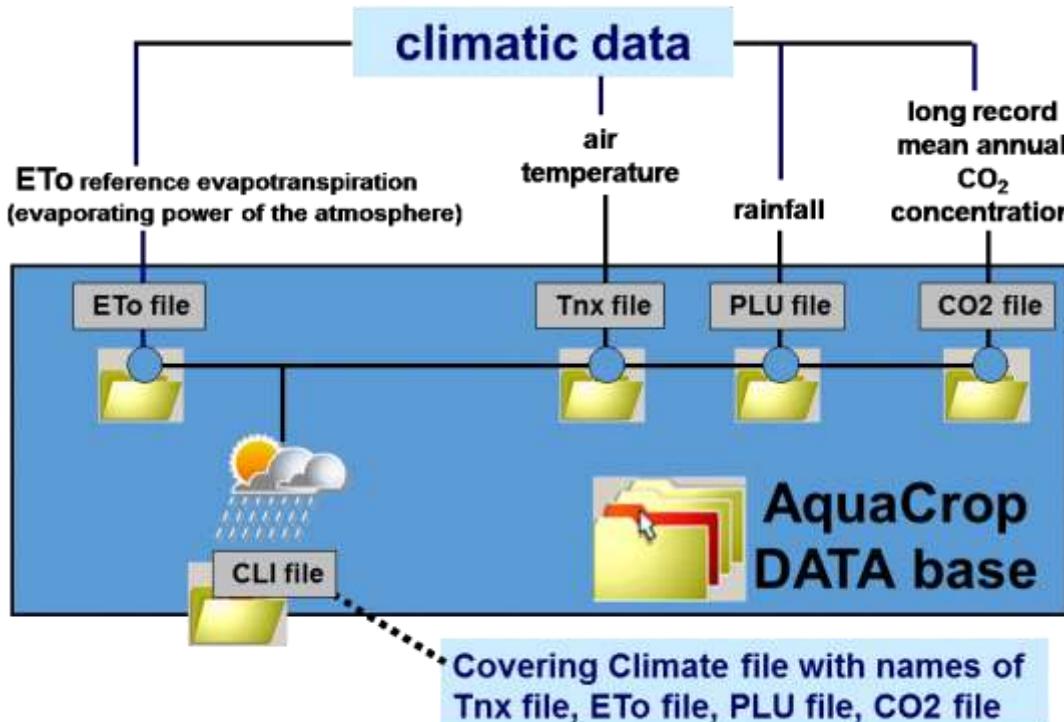


Figure 2.9a – Climate files (*.CLI) and files with climatic data (*.ETo, *.Tnx, *.PLU, *.CO2) available in AquaCrop data base

2.9.2 Creating air temperature, ETo and rainfall files

- Text files with climatic data

In the *Select climate file* menu, the user has the option to ‘Import climatic data’ from a text file (Fig. 2.9b1).

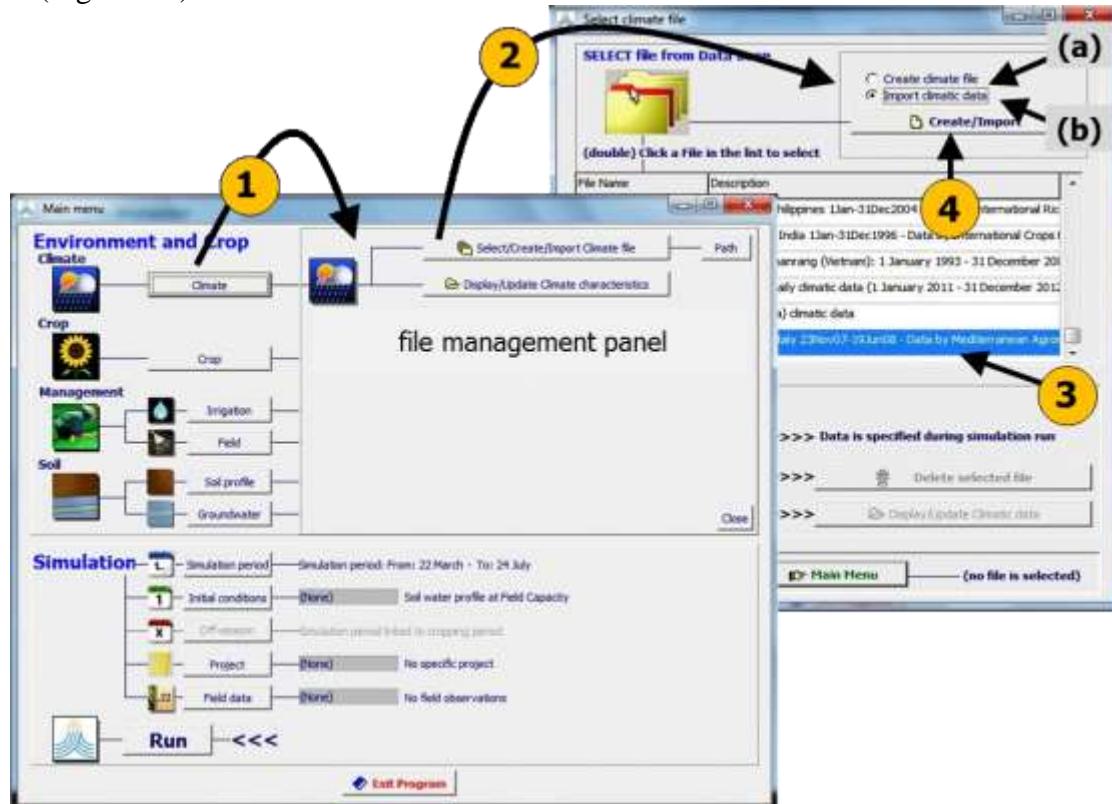


Figure 2.9b1 – By selecting (1) the <Climate> command and subsequently (2) the <Select/Create Climate file> command in the file management panel in the *Main menu*, the user gets access to the *Select climatic file* menu, in which (3) one of the available CLI files, or (4) the command (a) to <Create a climate file> (new CLI file) or (b) to <Import climatic data> (by creating air temperature, ETo and/or rainfall files) is selected

Type of data

Data that can be imported, consist of air temperature, ETo, or rainfall data, and/or other climatic data with which ETo can be calculated. By importing the data, AquaCrop will create the corresponding files containing the climatic data (files with extension ‘.Tnx’, ‘.ETo’ and/or ‘.PLU’). Data of climatic parameters, expressed in one of the units listed in Table 2.9b1, can be imported by AquaCrop.

Free format text files with climatic data (files with extension ‘.txt’)

The text file is a file with extension ‘.txt’ (as created by Notepad), in which climatic data for a specific time range are saved in columns (example in Tab. 2.9b2). It is typically a copy from a spreadsheet but contains only the numerical values: no headings, units, line numbers, or dates!

Table 2.9b1 – Climatic parameters and units recognized by AquaCrop for import

| Climatic parameter and Symbol | Possible units |
|---|---|
| Air temperature data | |
| Maximum air temperature (Tmax) | °C or °F |
| Mean air temperature (Tmean) | °C or °F |
| Minimum air temperature (Tmin) | °C or °F |
| Air Humidity data | |
| Maximum Relative Humidity (RHmax) | % |
| Mean Relative Humidity (RHmean) | % |
| Minimum Relative Humidity (RHmin) | % |
| Dewpoint temperature (Tdew) | °C or °F |
| Actual vapour pressure: e(act) | kPa, mbar, psi, atm or mmHG |
| Temperature of dry bulb (Tdry) | °C or °F |
| Temperature of wet bulb (Twet) | °C or °F |
| Wind speed data | |
| Wind speed at x m above soil surface: u(x) | m/sec, km/day, knot or ft/sec |
| Radiation and sunshine data | |
| Actual duration of sunshine in a day (n) | hour |
| Relative sunshine duration (n/N) | - |
| Solar or shortwave radiation (Rs) | MJ/m ² .day, W/m ² , J/cm ² .day, mm/day, cal/cm ² .day |
| Net radiation (Rn) | MJ/m ² .day, W/m ² , J/cm ² .day, mm/day, cal/cm ² .day |
| ET₀, Reference crop evapotranspiration | |
| Direct import of reference crop evapotranspiration (ET ₀) | mm/day |
| Rainfall data | |
| Rainfall (Rain) | mm or inch |

Table 2.9.b2 - Example of a text file containing climatic data. It consists of daily data, which are (column 1) rainfall in mm, (column 2) minimum and (column 3) maximum air temperature in °C, (column 4) hours of bright sunshine in hours/day, and (column 5) wind speed in m/sec

| | | | | |
|------|------|------|------|-----|
| 0 | 18 | 30 | 6.5 | 4.2 |
| 0 | 19 | 29.7 | 5.8 | 2.9 |
| 55.6 | 16.8 | 29.4 | 5.5 | 2.5 |
| 2.2 | 15.5 | 26.2 | 2.7 | 2.7 |
| 0 | 14.5 | 28.9 | 9.4 | 1.1 |
| 0 | 11.3 | 30.2 | 10.2 | 1.3 |
| 0 | 12.7 | 31.2 | 11 | 1.4 |
| 0 | 15.1 | 33.4 | 10.7 | 1.5 |
| 0 | 15.7 | 34.8 | 10.7 | 1.8 |

The file may contain daily, 10-daily or monthly climatic data. The text file consists of climatic data recorded in a specific time range (ranging from a few days up to several years) or of calculated averages for a number of years. Missing data has to be identified by a specific value. The default, which is -999.000, can be altered in the ‘Climatic parameter’ tabular-sheet of the ***Import climatic data*** menu (Fig. 2.9b4). The text file has lines and columns:

- Lines: There are as many lines (rows) as day’s, 10-day’s or months in the imported time range. Each line contains the climatic data (or average) for only one day, 10-day or month of the time range, and this in successive order;
- Columns: The text file can contain up to 10 columns. Each column contains the data of one of the climatic parameters listed in Table 2.9b1.

■ Importing climatic data

The ***Import climatic data*** menu contains 5 tabular sheets (Fig. 2.9b2);

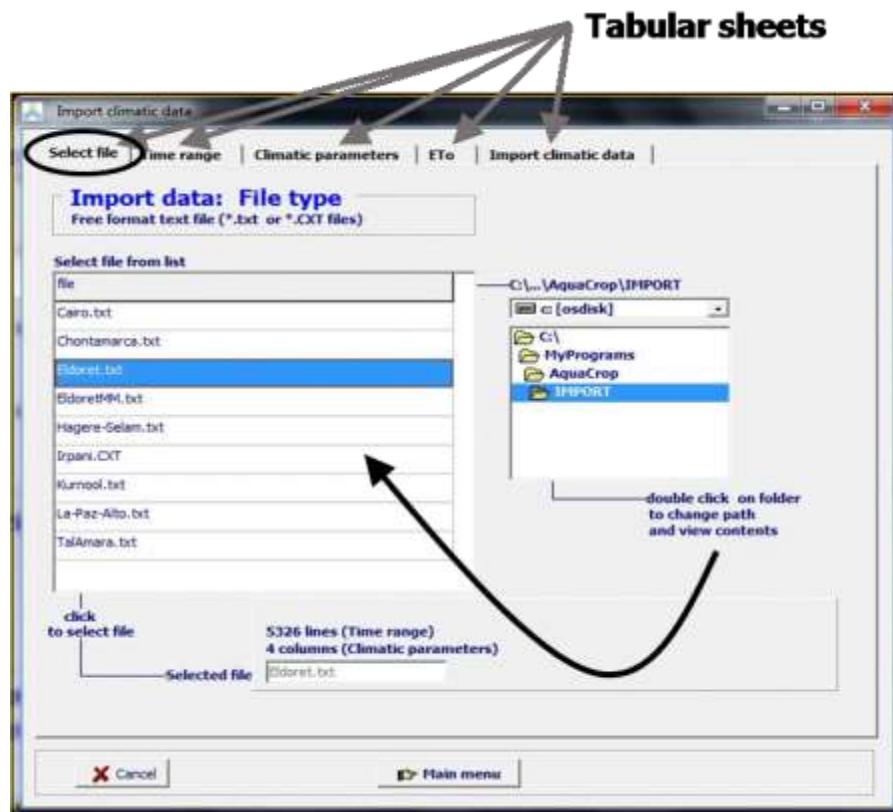


Figure 2.9b2 – Import climatic data menu with its tabular sheets: ‘Select file’ (displayed), ‘Time range’, ‘Climatic parameters’, ‘ETo’, and ‘Import climatic data’

- ‘**Select file**’: to select the text file, containing the climatic data to be imported;
- ‘**Time range**’: to specify the time range of the imported climatic data (lines in text file);
- ‘**Climatic parameters**’: to specify the climatic parameters and their units of the imported data (columns of text file);

- ‘**ETo**’: to specify coefficients for ETo calculation (if relevant);
- ‘**Import climatic data**’: to create ‘.Tnx’, ‘.ETo’, and/or ‘.PLU’ files (containing the imported climatic data), and to save the created file(s) in the AquaCrop data base.

Tabular sheet: ‘Select file’

In the tabular sheet ‘Select file’ (Fig. 2.9b2) the user selects the text file containing the climatic data. All text files (files with extension ‘.txt’ or ‘.CXT’) stored in the IMPORT sub directory of the AquaCrop folder are listed. By altering the path, the user can retrieve text files from other directories. Once a text file has been selected, the program displays the number of:

- Data lines (rows), which corresponds with the number of days, 10-day’s or months in the time range (from-to) covering the climatic data;
- Columns of the text file, which corresponds with the number of climatic parameters available in the text file.

In the example (Fig. 2.9b2), the ‘Eldoret.txt’ file has been selected, which contains 5,326 lines and 4 columns with climatic data (i.e. a long record of daily (minimum, maximum and average) air temperature and rainfall data for several years). The time range and climatic parameters are specified respectively in the ‘Time range’ and ‘Climatic parameters’ tabular sheets.

Tabular sheet: ‘Time range’

In the tabular sheet ‘Time range’ (Fig. 2.9b3), the user specifies the Type of data (daily, 10-daily or monthly) and the Time range (from date - to date). If the climatic data consists of averages of several years, the data should not be linked to a specific year and the year has not to be specified.

By adjusting the time range in the tabular sheet, the program displays the corresponding number of data records within this range. The number of records should match with the number of rows of the text file containing the meteorological data. For the example of the selected ‘Eldoret.txt’ file with its 5,326 lines in Fig. 2.9b2, there are indeed 5,326 days between the specified start (1 January 1999) and end (31 July 2013) of the time range (Fig. 2.9b3).

If the number of records does not match with the number of rows in the text file, a warning (‘Adjust time range’) is displayed and the climatic data cannot be imported.

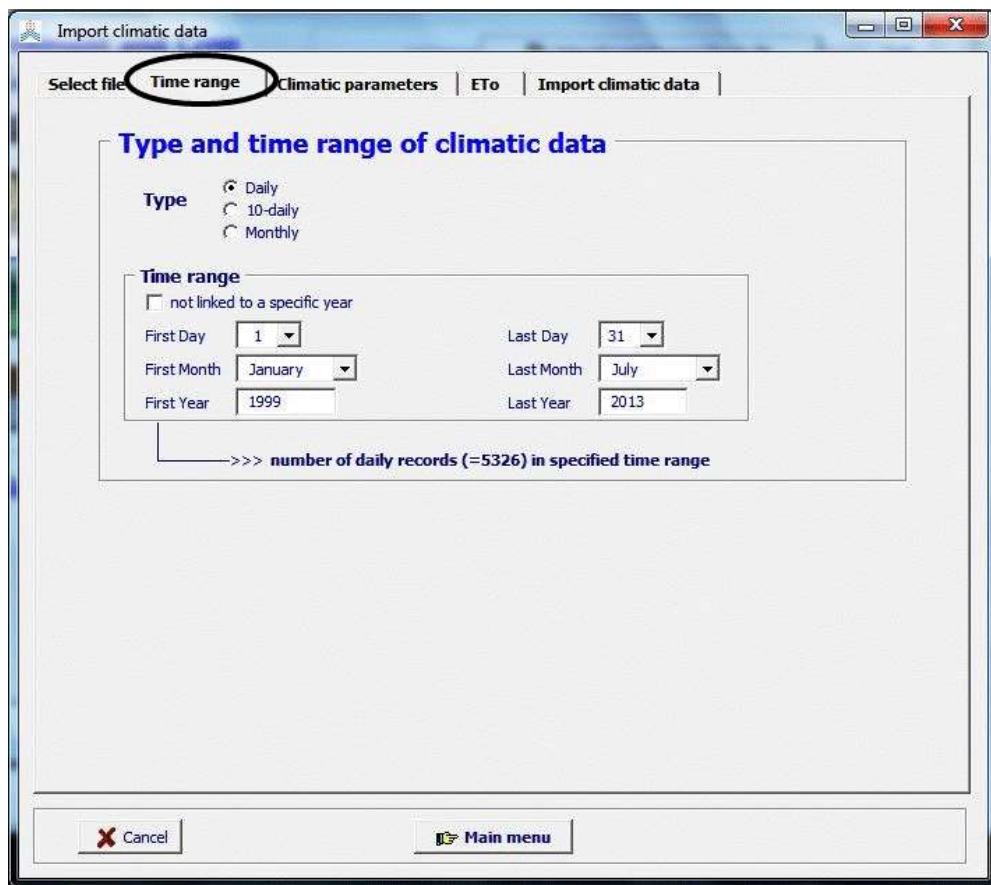


Figure 2.9b3 – The ‘Time range’ tabular sheet of the *Import climatic data* menu: for ‘Eldoret.txt’ (containing a long record of daily temperature and rainfall data)

Tabular sheet: ‘Climatic parameters’

In the tabular sheet ‘Climatic parameters’ (Fig. 2.9b4) the user specifies the climatic parameters and its units (the data stored in the columns).

By selecting one of the column numbers, a list pops up containing the climatic parameters which are recognized by AquaCrop (Tab. 2.9b1). The parameters are stored in 6 tabular sheets grouping them in ‘air Temperature’, ‘air Humidity’, ‘Wind speed’, ‘Sunshine/Radiation’, ‘ETo’, and ‘Rain’ data. An additional seventh folder ‘None’ is available, to specify that the column contains irrelevant data. The data in the column will be disregarded and is not available for import.

When a climatic parameter is specified for a column, the program displays:

- **Symbol, Unit** and program **Code** for the selected climatic parameter;
- Number of **Missing data** in each of the columns of the text file. The default value (-999.000) for undefined value will be used to identify missing data. The default value can be adjusted to the undefined value used in the specific text file. Procedures are available in AquaCrop to estimate ETo with missing air humidity, radiation, sunshine and/or wind speed data. Such procedures are not available to estimate missing

minimum and maximum air temperature data, rainfall data and directly imported ETo data. Hence, records with missing Tmax, Tmin, Rain and ETo data cannot be imported if they contain missing values;

- **Data range** (minimum and maximum value) for the selected climatic parameter as found in the text file. These should be within the program limits. If the program limits are smaller than the detected data range the data cannot be imported by the program;
- **Program limits** (upper and lower limit) used by the program for each of the selected climatic parameters. This feature allows for a range check of the imported data. If the user believes that the program limits are too narrow or too broad set, the user can alter the limits in the **Limits of climatic data** menu (Fig. 2.9b7). This menu is displayed by clicking on the <Update Data Range> command key at the bottom of the ‘Climatic parameters’ tabular sheet.

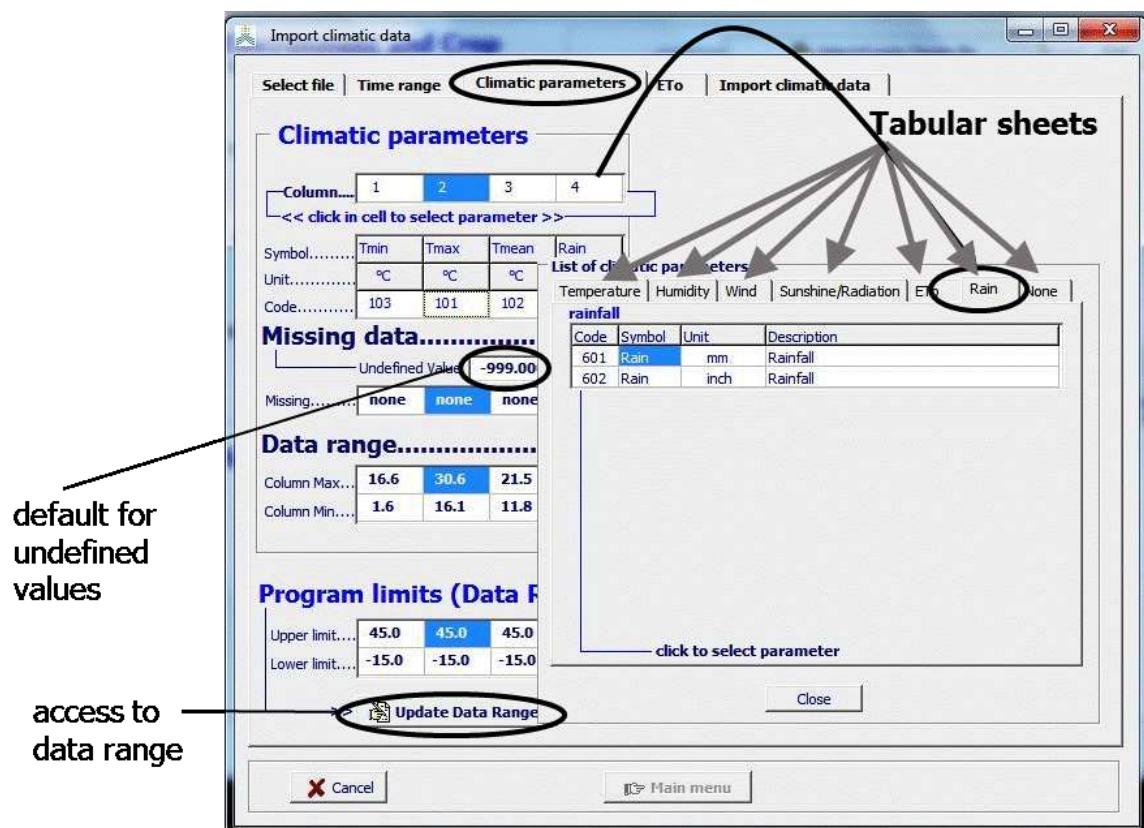


Figure 2.9b4 – The ‘Climatic parameters’ tabular sheet of the *Import climatic data* menu for ‘Eldoret.txt’ (containing a long record of daily temperature (minimum, maximum and average) and rainfall data)

Tabular sheet: ‘ETo’

If sufficient data is available to calculate ETo with the imported climatic data, information about its calculation and data required for its calculation, are specified in the tabular sheet ‘ETo’ (Fig. 2.9b5). It consists of:

- **Coordinates of Meteorological station** (Altitude and Latitude). They are required for the calculation of the psychrometric constant (γ), extra-terrestrial radiation (Ra) and

maximum hours of bright sunshine or day length (N). As long as the Altitude and Latitude are identical to their default settings (i.e. 222 m.a.s.l. and 22°22' N), a warning to ‘adjust the coordinates’ is displayed and the climatic data cannot be imported for ETo calculation;

- **Climatic data considered for ETo calculation.** ETo is calculated with the FAO Penman-Monteith method according to the calculation procedures outlined in the FAO Irrigation and Drainage paper Nr. 56 (Allen et al. 1998). The calculation procedures are presented in Annex IV. To compute ETo, (i) air temperature, (ii) air humidity, (iii) radiation and (iv) wind speed data are required. The data considered for its calculation are displayed. For the example in Fig. 2.6 (for ‘Eldoret.txt’, a text file containing a long record of daily temperature and rainfall data), only Tmin and Tmax are available (columns 1 and 2). The required vapour pressure will be estimated from Tmin, and the required solar radiation, will be estimated from the (Tmax-Tmin) difference. For wind speed, the specified average wind speed value will be used;
- **Coefficients required to estimate ETo when solar radiation, wind speed and/or air humidity data are missing.** Calculation procedures as outlined in the FAO Irrigation and Drainage paper Nr. 56 are used to estimate missing radiation, wind speed and air humidity data. Default values can be assigned to the coefficients by specifying the ‘Location’ of the meteorological station by means of the radio buttons (Fig. 2.9b5). The calculation procedures consist of:
 - Temperature difference method (using the square root of the difference between the maximum and minimum air temperature) to estimate **missing solar radiation** (Rs). The adjustment coefficient (k_{Rs}) is empirical and differs for ‘interior’ or ‘coastal’ regions. In the absence of a calibrated k_{Rs} value, the default value can be used by selecting the appropriate radio button for the location of the meteorological station (Tab. 2.9b3);
 - Selecting a general class of average wind speed, for **missing wind speed**. Enter a general value in the ‘Edit’ field or select an appropriate radio button for the location of the meteorological station (Tab. 2.9b3);
 - Estimating the actual vapour pressure, by assuming that dewpoint temperature (T_{dew}) is near the daily minimum air temperature (Tmin). This method can be used where **humidity data are lacking** or are of questionable quality. The relationships $T_{dew} \approx Tmin$ holds for humid and sub-humid locations. For arid regions, the air might not be saturated when its temperature is at its minimum. In these situations, T_{dew} might be better approximated by subtracting 2 up to 3°C from Tmin. In the absence of a calibration, the default values for the region can be used by selecting the appropriate radio button for the location of the meteorological station (Tab. 2.9b3).
- **Coefficients of the Angstrom formula** for the calculation of solar radiation if different from the default setting. When net radiation (Rn) is not specified, AquaCrop uses the Angstrom formula to estimate incoming solar radiation (Rs). When no calibration has been carried out for improved ‘a’ and ‘b’ constants of the formula, the default values (a = 0.25 and b = 0.50) are recommended. To estimate outgoing long wave radiation the ratio between the incoming solar radiation (Rs) and the clear sky solar radiation (Rso) is required. The adjustment for station elevation in the calculation of Rso, is

recommended in the absence of calibrated ‘a’ and ‘b’. If calibrated values for ‘a’ and ‘b’ are available they can be specified (Fig. 2.9b5).

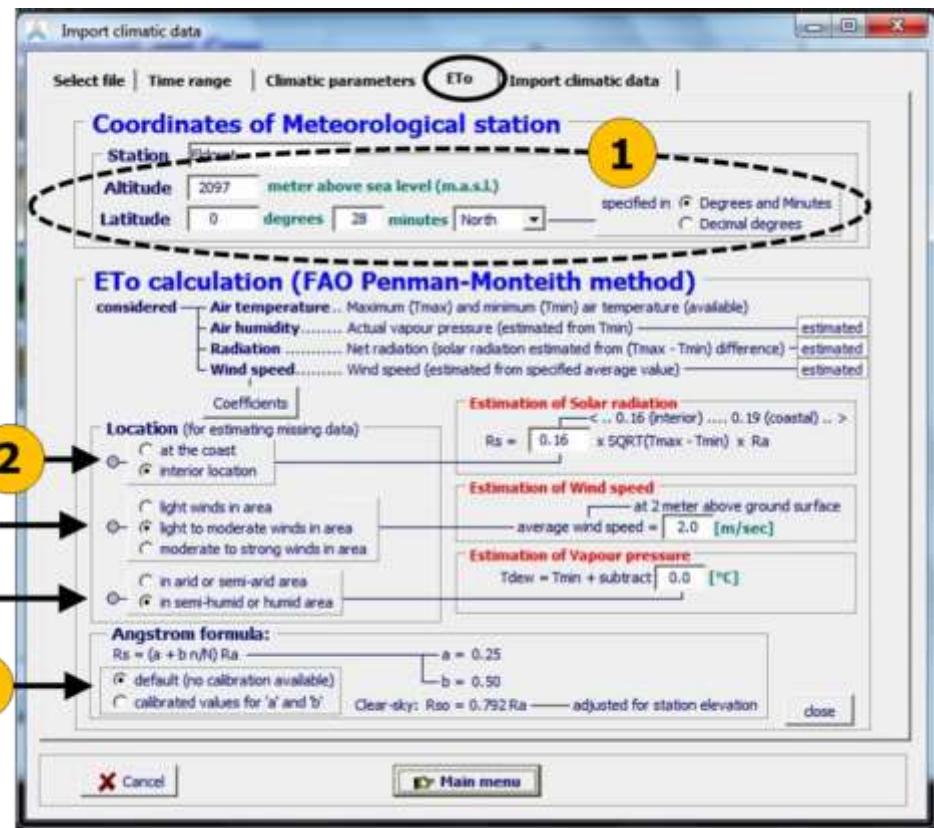


Figure 2.9b5 – The ‘ETo’ tabular sheet of the *Import climatic data* menu for ‘Eldoret.txt’ (containing a long record of daily temperature and rainfall data), with (1) specification of the coordinates; choices made for estimating missing (2) solar radiation, (3) wind speed, and (4) vapour pressure; and (5) values for coefficients of the Angstrom formula

Table 2.9b3 – Default values for estimating missing climatic data

| Missing parameter | Location of meteo-station | Default values | |
|--|--|---|-------------------------------|
| Solar radiation (Rs) | - at the coast - interior location | $k_{Rs} = 0.19$ $k_{Rs} = 0.16$ | temperature difference method |
| Wind speed at 2 meter above ground surface (u_2) | - light winds - light to moderate winds - moderate to strong winds | $u_2 = 0.5 \text{ m/sec}$ $u_2 = 2.0 \text{ m/sec}$ $u_2 = 4.0 \text{ m/sec}$ | |
| Vapour pressure: dewpoint temperature | - in arid or semi-arid area - in semi-humid or humid area | $T_{dew} \approx T_{min} - 2^\circ\text{C}$ $T_{dew} \approx T_{min}$ | |

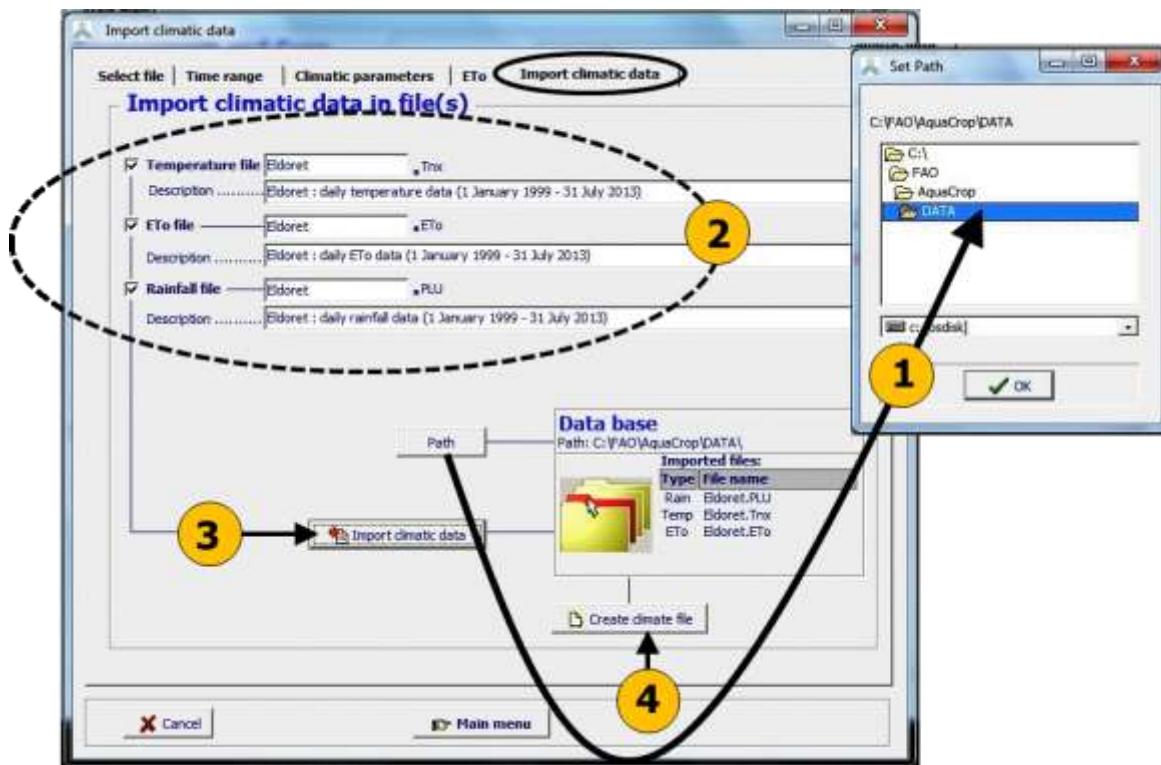


Figure 2.9b6 – The ‘Import climatic data’ tabular sheet of the *Import climatic data* menu for ‘Eldoret.txt’ (containing a long record of daily temperature and rainfall data), with specification of (1) folder, and (2) names and description of files with climatic data. By selecting (3) the <Import climatic data> command the climatic data is imported in the required format, and (4) a covering climate file can be created.

Tabular sheet: ‘Import climatic data’

In the tabular sheet ‘Import climatic data’ (Fig. 2.9b6), the user can adjust:

- Folder in which the files with climatic data needs to be stored. By selecting the <Path> command, the user can alter the directory from its default path which is the ‘DATA’ subdirectory of the AquaCrop folder;
- Default file names and description for Temperature (file with extension ‘.Tnx’), ETo (extension ‘.ETo’), and Rainfall (extension ‘.PLU’) files. These files can only be created if (i) the Time range is well set, (ii) sufficient climatic data is available, (iii) the climatic data is within the program limits, and (iv) the coordinates of the meteorological station are adjusted (only required when ETo is calculated);
- Default file name and description for the covering climate file (extension ‘.CLI’). A covering climate file can only be created if a ‘Tnx’, ‘ETo’ and ‘PLU’ file are created (as is the case for ‘Eldoret.txt’, Fig. 2.9b6);
- By selecting the <Content> command for the covering climate file, the additional required name of the CO₂ file can be adjusted from its default (MaunaLoa.CO₂).

For the example in Fig. 2.9b6, for ‘Eldoret.txt’ (a text file containing a long record of daily temperature and rainfall data): a **temperature file** (‘Eldoret.Tnx’ containing the imported daily Tmin and Tmax values), an **ETo file** (‘Eldoret.ETo’ containing calculated daily ETo

estimates), and a **rainfall file** ('Eldoret.PLU' containing the imported daily rainfall data) can be created and are selected for creation. Since a Tnx, ETo, as well as a PLU file are available, the option to create a **covering climate file** ('Eldoret.CLI') is available and is selected for creation with the default MaunaLoa.CO2 file.

By selecting the <Create file(s)> command, the selected files (with the imported data) are created, and stored in the specified folder (default is the data base 'DATA' of AquaCrop).

- **Data range**

The **Limits of climatic data** menu (Fig. 2.9b7) contains the data range (lower and upper limit) assigned by the program to the various climatic parameters that can be imported (Tab. 2.9b4). The following limits can be adjusted to obtain a more refined or flexible range check of the imported data:

- **Upper limit for rainfall data.** The upper limit for rainfall data differs with the type of rainfall data (daily, 10-daily or monthly values).
- **Limits for air temperature, relative humidity and vapour pressure.** Since these limits are linked, changing the limits for one parameter will alter the limits for the linked climatic parameters.
- **Upper limit for wind speed.** Daily, 10-daily and monthly wind speed are always expressed as the average daily value.
- **Upper limits for sunshine and radiation data.** The upper limits are determined by the latitude of the station and the time of the year. However a degree of over-estimation, that the user still finds acceptable, is allowed. The latitude and altitude are specified in the 'ETo' tabular sheet of the **Import climatic data** menu (Fig. 2.9b5).
- **Upper limit for direct imported ETo values.** Daily, 10-daily and monthly ETo are always expressed in AquaCrop as the average daily value.

Table 2.9b4 – Defaults for range check of climatic data

| Climatic parameter | Lower limit | Upper limit |
|--|-------------|---|
| Total rainfall | 0 mm | 300 mm/day 1,000 mm/10-day 2,000 mm/month |
| Air temperature | -15 °C | + 45 °C |
| Relative humidity | 15 % | 100% |
| Average daily wind speed | 0 m/sec | 8 m/sec |
| Deviation from maximum possible daily radiation (given by latitude and time of year) | 0 % | 5 % |
| Average daily ETo | 0 mm/day | 10 mm/day |

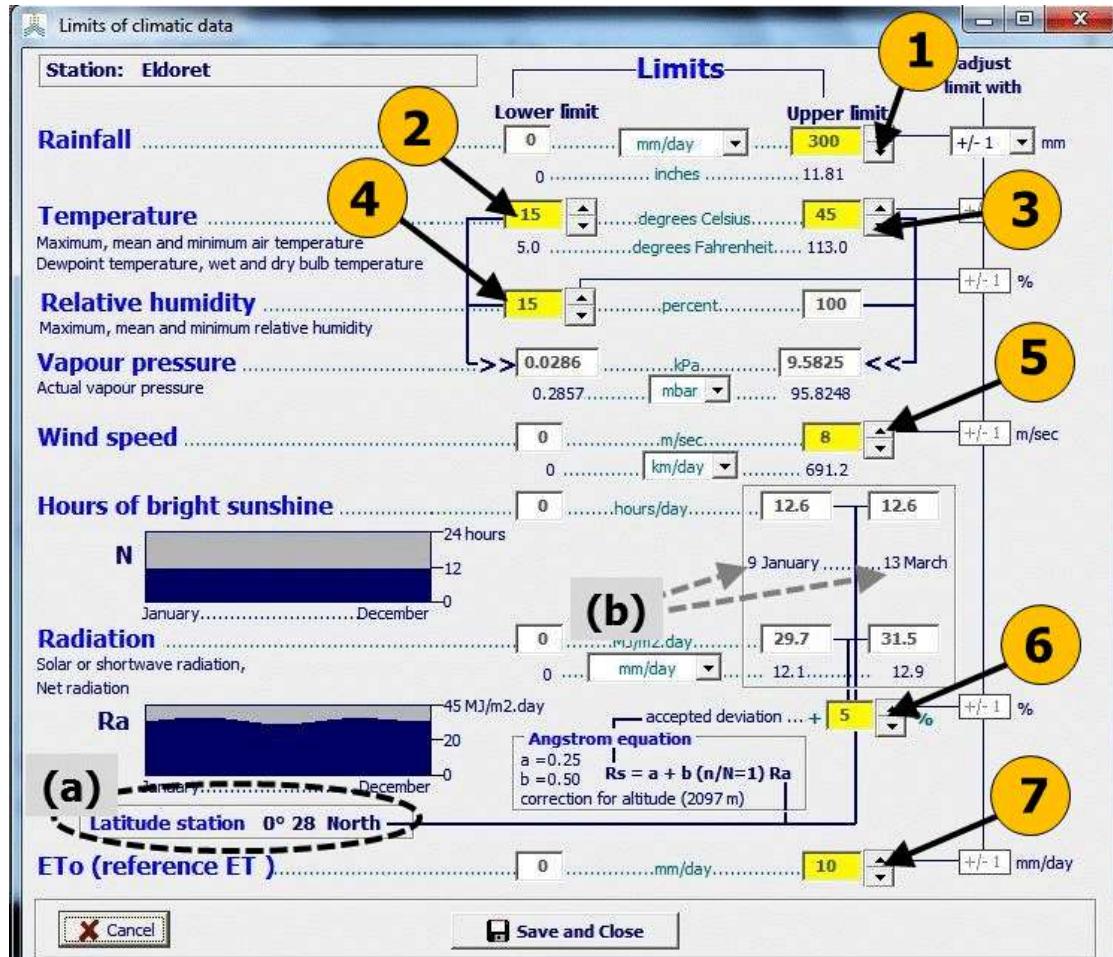


Figure 2.9b7 – The *Limits of climatic data* menu in which upper and/or lower limits can be adjusted for (1) total rainfall, (2) and (3) air temperature, (4) relative humidity, (5) daily wind speed, (6) deviation from maximum possible daily radiation (given by (a) latitude and (b) time of the year), and (7) daily ETo

2.9.3 CO₂ files

Mean annual atmospheric CO₂ concentrations are stored in CO₂ files. The CO₂ file that needs to be created or can be used depends on the type of application:

- **Running simulations with historical climatic data or for the near future:**

When running simulations with historical climatic data, or for the near future (next 10 years), there is no need to create a CO₂ file, since the (default assigned) ‘MaunaLoa.CO₂’ file (stored in the SIMUL subdirectory of AquaCrop) can be used. It contains the mean annual atmospheric CO₂ concentration measured at Mauna Loa Observatory since 1958. For earlier years, data obtained from firn and ice samples are used, and for future estimates an increase of 2.0 ppm is considered (which can be assumed to be valid for the next 10 years);

- **Running simulations for future years:**
- For crop yield estimates for future years, CO₂ files from SRES (Special Report on Emissions Scenarios), containing data derived from emissions scenarios are available in the DATA subdirectory of AquaCrop ('A1B.CO₂', 'A2.CO₂', 'B1.CO₂' and 'B2.CO₂'). The CO₂ projections presented in those files assume different socio-economic storylines (Fig. 2.9c);
- Next to the 4 CO₂ files from SRES, four different RCP's ('RCP2-6.CO₂', RCP4-5.CO₂', 'RCP6-0.CO₂' and 'RCP8-5.CO₂') are also available in the DATA subdirectory of AquaCrop. As the SRES set, the RCPs (Representative Concentration Pathways) represent a broad range of climate outcomes. Each RCP results from different combinations of economic, technological, demographic, policy, and institutional futures (Fig. 2.9c);
- The user can also create:
 - CO₂ file containing (observed and/or projected) annual atmospheric CO₂ concentrations for a number of years;
 - CO₂ file containing only one specific annual atmospheric CO₂ concentration (e.g. 550 ppm) for testing its effect on crop production.

When creating CO₂ files the file structure should be respected (see 2.23 'Input files').

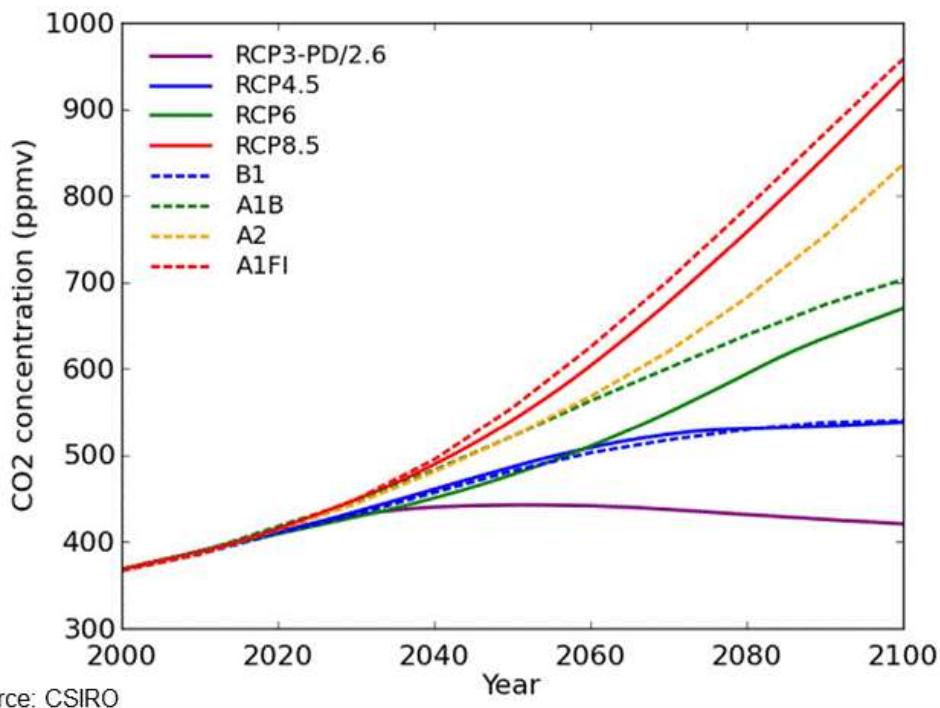


Figure 2.9c – Plot of the different CO₂ concentrations according to four different SRES and four different RCP's scenarios available in the data base of AquaCrop

2.9.4 Creating covering climate files

With climatic data stored in Tnx, ETo, PLU and CO2 files, a covering climate file (extension ‘.CLI’) can be created, by selecting the option ‘Create climate file’ in the **Select climatic file** menu (Fig. 2.9b6). The CLI file is composed in the **Create climate file** menu (Fig. 2.9d).

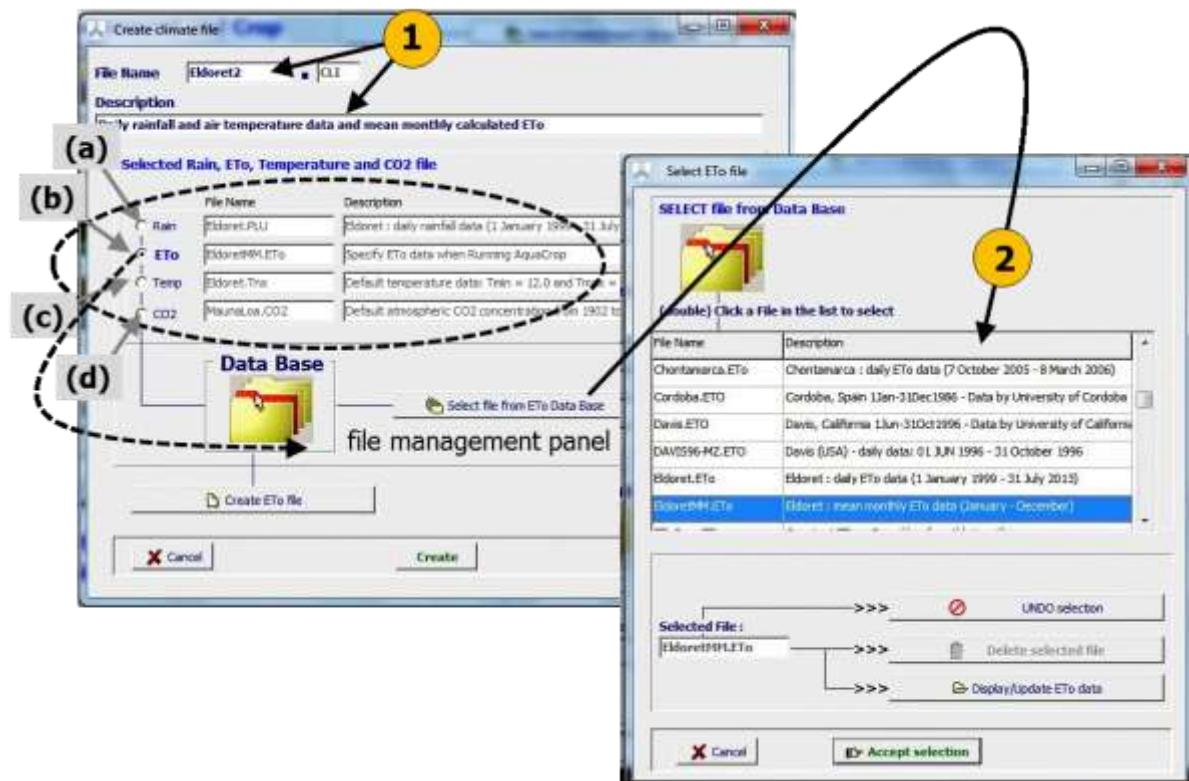
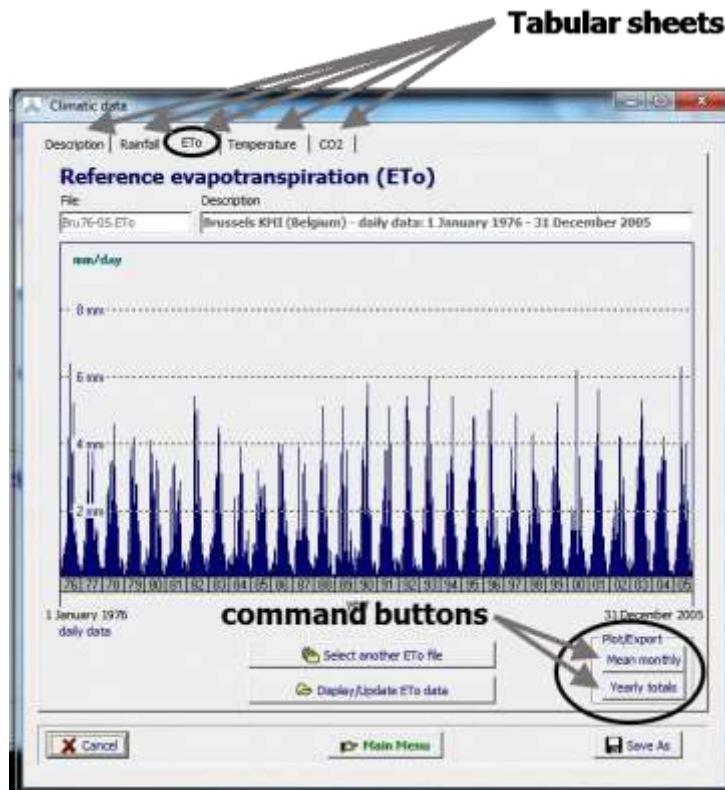


Figure 2.9d – *Create climate file* menu in which the user composes the covering climate file (1) by specifying its name and description, and (2) by selecting a (a) rainfall, (b) ETo, (c) air temperature and (d) CO2 file from the Data Base.

2.9.5 Display and update of climatic data and export of aggregated data

In the *Climatic data* and the *Display of climate characteristics* menus, the entered climatic data is displayed and grouped in the various tabular sheets (Fig. 2.9e1). In those sheets, command buttons are available:

- to update the climatic data by selecting another Rainfall, ETo, Temperature or CO2 file or by adjusting the climatic data directly in one of the files;
- to plot mean monthly and yearly totals of the climatic data (Tab. 2.9e). The data help to evaluate the climatic conditions in which the crop is cultivated.



Figurer 2.9e1 – Command buttons in the lower right corner of the ‘ETo’ tabular sheet of the *Climatic data* menu, to plot mean monthly and yearly totals

Table 2.9e – Command buttons available in the lower right corner of the tabular sheets of the *Climatic data* and the *Display of climate characteristics* menus

| Tabular sheet | Command buttons | Description |
|---------------|--|--|
| Rainfall | <ul style="list-style-type: none"> – Mean monthly (with the option to display rainfall with or without mean ETo) – Yearly totals | <p>Plot of</p> <ul style="list-style-type: none"> • mean monthly rainfall, • mean monthly rainfall, ETo and half of ETo, (Fig. 2.9e2), • total yearly rainfall (Fig. 2.9e3) within the period of available climatic data; |

| | | |
|-------------|---|---|
| ETo | <ul style="list-style-type: none"> – Mean monthly (with the option to display as ‘mm/day’ or ‘mm/month’) – Yearly totals | <p>Plot of</p> <ul style="list-style-type: none"> • mean monthly ETo (mm/day), • mean monthly ETo (mm/month), • total yearly ETo <p>within the period of available climatic data</p> |
| Temperature | <ul style="list-style-type: none"> – Mean monthly (with the option to display as growing degree-days) – Yearly values (with the option to display as growing degree days) | <p>Plot of</p> <ul style="list-style-type: none"> • mean monthly air temperatures, • monthly growing degree-days (2.9e4), • mean yearly air temperatures, • total yearly growing degree-days <p>within the period of available climatic data.</p> <p>When the data is displayed as growing degree-days, the base and upper temperatures for crop development for the selected crop are considered</p> |

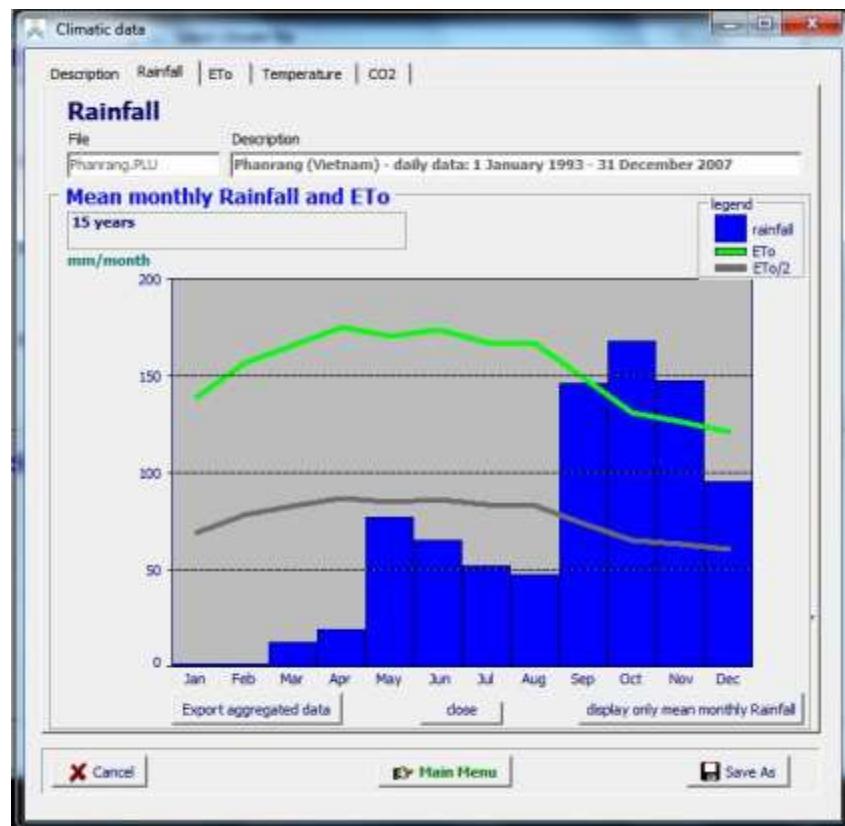


Figure 2.9e2 – Mean monthly Rainfall and ETo in Phanrang (Vietnam) for the 1993 – 2007 period in the ‘Rainfall’ tabular sheet of the *Climatic data* menu

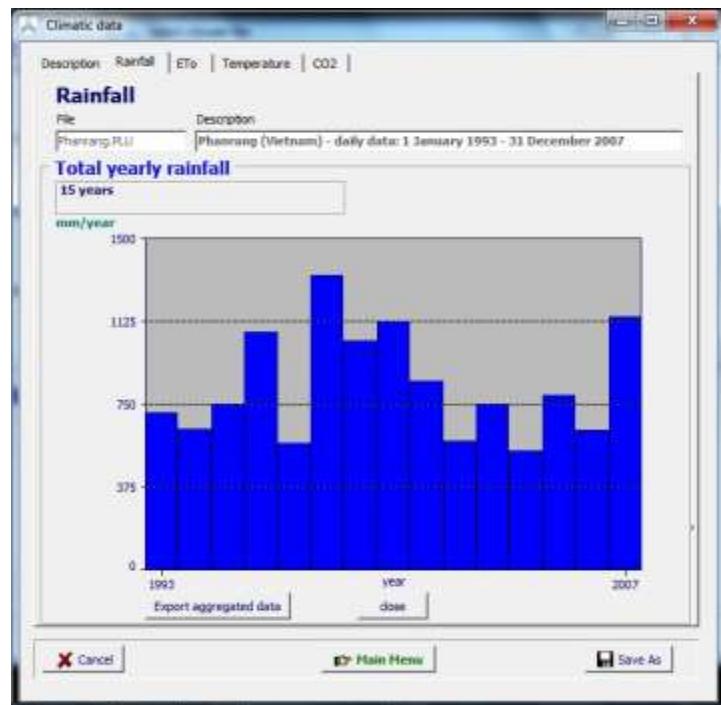


Figure 2.9e3 – Total yearly rainfall in Phanrang (Vietnam) for the 1993 – 2007 period in the ‘Rainfall’ tabular sheet of the *Climatic data* menu

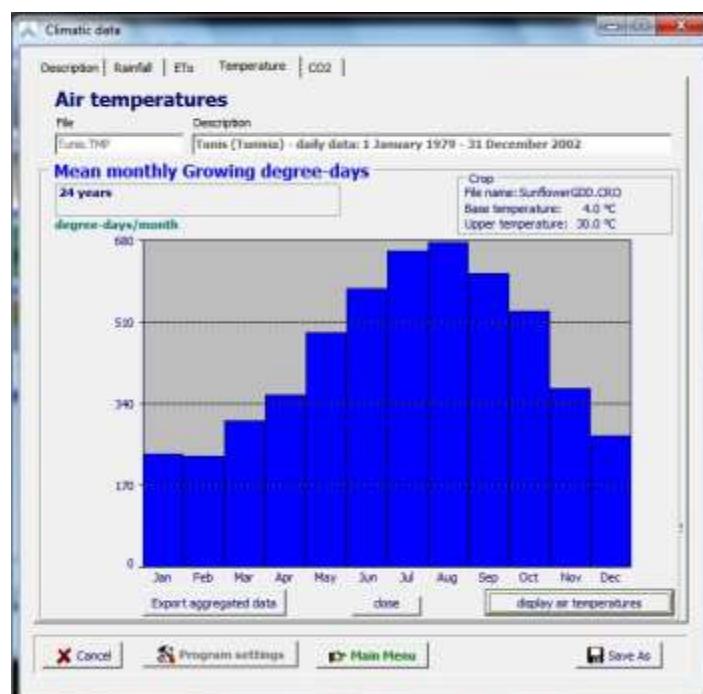


Figure 2.9e4 – Mean monthly Growing degree-days for a crop with a base temperature for crop development of 4 °C and an upper temperature of 30 °C, in

Tunis (Tunisia) for the 1979 – 2002 period in the ‘Temperature’ tabular sheet of the *Climatic data* menu

The mean monthly and yearly totals of rainfall, ETo, air temperatures and growing degree-days can be exported for further analysis (e.g. frequency analysis) via the ‘Export aggregated data’ command at the lower left corner of the box in which mean monthly and yearly totals are displayed (Fig. 2.9e2 to 2.9e4). In the *Export aggregated climatic data* menu, the data to be exported, the name of the files containing the aggregated data, and the path are specified (Fig. 2.9e5). By default the output is saved in the OUTP directory of AquaCrop.

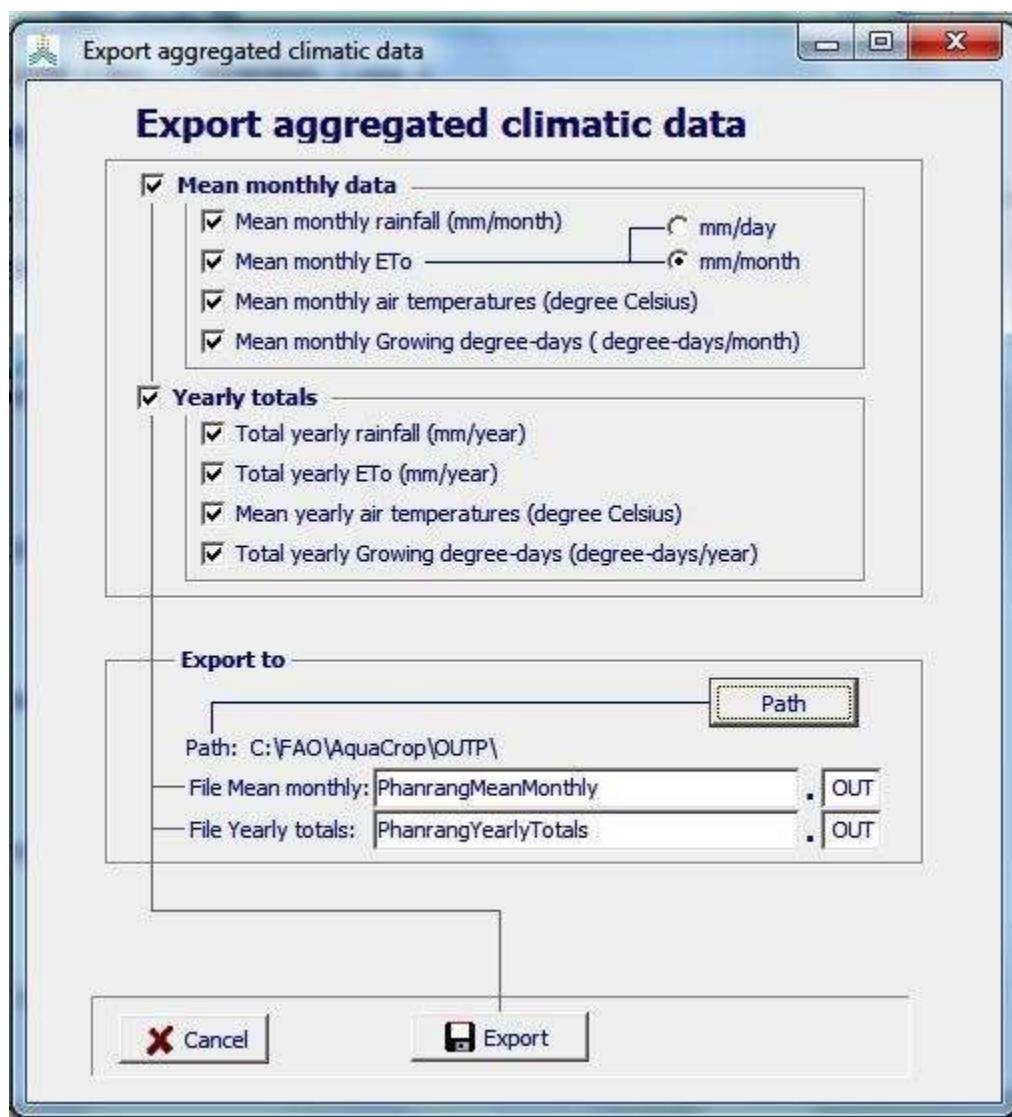


Figure 2.9e5 – The *Export aggregated climatic data* menu

2.9.6 Program settings

From the *Climatic data* menu the user has access to the program settings listed in Table 2.9f. Distinction is made in program settings for 10-day or monthly rainfall, and for Temperature parameters.

Table 2.9f – Program settings for temperature parameters and for procedures when simulating with 10-day or monthly rainfall data

| Symbol | Program parameter | Default |
|--------|--|--|
| | <p>Temperature parameters</p> <ul style="list-style-type: none"> ▪ Method to estimate growing degree days (see Chapter 3) ▪ Default minimum (T_n) and maximum (T_x) air temperature in the absence of a temperature file | Method 3 $T_n = 12^{\circ}\text{C}$ $T_x = 28^{\circ}\text{C}$ |
| | <p>10-day or monthly rainfall</p> <p>Procedures to estimate effective rainfall, surface runoff and soil evaporation when rainfall data consists of 10-day or monthly totals (see Chapter 3)</p> <ul style="list-style-type: none"> ▪ Effective rainfall: calculation procedure ▪ Effective rainfall: percentage (fraction of rainfall) ▪ Surface runoff: showers per 10-day ▪ Soil evaporation: root number | USDA-SCS 70 2 5 |

2.9.7 Training videos about climate

A set of training modules (MP4 videos) are posted in an ‘AquaCrop Training’ channel of YouTube. The modules about climate are listed in Table 2.9g. For the playlist go to FAO AquaCrop website <http://www.fao.org/nr/water/aquacrop.html>

Table 2.9g – Set of training modules about climate

| Video | Learning objective | Length [min:sec] |
|---|--|------------------|
| 02.1 Required weather data | Know the required weather data | 08:33 |
| 02.2 Reference evapotranspiration | Understand the concept of the reference evapotranspiration (ETo) | 10:21 |
| 02.3 Determination of reference evapotranspiration | Become familiar with the determination of reference evapotranspiration | 19:49 |
| 02.4 Import climatic data | Know how to import climatic data | 19:35 |

2.10 Crop characteristics

2.10.1 Crop parameters

■ Crop types

The number and type of crop parameters vary slightly with the crop types selected when creating a new crop in AquaCrop (see 2.6.3). Distinction is made between:

- fruit/grain producing crops (with a yield formation period, starting at flowering, during which the Harvest Index builds up);
- leafy vegetable crops (where flowering information is not considered and the Harvest Index builds up starting from germination);
- root and tuber crops (with a yield formation period, starting at tuber formation or root enlargement, during which the Harvest Index builds up);
- forage crops (crops undergoing cutting more than once a year possibly causing some of the crop characteristics to be altered after a cutting).

■ Calibrated crops

The data base of AquaCrop contains calibrated and validated crop parameters (described in Annex 1. Crop parameters) for the following crops: Barley, Cotton, Maize, Potato, Quinoa, Rice, Sorghum, Soybean, Sugar beet, Sugar cane, Sunflower, Tef, Tomato, and Wheat.

In literature more crop files are available. They might be only valid for the environment in which they are described, and might need further calibration when the environmental conditions are different from the one described in the publications. A digital library of references to all AquaCrop publications can be found on:

https://www.zotero.org/groups/aquacrop_publications

This online Zotero group contains a **public library** with all references to peer reviewed journal articles and PhD manuscript about calibration or application of the AquaCrop model. The group library can be consulted online by everyone. The ability to download an article depends whether or not you are subscribed to the journal, or whether the journal is open access.

■ Conservative, cultivar specific and non-conservative crop parameters

A distinction is made between:

- **Conservative crop parameters** which do not change substantially with time, management practices, geographic location or climate. They are also assumed not to change with cultivars unless shown otherwise. Examples are the thresholds for stresses and the normalized biomass water productivity (WP*);
- **Cultivar specific and non- conservative parameters** These parameters might require an adjustment when selecting a cultivar different from the one considered for crop calibration, or when the environmental conditions differ from the conditions assumed at calibration (field management and conditions in the soil profile) or when the planting method is altered.

The crop parameters are listed in Table 2.10a.

Table 2.10a – List of the crop parameters and their type

| 1. Crop Phenology | | |
|---|--|--|
| Symbol | Description | Type ^{(1), (2), (3), (4)} |
| 1.1 Threshold air temperatures for growing degree days | | |
| T _{base} | Base temperature (°C) | Conservative ⁽¹⁾ |
| T _{upper} | Upper temperature (°C) | Conservative ⁽¹⁾ |
| 1.2 Development of green canopy cover | | |
| cc _o | Canopy size of the average seedling at 90% emergence, or canopy size of the transplanted seedling (cm ²) | Conservative ⁽²⁾ Management ⁽³⁾ |
| | Number of plants per hectare | Management ⁽³⁾ |
| | Time from sowing to emergence (days or GD days) or recovery time (for transplanted seedlings) | Management ⁽³⁾ |
| CGC | Canopy growth coefficient (fraction per day or per growing degree day) | Conservative ⁽¹⁾ |
| CC _x | Maximum canopy cover (fraction soil cover) | Management ⁽³⁾ |
| | Time from sowing to start senescence (days or GD days) | Cultivar ⁽⁴⁾ |
| CDC | Canopy decline coefficient (fraction per day or per growing degree day) | Conservative ⁽¹⁾ |
| | Time from sowing to maturity, i.e. length of crop cycle (days or GD days) | Cultivar ⁽⁴⁾ |
| 1.3 Flowering or start of yield formation | | |
| | Time from sowing to flowering or to the start of yield formation (days or GD days) | Cultivar ⁽⁴⁾ |
| | Length of the flowering stage (days or GD days) | Cultivar ⁽⁴⁾ |
| | Crop determinacy linked/unlinked with flowering | Conservative ⁽¹⁾ |
| 1.4 Development of root zone | | |
| Z _n | Minimum effective rooting depth (m) | Management ⁽³⁾ |
| Z _x | Maximum effective rooting depth (m) | Management ⁽³⁾ |
| | Shape factor describing root zone expansion | Conservative ⁽¹⁾ |

(1) Conservative generally applicable

(2) Conservative for a given specie but can or may be cultivar specific

(3) Dependent on environment and/or management

(4) Cultivar specific

Table 2.10a. continued.

| 2. Crop transpiration | | |
|--|---|--|
| Symbol | Description | Type ^{(1), (2), (3), (4)} |
| K _{cTr,x} | Crop coefficient when canopy is complete but prior to senescence | Conservative ⁽¹⁾ |
| 100 f _{age} | Decline of crop coefficient (% of CC _x per day) as a result of ageing, nitrogen deficiency, etc. | Conservative ⁽¹⁾ |
| S _{x,top} | Maximum root water extraction ($m^3 m^{-3} day^{-1}$) in top quarter of root zone | Conservative ⁽¹⁾ |
| S _{x,bot} | Maximum root water extraction ($m^3 m^{-3} day^{-1}$) in bottom quarter of root zone | Conservative ⁽¹⁾ |
| | Effect of canopy cover in reducing soil evaporation in late season stage (% reduction in soil evaporation) | Conservative ⁽¹⁾ |
| 3. Biomass production and yield formation | | |
| 3.1 Crop water productivity | | |
| WP* | Water productivity normalized for ETo and CO ₂ (gram/m ²) | Conservative ⁽¹⁾ |
| f _{yield} | Reduction coefficient describing the effect of the products synthesized during yield formation on the normalized water productivity | Conservative ⁽¹⁾ |
| | Crop performance under elevated atmospheric CO ₂ concentration (%) | Management ⁽³⁾ Cultivar ⁽⁴⁾ |
| 3.2 Harvest Index | | |
| HI _o | Reference harvest index (%) | Cultivar ⁽⁴⁾ |
| | Excess of potential fruits (%) | Conservative ⁽²⁾ |
| | Possible increase (%) of HI due to water stress before flowering | Conservative ⁽¹⁾ |
| | Coefficient describing positive impact of restricted vegetative growth during yield formation on HI | Conservative ⁽¹⁾ |
| | Coefficient describing negative impact of stomatal closure during yield formation on HI | Conservative ⁽¹⁾ |
| | Allowable maximum increase (%) of specified HI | Conservative ⁽¹⁾ |

(1) Conservative generally applicable

(2) Conservative for a given specie but can or may be cultivar specific

(3) Dependent on environment and/or management

(4) Cultivar specific

Table 2.10a. continued.

| 4. Stresses | | |
|-----------------------------------|---|---|
| Symbol | Description | Type ^{(1), (2), (3), (4)} |
| 4.1 Soil water stresses | | |
| pexp,lower | Soil water depletion threshold for canopy expansion - Upper threshold | Conservative ⁽¹⁾ |
| pexp,upper | Soil water depletion threshold for canopy expansion - Lower threshold | Conservative ⁽¹⁾ |
| | Shape factor for Water stress coefficient for canopy expansion | Conservative ⁽¹⁾ |
| psto | Soil water depletion threshold for stomatal control – Upper threshold | Conservative ⁽¹⁾ |
| | Shape factor for Water stress coefficient for stomatal control | Conservative ⁽¹⁾ |
| psen | Soil water depletion threshold for canopy senescence – Upper threshold | Conservative ⁽¹⁾ |
| | Shape factor for Water stress coefficient for canopy senescence | Conservative ⁽¹⁾ |
| | Sum(ETo) during stress period to be exceeded before senescence is triggered | Conservative ⁽¹⁾ |
| ppol | Soil water depletion threshold for failure of pollination – Upper threshold | Conservative ⁽¹⁾ |
| | Vol% at anaerobic point (with reference to saturation) | Cultivar ⁽⁴⁾ Environment ⁽³⁾ |
| 4.2 Soil fertility stress | | |
| | Stress at calibration (%) | (calibration) |
| | Shape factor for the stress coefficient for canopy expansion | Management ⁽³⁾ |
| | Shape factor for the stress coefficient for Maximum Canopy Cover | Management ⁽³⁾ |
| | Shape factor for the stress coefficient for Crop Water Productivity | Management ⁽³⁾ |
| | Shape factor for the response of Decline of Canopy Cover to stress | Management ⁽³⁾ |
| 4.3 Air temperature stress | | |
| | Minimum air temperature below which pollination starts to fail (cold stress) (°C) | Conservative ⁽¹⁾ |
| | Maximum air temperature above which pollination starts to fail (heat stress) (°C) | Conservative ⁽¹⁾ |
| | Minimum growing degrees required for full crop transpiration (°C - day) | Conservative ⁽¹⁾ |

(1) Conservative generally applicable

(2) Conservative for a given specie but can or may be cultivar specific

(3) Dependent on environment and/or management

(4) Cultivar specific

Table 2.10a. continued.

| Symbol | Description | Type ^{(1), (2), (3), (4)} |
|---------------------------------|---|------------------------------------|
| 4.4 Soil salinity stress | | |
| EC _e _n | Electrical conductivity of the saturated soil-paste extract: lower threshold (at which soil salinity stress starts to occur) | Conservative ⁽¹⁾ |
| EC _e _x | Electrical conductivity of the saturated soil-paste extract: upper threshold (at which soil salinity stress has reached its maximum effect) | Conservative ⁽¹⁾ |
| | Shape factor for Soil salinity stress coefficient | Conservative ⁽¹⁾ |
| | Distortion (%) of Canopy Cover due to salinity stress | Management ⁽³⁾ |
| | Response (%) of stomatal stress to EC _{sw} (Electrical conductivity of the soil water) | Management ⁽³⁾ |

(1) Conservative generally applicable

(2) Conservative for a given specie but can or may be cultivar specific

(3) Dependent on environment and/or management

(4) Cultivar specific

- **Training video about crop parameters**

In training module (MP4 video) Nr. 04.1 (part 1) the type of crop parameters are explained (Tab. 2.10b). The training videos are posted in an ‘AquaCrop Training’ channel of YouTube. For the playlist go to FAO AquaCrop website <http://www.fao.org/nr/water/aquacrop.html>

Table 2.10b – Training module about the type of crop parameters

| Video | Learning objective | Length [min:sec] |
|-----------------------------------|-----------------------------------|------------------|
| 04.1 Crop parameters | Know the required crop parameters | - |
| – Part 1. Type of crop parameters | | 06:23 |

2.10.2 Tuning of crop parameters

When running a simulation for a specific cultivar and in a specific environment (as described by the selected climate, crop, field management conditions, ..) the conservative crop parameters do not require adjustment. The cultivar specific and non-conservative crop parameters might require an adjustment since they vary with the selected cultivar and might be affected by field management, conditions in the soil profile, or the climate (Fig. 2.10b1). This section deals with the tuning of the crop parameters:

- affected by planting and management such as the type of planting method, the plant density, the maximum canopy cover and the time to reach 90% seedling emergence;
- cultivar specific crop parameters such as the duration of flowering and the time to reach various stages of crop development: the maximum canopy cover, the start of canopy senescence, physiological maturity, and flowering;
- affected by conditions in the soil profile such as the maximum effective rooting depth and the time to reach that depth.

Additionally the crop needs to be calibrated for soil fertility stress (see section 2.10.12 of this chapter) and for soil salinity stress (see section 2.10.14).

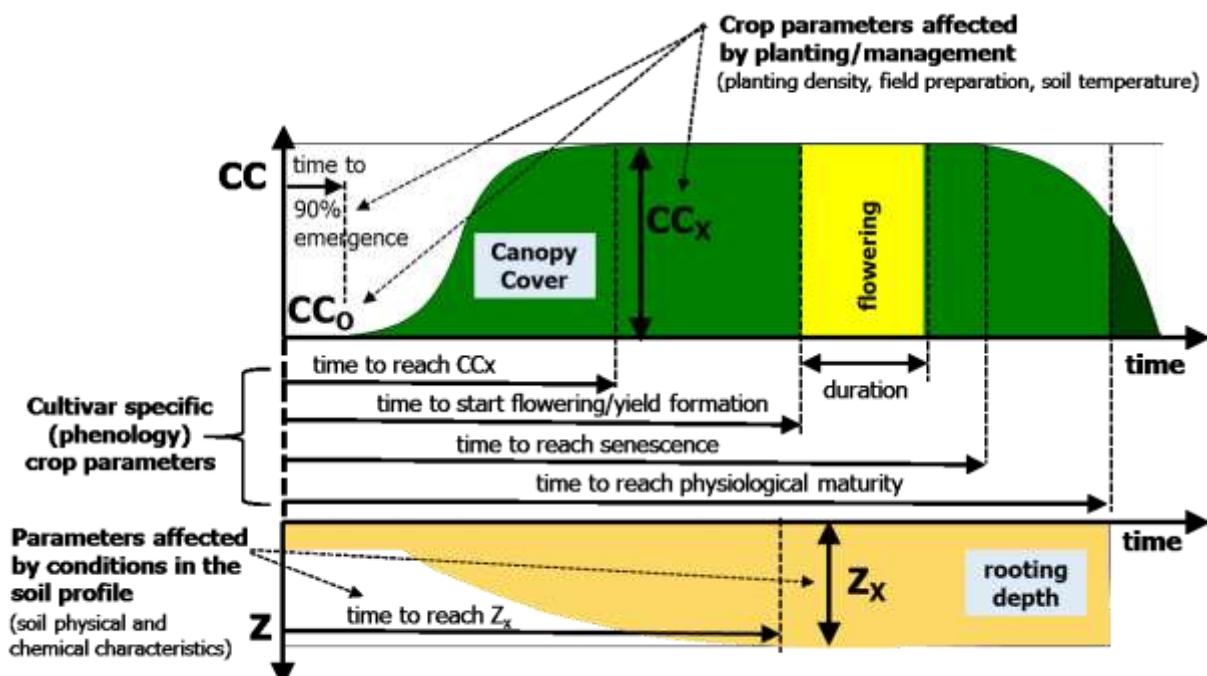


Figure 2.10b1 – Crop parameters to be tuned to the selected cultivar and the environmental conditions

The tuning covered in this section consists in:

1. Specifying the environment in which the crop is cultivated in the **Main menu**:
 - Load the climate in which the crop is cultivated ;
 - Load the crop file (in **calendar day mode**) that needs to be tuned;
 - Specify the planting day for the season for which fine-tuning data is available;
 - Irrigation and Field management, Soil profile and Groundwater table files need not to be loaded, since crop development in the crop file is described in the absence of water, fertility and salinity stress;
2. Calibration of the crop parameters in the **Crop characteristics** menu
 - Adjust (in **calendar day mode**) the cultivar specific crop parameters (phenology), and the crop parameters affected by planting and management, and by conditions in the soil profile. Only the ‘Limited set’ of crop parameters are required;
 - Switch from calendar day to **growing degree mode** to assure that the length and duration of the crop development stages will be adjusted to the temperature regime when running simulations for other years;
 - Save the fine-tuned crop parameters.

A set of training modules (MP4 videos) are posted in an ‘AquaCrop Training’ channel of YouTube. The modules about tuning of crop parameters are listed in Table 2.10c.

For the playlist go to FAO AquaCrop website <http://www.fao.org/nr/water/aquacrop.html>

Table 2.10c – Set of training modules about tuning of crop parameters

| Video | Learning objective | Length [min:sec] |
|--|-----------------------------------|------------------|
| 04.1 Crop parameters | Know the required crop parameters | - |
| – Part 1. Type of crop parameters | | 06:23 |
| – Part 2. Tuning of crop parameters | | 15:59 |
| – Part 3. Crop development adjustment to temperature regimes | | 08:15 |

- **Parameters affected by planting and management:**

- **Type of planting method** (Fig. 2.10b2, direct sowing or transplanting): AquaCrop makes a distinction between direct sowing and transplanting. When the crop is sown, the size of the canopy of the germinating seedling is given (it is a conservative parameter). On the other hand, the size of the transplanted seedling depends on the time the plant remained in the nursery, and its size needs to be specified by the user;
- **Plant density**, which will determine the initial (CC_0) canopy cover. The plant density is specified by (Fig. 2.10b2):
 1. the planting density;
 2. selecting one of the CC_0 classes (ranging from very small to very high cover);
 3. specifying directly the percentage of CC_0 (which might be useful for transplanted seedlings). The corresponding plant density will be derived from CC_0 and the canopy size of the seedling; or
 4. selecting the <estimate> command to estimate plant density either from sowing rate or plant spacing.
- **Maximum canopy cover (CC_x)**, that will be reached at mid-season, is generally around 75 % up to 100 %. CC_x varies with crop type but it is also determined by planting density. CC_x is specified by selecting one of the predefined classes or as direct input (Fig. 2.10b3);
- **Time to reach 90% seedling emergence** (affected by field preparation and soil temperature) (Fig. 2.10b3).

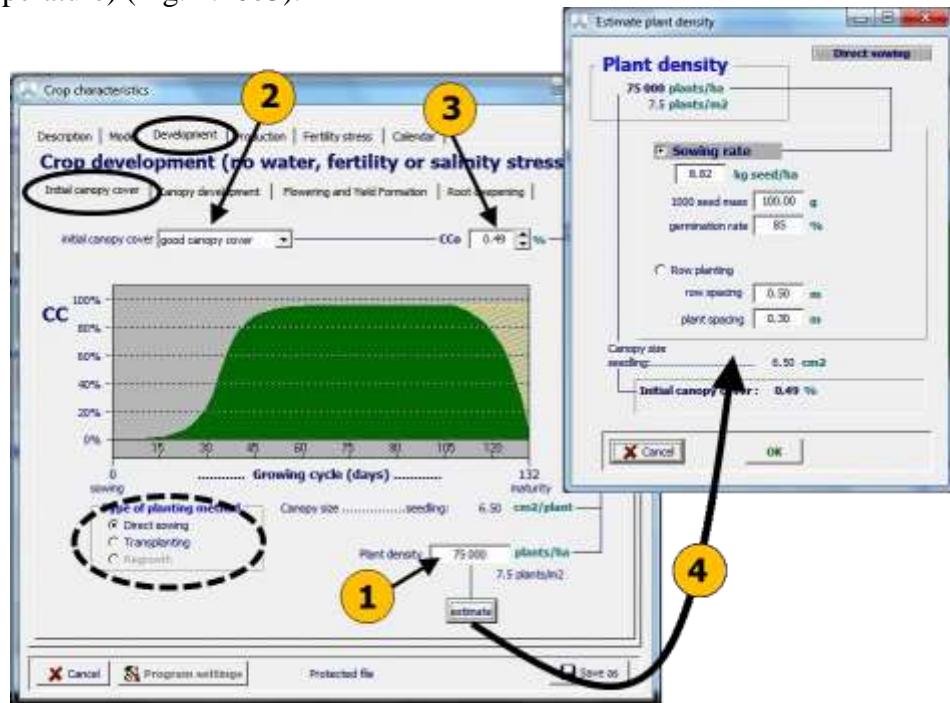


Figure 2.10b2 – The ‘Initial canopy cover’ tabular sheet of the ‘Development’ tabular sheet of the *Crop characteristics* menu in which the type of planting method (dotted oval) and the initial canopy cover (CC_0) is determined (1) by specifying plant density, (2) by selecting a predefined CC_0 class, (3) by specifying the percentage or (4) from sowing rate or plant spacing data

- **Cultivar specific crop parameters:**

Many of the differences between crop cultivars are related to the **timing of developmental stages**. The timing to reach a particular stage, or its duration, are specified in the ‘Development’ tabular sheet of the *Crop characteristics* menu (Fig. 2.10b3):

- **Time to reach maximum canopy cover (CC_x):** Altering the time required to reach CC_x, results in an automatic fine tuning of CGC (Canopy Growth Coefficient) to the local conditions;
- **Time to start of canopy senescence:** It is the time when green leaf area start to decline as a result of yellowing of leaves, under optimal conditions with no water stress;
- **Time to physiological maturity (length of crop cycle):** At the time of maturity the simulation of biomass production and yield formation will be halted. Harvest does not necessarily coincide with crop maturity;
- **Time to start flowering (or the start of yield formation);**
- **Duration of flowering.**

Reference Harvest Index (HI_o): HI_o is conservative to a fair extent but can be cultivar specific (through plant breeding and biotechnology). It is the representative HI reported in the literature for the chosen crop species under non-stress conditions, and is specified in the ‘Harvest Index’ tabular sheet of the ‘Production’ tabular sheet of the *Crop characteristics* menu.

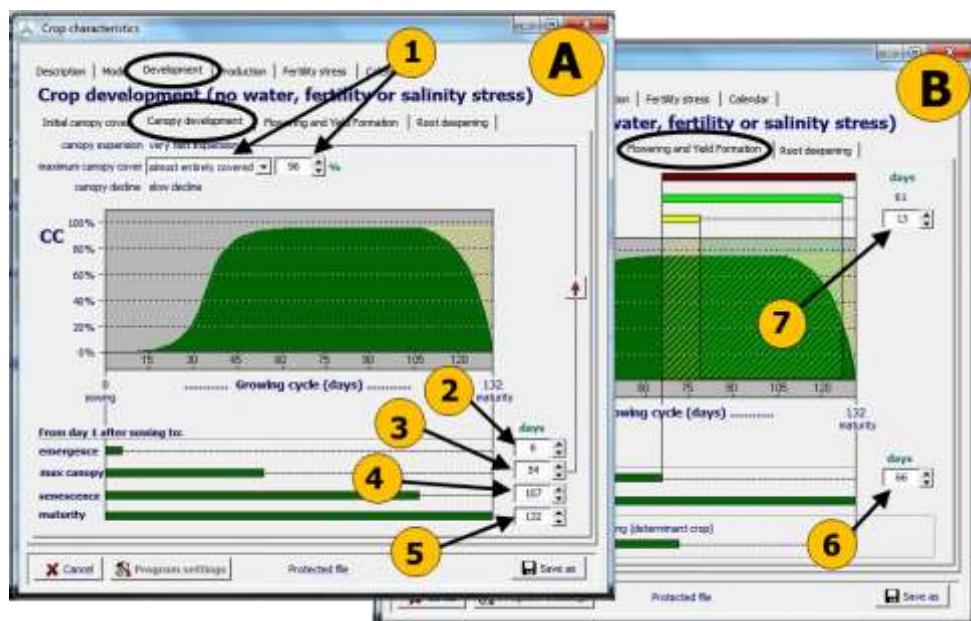


Figure 2.10b3 – The (A) ‘Canopy development’ and (B) ‘Flowering and yield formation’ tabular sheet of the ‘Development’ tabular sheet of the *Crop characteristics* menu including: (1) the maximum canopy cover (CC_x) by selecting a class or specifying the percentage, and the time to reach (2) 90% seedling emergence, (3) maximum canopy cover, (4) start of canopy senescence, (5) physiological maturity, and the (6) start of flowering or yield formation, and (7) the duration of flowering

- **Parameters affected by conditions in the soil profile:**

The maximum effective rooting depth (Z_x) and root deepening rate (or the time to reach Z_x) are affected by soil physical (temperature, mechanical impedance, aeration) and soil chemical (pH, salinity, high levels of aluminum or manganese) characteristics. They are specified in the ‘Root deepening’ tab-sheet of the ‘Development’ tab-sheet of the ***Crop characteristics*** menu (Fig. 2.10b4):

- **Maximum effective rooting depth (Z_x):** It can be specified by selecting one of the predefined classes or by entering directly the numeric value in meter;
- **Time to reach Z_x :** By altering the time from sowing to Z_x , the corresponding root zone expansion rate is defined. The average root zone expansion is displayed as a reference, although in AquaCrop the expansion is described by an exponential function. Knowledge of the typical root zone expansion, can be used to estimate the time when Z_x will be reached. Root zone expansion rates are often about 1 cm/day but may be up to 2 cm/day if the environment is optimal for growth (soil not cold, and soil layers not limiting growth).

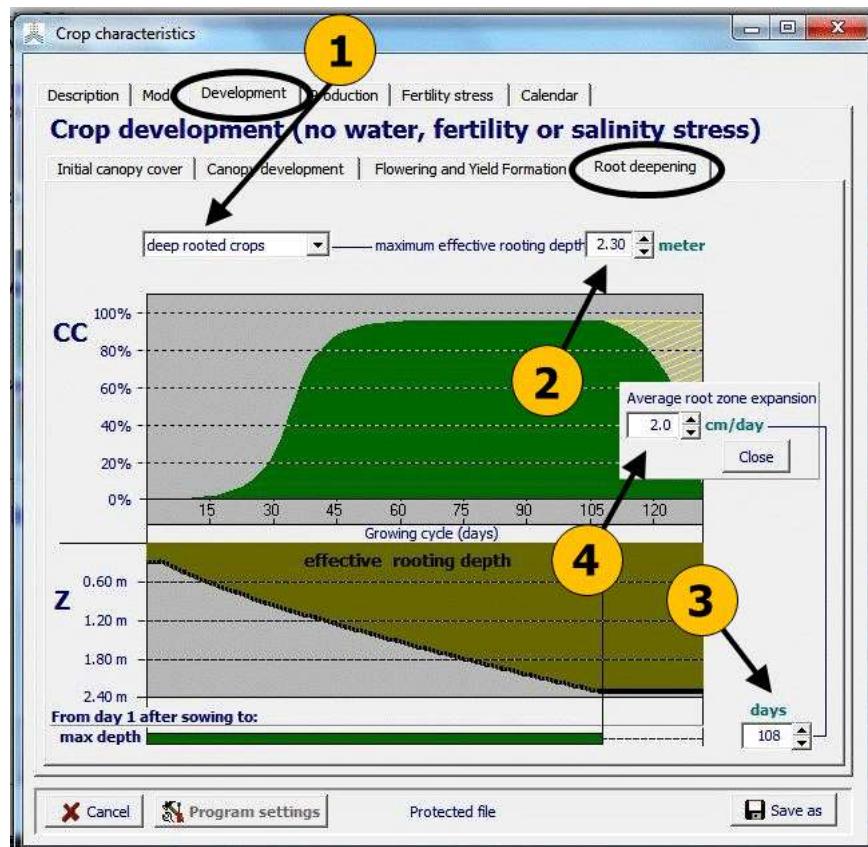


Figure 2.10b4 – The ‘Root deepening’ tabular sheet of the ‘Development’ tabular sheet of the *Crop characteristics* menu including: the maximum effective rooting depth (Z_x), specified by (1) selecting a predefined class, or (2) by entering the value in meter, and the time to reach Z_x specified by (3) the time to reach Z_x , or (4) the average root zone expansion rate

- **Calendar of the growing cycle**

An overview of the calendar of the growing cycle is displayed in the ‘Calendar’ tabular sheet of the ***Crop characteristics*** menu (Fig. 2.10b5 A). The planting date and the length of the different growth stages can be adjusted with the help of the spin buttons. The length of the corresponding FAO56 stages can be displayed as well. These stages were defined in earlier FAO publications (Irrigation and Drainage Papers Nr. 24, 33 and 56) in which indicative values for lengths of crop development stages for various planting period and climate regions for common agriculture crops are presented.

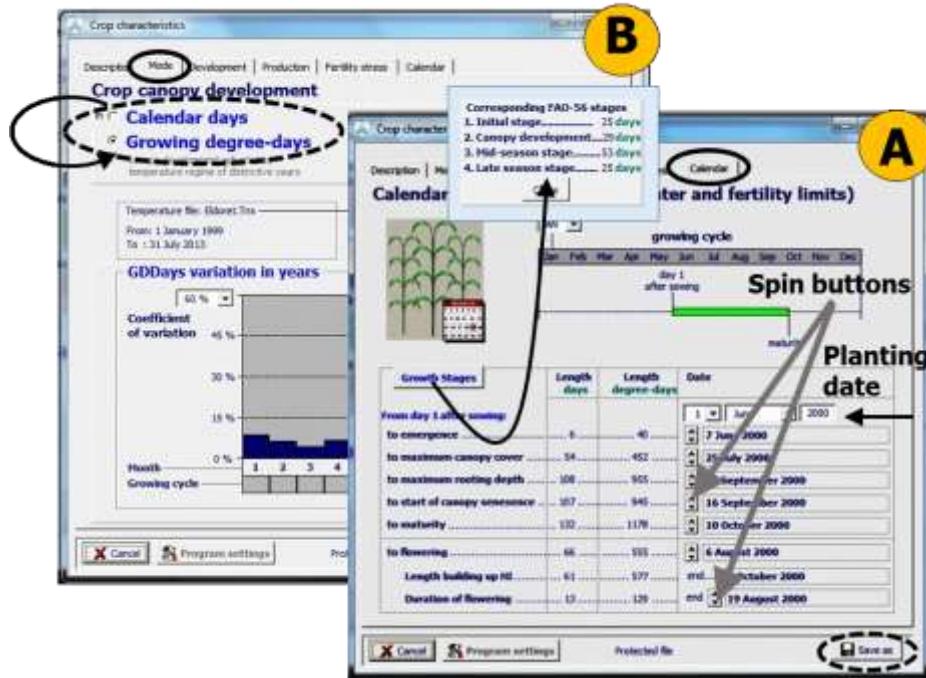


Figure 2.10b5 – (A) The ‘Calendar’ tabular sheet, to inspect or adjust the calendar of the growing period, and **(B)** The ‘Mode’ tabular sheet of the *Crop characteristics* menu to switch between calendar and thermal time. With the <Save as> command the fine-tuned crop characteristics can be saved in a new crop file.

▪ Converting calendar into thermal time

At the end of the fine-tuning process, it is strongly recommended to convert the calendar time into thermal time. As such the length and duration of the crop development stages will be adjusted to the temperature regimes of the distinctive years in which simulations are run. This is done in the ‘Mode’ tabular sheet of the ***Crop characteristics*** menu (Fig. 2.10b5). Make sure that the representative climate file and sowing date are correctly selected before the conversion.

▪ Save the fine-tuned crop parameters in a new crop file

Crop files which come with the AquaCrop software contain crop parameters that are calibrated and validated by FAO. After fine-tuning the crop parameters, the adjustments cannot be saved in the protected file. Select the <Save as> command to save the fine-tuned crop parameters in a new crop file (Fig. 2.10b5 A).

2.10.3 Crop characteristics menu

The crop characteristics required by the program can be displayed in the *Display of crop characteristics* menu and updated in the *Crop characteristics* menu (Fig. 2.10c).

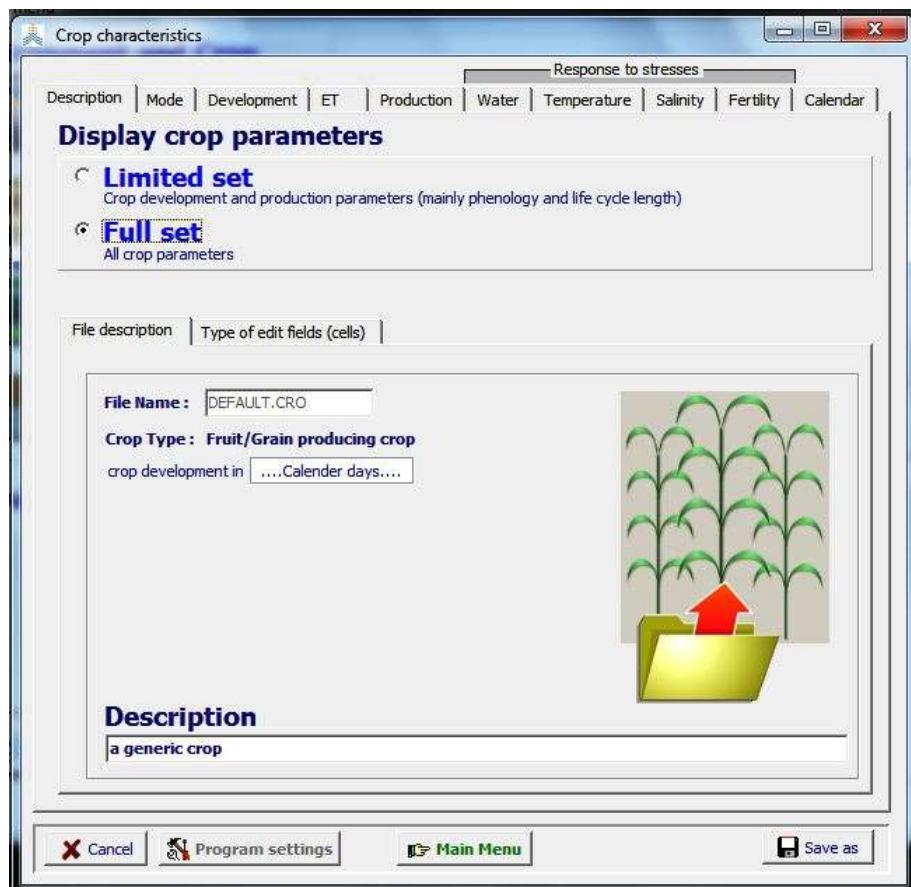


Figure 2.10c – The *Crop characteristics* menu with its 10 tabular sheets

The ‘Full set’ of crop characteristics are grouped in 10 different tabular sheets (Fig. 2.10d):

Table 2.10d – List of tabular sheets in the *Display of crop characteristics* menu and updated in the *Crop characteristics* menu

| | |
|--------------------|--|
| Description | General information Two types of display mode of crop parameters can be selected (Fig. 2.10c) |
| Mode | To switch between ‘calendar days’ and ‘Growing degree-days’ mode |
| Development | Crop development in the absence of water, soil fertility and/or soil salinity stress |

| | |
|---|--|
| <ul style="list-style-type: none"> - Flowering and yield formation or Root/Tuber formation; - Root deepening | |
| ET <ul style="list-style-type: none"> - Coefficients - Water extraction pattern | Evapotranspiration in the absence of water, soil fertility and/or soil salinity stress |
| Production <ul style="list-style-type: none"> - Crop water productivity - Harvest Index | Crop production in the absence of water, soil fertility and/or soil salinity stress |
| Water stress <ul style="list-style-type: none"> - Canopy expansion - Stomatal closure - Early canopy senescence - Aeration stress - Harvest Index <ul style="list-style-type: none"> - Before flowering - During flowering - During yield formation - Overview | Responses to water stress |
| Temperature stress <ul style="list-style-type: none"> - Crop development - Crop transpiration - Pollination | Responses to air temperature stress |
| Salinity stress <ul style="list-style-type: none"> - Salt tolerance - Crop response <ul style="list-style-type: none"> - Canopy Cover - Stomatal closure | Responses to soil salinity stress |
| Fertility stress <ul style="list-style-type: none"> - Canopy - Water productivity - Transpiration - Biomass - Biomass – stress relationship - Ks curves - Crop parameters | Responses to soil fertility stress |
| Calendar | Crop calendar in the absence of water, soil fertility and/or soil salinity stress |

2.10.4 Tabular sheet: Description

▪ **Display crop parameters**

In this tabular sheet the display mode of crop parameters can be selected (Fig. 2.10c):

- **Limited set:** Crop development and production parameters describing mainly phenology and life cycle length are displayed in 5 tabular sheets. These parameters might require some fine-tuning when selecting a cultivar different from the one considered for crop calibration, or when the environmental conditions differ from the conditions assumed at calibration or when the planting method is altered (see 2.10.2 Tuning of crop parameters).
- **Full set:** All crop parameters are displayed in the 10 tabular sheets (Table 2.10c).

The ‘Description’ sheet might contain up to three tabular sheets:

▪ **File description**

Display of File name, crop type, mode and the description of the crop file.

▪ **Type of edit fields (cells)**

- only displayed when the ‘Full set’ of crop parameters is displayed

Crop parameters are displayed in edit-fields (cells). The colour of the edit fields varies depending on the type of parameters. The conservative parameters (displayed in silver cells) are crop specific but do not change materially with time, management practices, geographic location or climate. They are also assumed not to change with cultivars unless shown otherwise. They were calibrated with data of the crop grown under favourable and non-limiting conditions but remain applicable for stress conditions via their modulation by stress response functions. The other parameters (displayed in white cells) are cultivar specific or less conservative and affected by the climate, field management or conditions in the soil profile. The crop parameters are listed in Table 2.10a.

▪ **Protected files**

- only displayed when a protected crop file is loaded

Crop files which come with the AquaCrop software contain crop parameters that are calibrated and validated by FAO. Although the user can alter the crop parameters in the **Crop characteristics** menu, the adjustments cannot be saved in the protected file. Select the <Save as> command to save the updated crop parameters in a new crop file.

2.10.5 Tabular sheet: Mode

In the ‘Mode’ tabular sheet, the user can change the mode of crop development (Fig. 2.10e1).

After fine-tuning the growing cycle to the environment (typically done in calendar days), and considering the characteristics of the crop cultivar, it is advised to switch from the calendar mode to the growing degree-days (GDD) mode (see 2.10.2). By running AquaCrop in GDD mode, the length and duration of the crop development stages are automatically adjusted to the temperature regimes of the distinctive years of the simulation run.

To assess the importance of running in growing degree-days, the coefficient of variation (CV) of the monthly GDD’s (for the complete years available in the temperature file), can be displayed in the ‘Mode’ tabular sheet (Fig. 2.10e2). CV is defined as the ratio of the standard deviation to the mean, and is expressed in percentage. The months of the growing cycle are colored green in the graph. When the mean of GDD’s are close to zero (typically in the winter months of temperate climates), the coefficient of variation becomes sensitive to small changes in the mean.

For the purpose of GDD calculations a base temperature (below which crop development does not progress) and an upper temperature (above which the crop development no longer increases) are required (see Chapter 3 – section 3.2 Growing degree days). These temperatures are conservative for a given specie but may be cultivar specific for lines bred in drastically different environments. The base and upper temperatures are specified in the response to ‘Temperature’ stress tabular sheet (see 2.10.10).

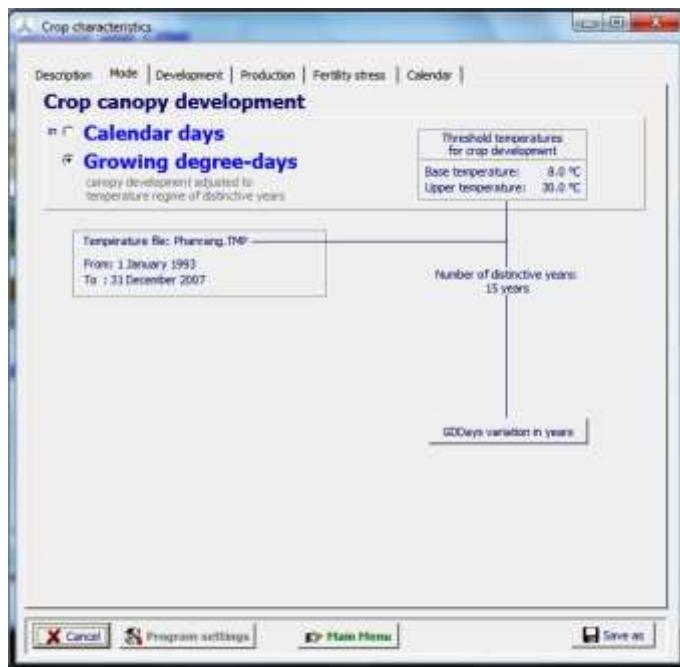


Figure 2.10e1 – The ‘Mode’ tabular sheet in the *Crop characteristics* menu

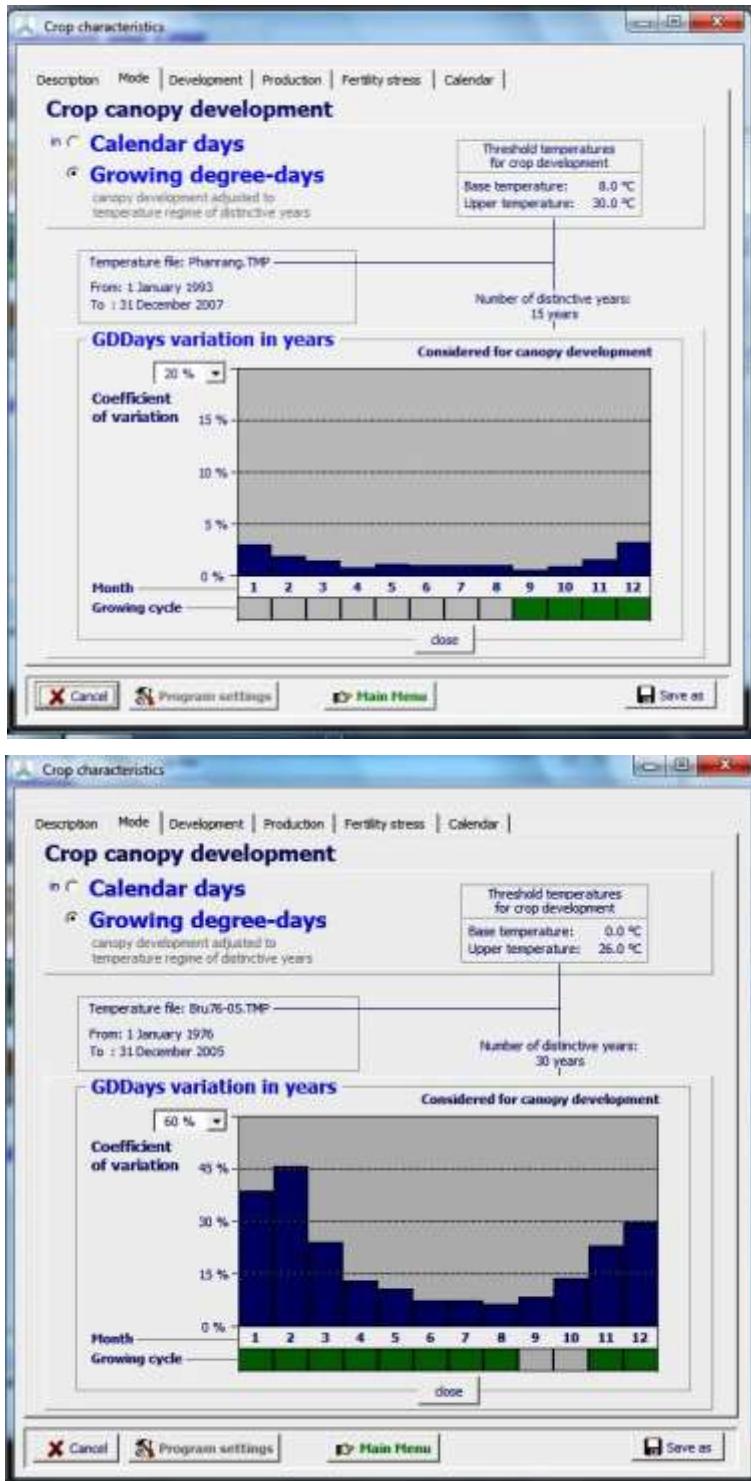


Figure 2.10e2– Display of the variations in growing degree-days in the distinctive months (top) of the 15 years of the Phanrang (Vietnam) temperature file, and (bottom) of the 30 years of the Brussels (Belgium) temperature file in the tabular sheet ‘Mode’. The base an upper temperatures are those for rice (Phanrang) and winter wheat (Brussels)

2.10.6 Tabular sheet: Development

In figure 2.10f1 the crop development for non-limiting conditions is plotted for fruit/grain producing crops. Instead of LAI, AquaCrop uses green canopy cover (CC) which is the fraction of soil surface covered by the green canopy. Crop development can be specified in growing degree days (GDD) or calendar days. Crop development parameters are grouped in 4 folders:

- Initial canopy cover (initial canopy cover at 90% emergence);
- Canopy development (canopy expansion and decline);
- Flowering and Yield formation (or Root/Tuber formation);
- Root deepening.

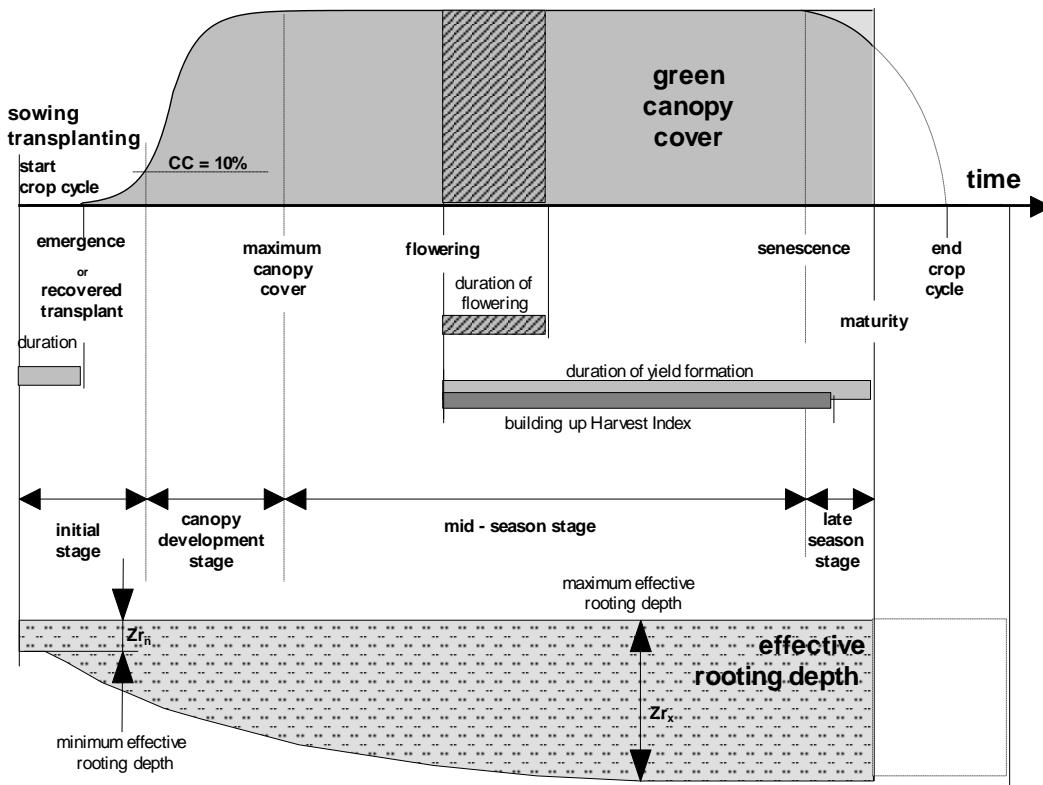


Figure 2.10f1 – Schematic representation of crop development for fruit/grain producing crops

- **Initial canopy cover**

The initial canopy cover (CC_0) is required to describe canopy expansion (Chapter 3 – Section 3.4.1 ‘Green canopy cover throughout the crop cycle’). It is the product of plant density (number of plants per hectare) and the canopy size of the seedling (cc_0).

Type of planting method

- Direct sowing: CC_0 refers to the initial canopy cover at 90% emergence and is obtained by multiplying plant density by the canopy size of the average seedling at 90% emergence (cc_0);
- Transplanting: CC_0 refers to the initial canopy cover after transplanting and is obtained by multiplying plant density by the canopy size of the transplanted seedling (cc_0).

Since the canopy size of the transplanted seedling is likely to be larger than the canopy size of the germinating seedling, the user will have to confirm or adjust the proposed default size, when altering the method of planting (Fig. 2.10f2).

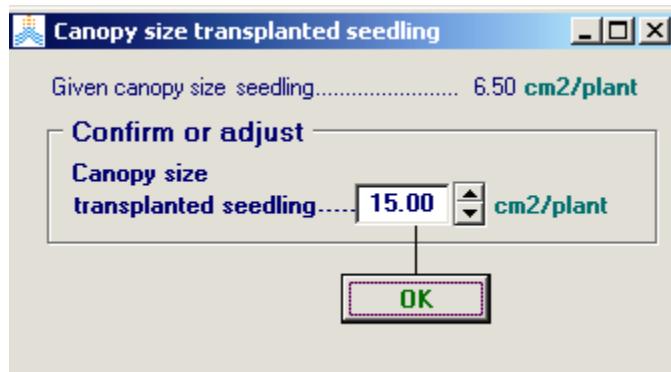


Figure 2.10f2 – Confirming the canopy size of the transplanted seedling when altering the planting method from direct sowing to transplanting in the *Canopy size transplanted seedling* menu

Specifying the initial canopy cover (CC_0)

CC_0 can be specified by:

- specifying the plant density in the *Crop characteristics* menu;
- specifying the sowing rate or plant spacing. This option becomes available by clicking on the <estimate> command in the *Crop characteristics* menu. The plant density in the *Estimate plant density* menu is calculated from the specified sowing rate and approximate germination rate, or from the specified row and plant spacing (Fig. 2.10f3);
- selecting one of the classes ranging from very small to very high cover (Tab. 2.10f1);
- specifying directly the percentage in the *Crop characteristic* menu, which might be required for transplanted seedlings.

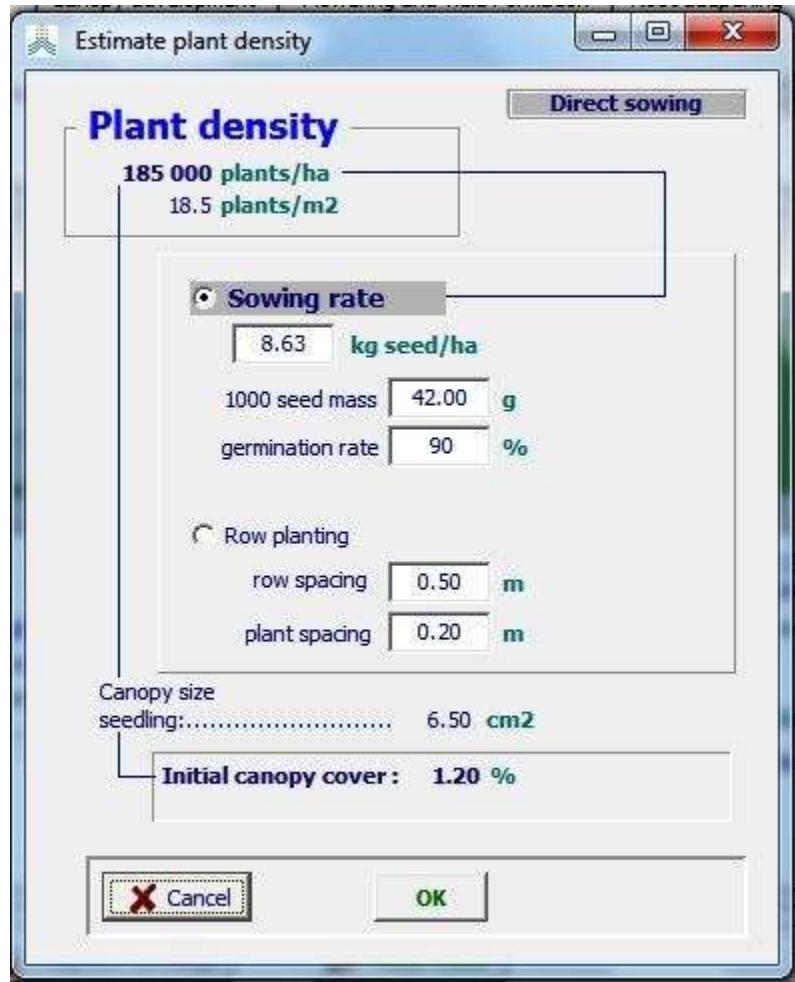


Figure 2.10f3 – Estimation of plant density from sowing rate or plant density in the *Estimate plant density* menu

Table 2.10f1 – Classes, corresponding default values, and ranges for the initial canopy cover (CC_0)

| Class | Default value | Range |
|--|---------------|------------------|
| Very small cover | 0.10 % | 0.10 ... 0.12 % |
| Small canopy cover | 0.20 % | 0.13 ... 0.30 % |
| Good canopy cover | 0.40 % | 0.31 ... 0.50 % |
| High canopy cover | 0.70 % | 0.51 ... 0.70 % |
| Very high cover (mostly for transplants) | 1.50 % | 0.71 ... 10.00 % |

- **Canopy development**

Canopy expansion for no stress condition is described by two equations (see Chapter 3 – section 3.4.1 ‘Green canopy cover throughout the crop cycle’) requiring information on (i) initial canopy cover (CC_o), (ii) maximum canopy cover (CC_x) for that plant density under optimal conditions, and (iii) canopy growth coefficient (CGC). Once senescence starts, CC declines. To simulate the canopy decline, the starting time of senescence and a canopy decline coefficient (CDC) are required. The crop parameters governing canopy expansion and decline are displayed in the canopy development sheet of the *Crop characteristics* menu (Fig. 2.10f4).

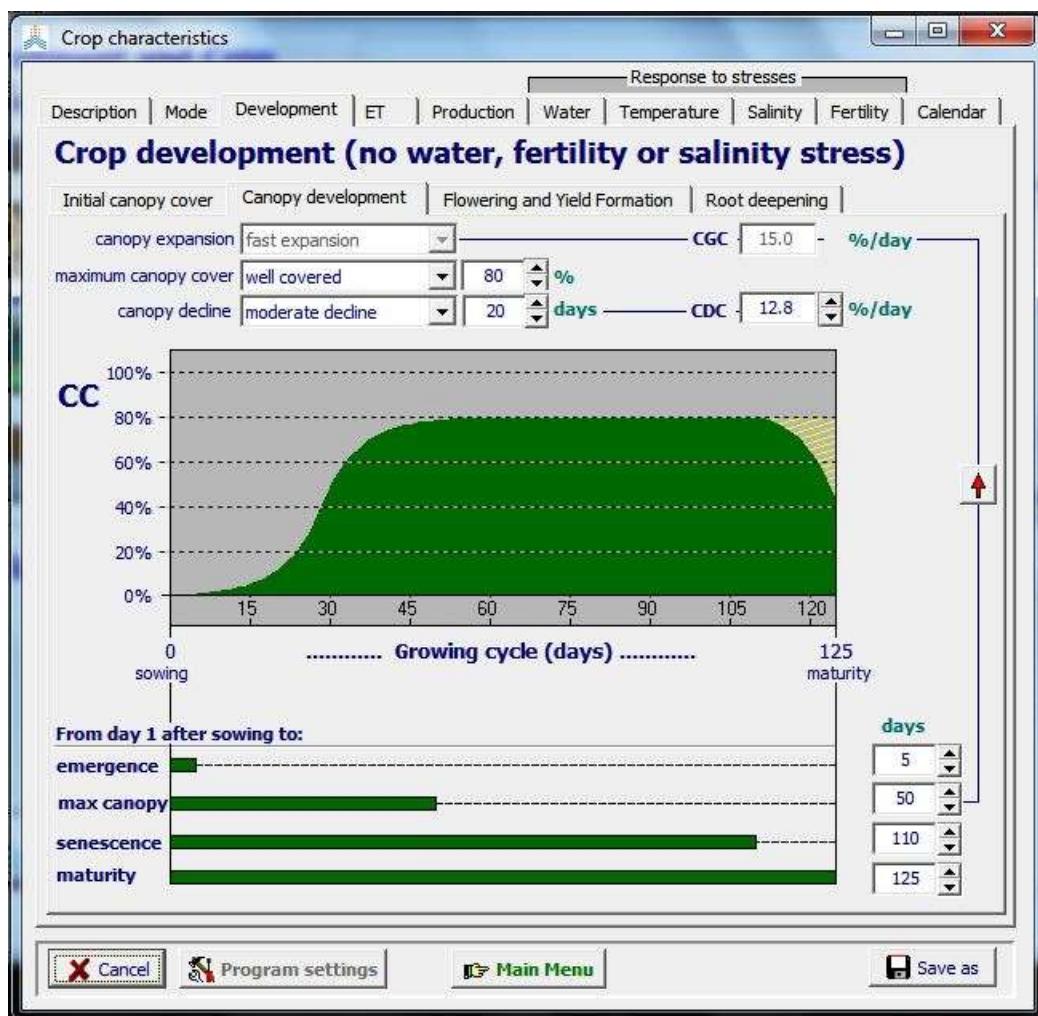


Figure 2.10f4 – Specification of canopy development in the *Crop characteristics* menu

Time to emergence: It is the time required from sowing to reach 90% emergence. Because field preparation, soil temperature and water content vary with each case, the time to emergence is user specific.

Canopy Growth Coefficient (CGC) and the corresponding time to reach maximum canopy: CGC is a conservative crop parameter. AquaCrop provides alternative procedures to specify CGC or the corresponding time required to reach CC_x :

- If the red arrow is downwards (Fig. 2.10f4) the time to reach maximum canopy cover is derived from the specified canopy growth coefficient;
- If the red arrow is upwards the canopy growth coefficient is derived from the specified time to reach maximum canopy cover;
- The canopy growth coefficient can also be specified by selecting one of the classes ranging from very slow to very fast expansion (Tab. 2.10f2).

Table 2.10f2 – Classes, corresponding default values, and ranges for the Canopy Growth Coefficient (CGC) for no stress conditions

| Class | Default value | Range |
|---------------------|---------------|---------------------|
| Very slow expansion | 3 %/day | 2.0 ... 4.0 %/day |
| Slow expansion | 6 %/day | 4.1 ... 8.0 %/day |
| Moderate expansion | 10 %/day | 8.1 ... 12.0 %/day |
| Fast expansion | 15 %/day | 12.1 ... 16.0 %/day |
| Very fast expansion | 18 %/day | 16.1 ... 40.0 %/day |

Maximum canopy cover (CC_x): Maximum canopy cover is dependent on plant density, CC per seedling at 90% emergence, and CGC. The user selects one of the classes which range from ‘thinly covered’ to ‘entirely covered’ (Tab. 2.10f3). AquaCrop displays the corresponding ground cover at maximum canopy. CC_x can also be specified by entering directly the percentage.

Table 2.10f3 – Classes, corresponding default values, and ranges for the expected maximum canopy cover (CC_x) for no stress conditions

| Class | Default value | Range |
|-------------------------|---------------|--------------|
| Very thinly covered | 40 % | 11 ... 64 % |
| Fairly covered | 70 % | 65 ... 79 % |
| Well covered | 90 % | 80 ... 89 % |
| Almost entirely covered | 95 % | 90 ... 98 % |
| Entirely covered | 99 % | 99 ... 100 % |

Senescence starting time: The time at which canopy senescence starts for optimal conditions. The senescence starting time depends on phenology and is cultivar specific.

Canopy Decline Coefficient (CDC): By selecting one of the classes for canopy decline ranging from very slow to very fast decline (Tab. 2.10f4), the canopy decline coefficient (CDC) is derived from the number of days required to achieve full senescence. The canopy decline coefficient can also be specified directly. The canopy decline coefficient is assumed to be conservative.

Table 2.10f4 – Classes, corresponding default values, and ranges for canopy decline expressed in days to achieve full senescence

| Class | Default value | Range |
|-------------------|---------------|-------------------|
| Very slow decline | 5 weeks | more than 31 days |
| Slow decline | 4 weeks | 25 ... 31 days |
| Moderate decline | 3 weeks | 18 ... 24 days |
| Fast decline | 2 weeks | 13 ... 17 days |
| Very fast decline | 10 days | less than 13 days |

Time to maturity: The user specifies the time at which maturity is reached. Although the crop can be harvested later it is assumed that the crop production no longer changes.

- **Flowering and yield formation (fruit/grain producing crops)**

The crop parameters to be specified are (i) the time of start of flowering, (ii) duration of flowering, (iii) the time required to build up the Harvest Index (HI), and (iv) if determinancy linked with flowering (Fig. 2.10f5). These parameters are mainly cultivar specific.

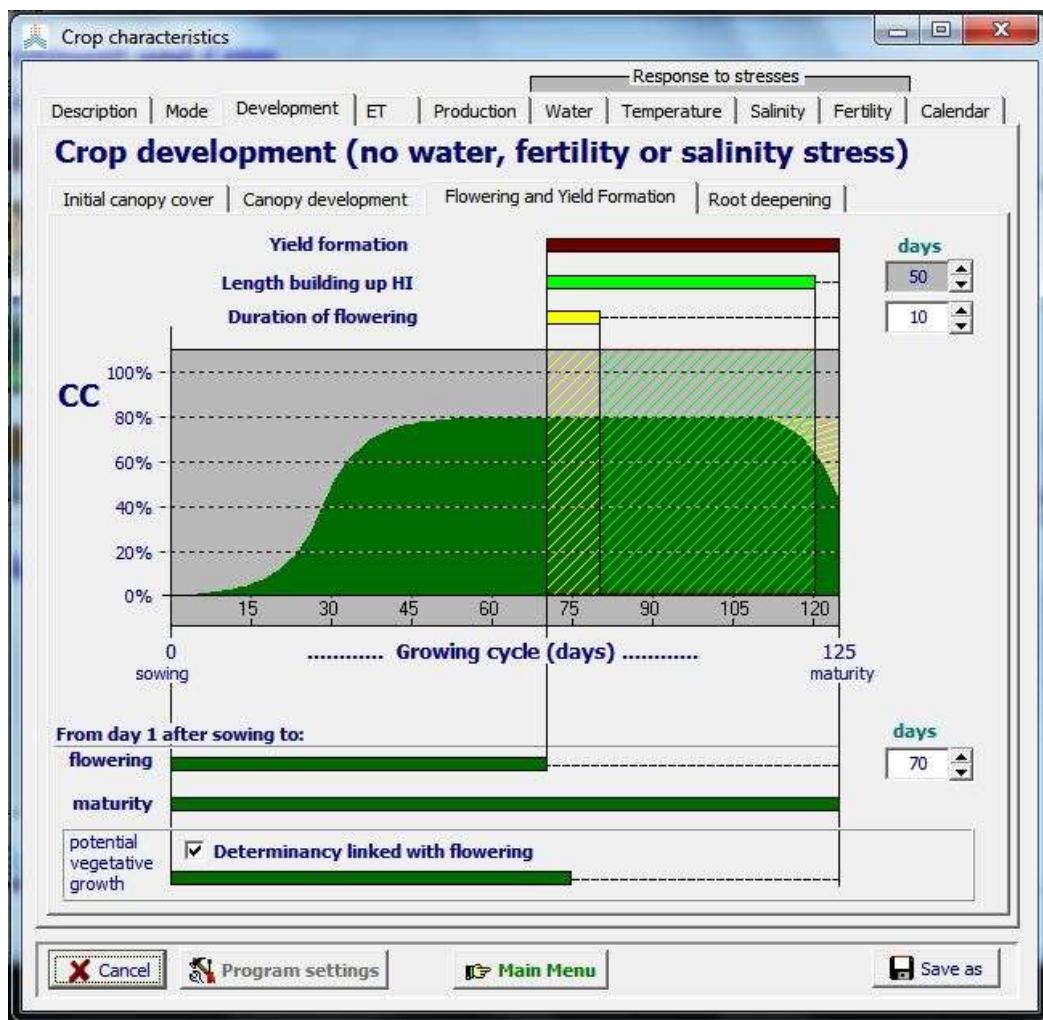


Figure 2.10f5 – Specification of flowering and time required to build up the Harvest Index for fruit/grain producing crops in the *Crop characteristic* menu for a crop where determinancy is linked with flowering

If the <Determinancy linked with flowering> check button is checked (Fig. 2.10f5), the crop is determinant, and the canopy cover is assumed to have the potential growth (if $CC < CC_x$) up to peak flowering (set at half of the duration of flowering) but not thereafter. If due to the selection of the time of flowering, CC_x can not be reached at peak flowering, AquaCrop adjust in the *Crop characteristics* menu the duration of flowering until the conditions can be fulfilled.

If the determinancy button is not checked (Fig. 2.10f6) the canopy development can stretch till canopy senescence. The corresponding period for potential vegetative growth is displayed.

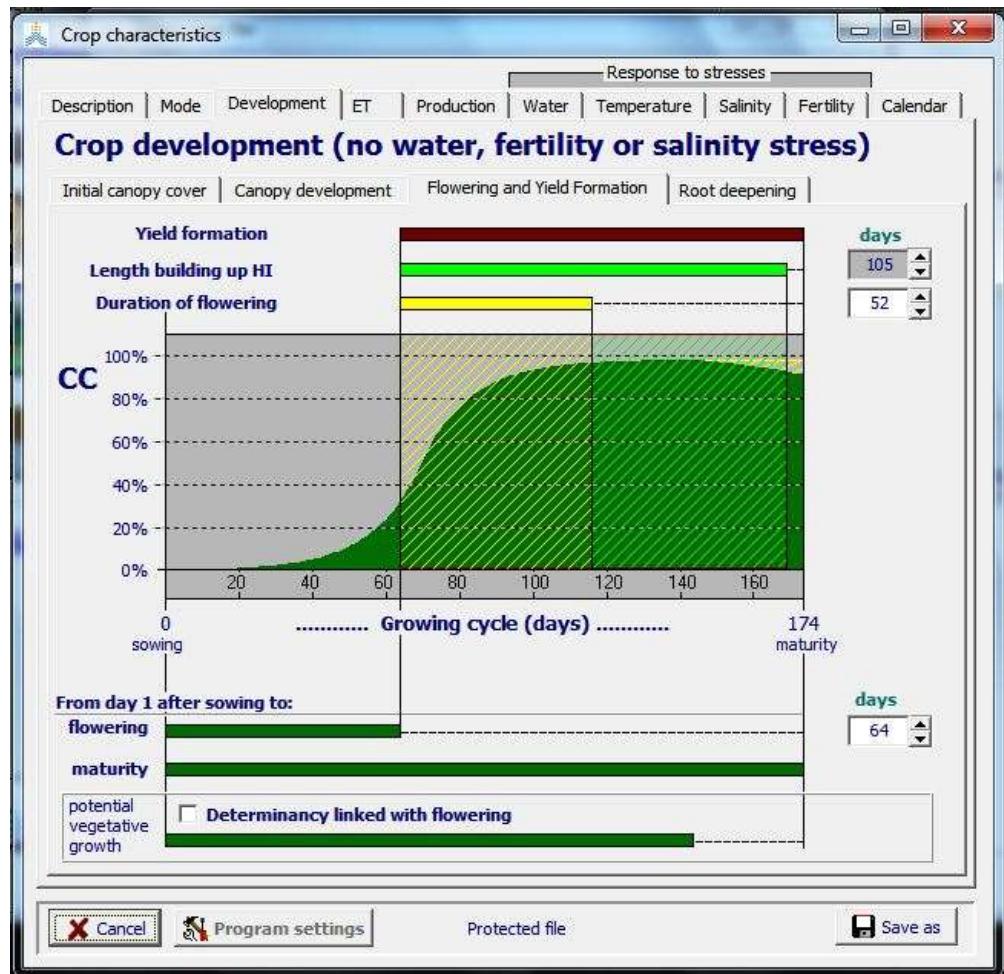


Figure 2.10f6 – Specification of flowering and time required to build up the Harvest Index for fruit/grain producing crops in the *Crop characteristic* menu for a crop where determinancy is not linked with flowering, such as cotton

The time required for the Harvest Index (HI) to increase from 0 (at flowering) to its reference values (HI_o) under optimal conditions is the duration for building up HI. The Harvest Index should be able to reach its reference value at or shortly before maturity.

- **Root/Tuber formation (root/tuber crops)**

The crop parameters to be specified are (i) the start of tuber formation or root enlargement, and (ii) the time required to build up the Harvest Index (HI) (Fig. 2.10f7). These parameters are mainly cultivar specific.

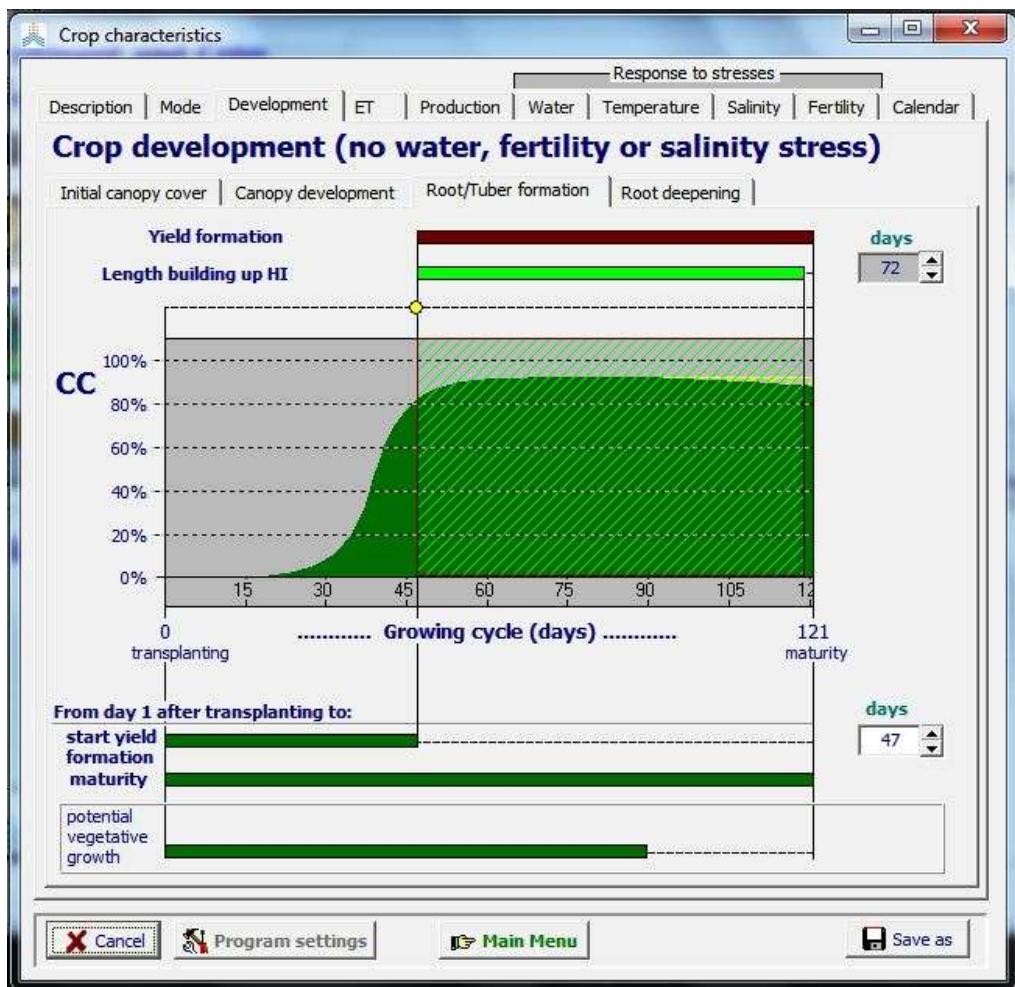


Figure 2.10f7 – Specification of the start of yield formation and the time required to build up the Harvest Index for root/tuber crops in the *Crop characteristic* menu

Root/Tuber crops are assumed to be indeterminant. Hence the canopy development can stretch till canopy senescence. The corresponding period for potential vegetative growth is displayed in the menu.

The time required for the Harvest Index (HI) to increase from 0 (at the start of tuber formation or root enlargement) to its reference values (HI_o) under optimal conditions is the duration for building up HI. The Harvest Index should be able to reach its reference value at or shortly before maturity.

- **Root deepening**

The crop parameters for root deepening are (i) the maximum effective rooting depth and (ii) the time reached, (iii) the minimum effective rooting depth and (iv) a shape factor for the rooting depth (Z) time curve (Fig. 2.10fb8). The maximum effective rooting depth and the required to reach it, are user specific as root development is strongly impacted by local soil conditions and the life cycle length of the crop.

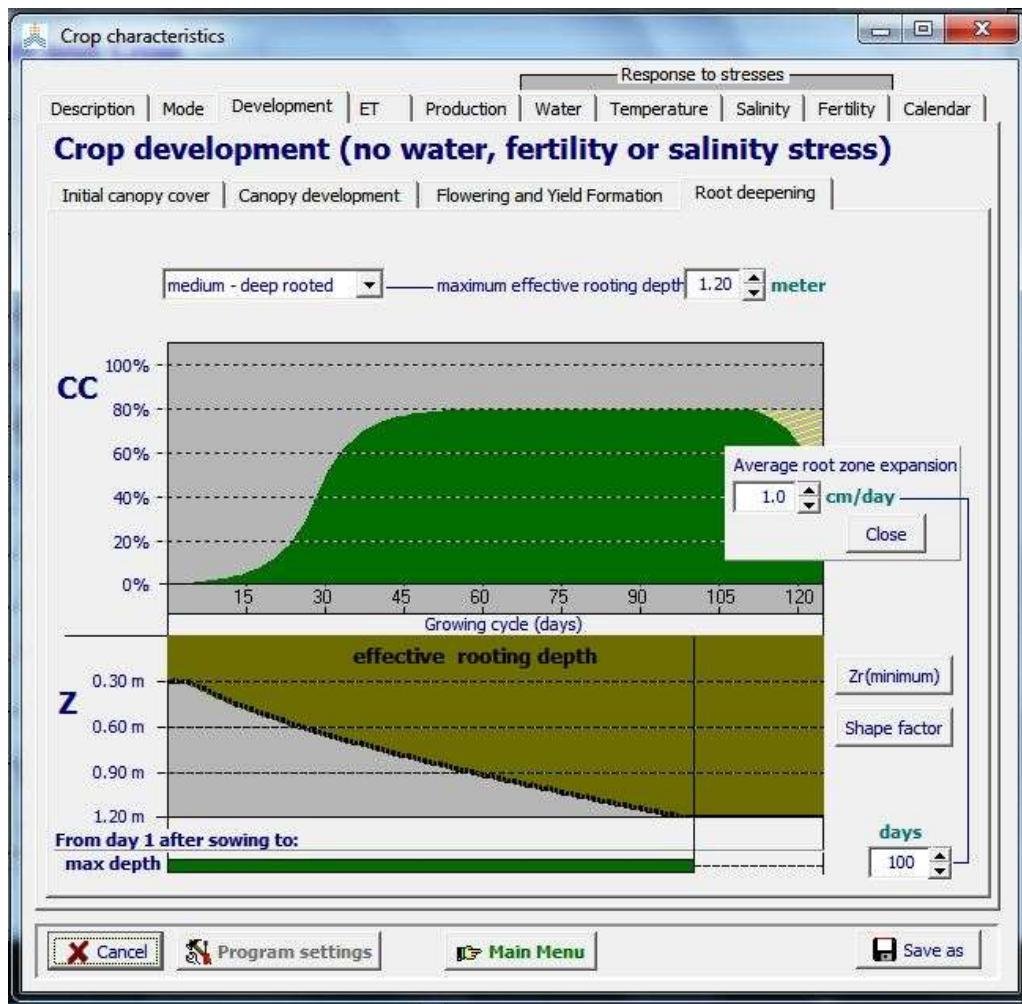


Figure 2.10f8 – Specification of root deepening in the *Crop characteristic* menu

The **maximum effective rooting depth** can be specified by:

- selecting one of the classes which range from ‘shallow rooted crops’ to ‘very deep-rooted crops’ (Tab. 2.10f5). The shallow rooted crops category is only applicable to rice and crops with very short life cycle such as radish. AquaCrop displays the corresponding maximum effective rooting depth;
- by entering directly the numeric value in meter.

Table 2.10f5 – Classes, corresponding default values, and ranges for maximum effective rooting depth of the fully developed crop under optimal conditions

| Class | Default value | Range |
|------------------------------------|---------------|---------------|
| Shallow rooted crops | 0.40 m | 0.10 ... 0.59 |
| Shallow – medium rooted | 0.80 m | 0.60 ... 0.99 |
| Medium rooted crops | 1.20 m | 1.00 ... 1.39 |
| Medium – deep rooted | 1.60 m | 1.40 ... 1.79 |
| Deep rooted crops | 2.00 m | 1.80 ... 2.19 |
| Very deep rooted crops (perennial) | 2.40 m | 2.20 ... 4.00 |

The **time required to reach the maximum effective rooting depth** can be specified by:

- specifying the average root zone expansion rate. As a general rough guide for field crops in general, the roots deepening rate is about 1 cm per day but might be up to 2 cm per day when the environment is optimal for growth, the soil is not cold and soil layers that limits growth are absent;
- specifying the directly the days at which the maximum rooting depth is reached.

The **minimum effective rooting depth** refers to the depth from which the germinating seedling can extract water. For simulation purposes a depth of 0.20 to 0.30 m is generally considered.

By varying the **shape factor** of the Z versus time curve, the expansion rate of the root zone can be altered between planting and the time when the maximum rooting depth is reached.

The effective rooting depth will not reach its maximum value if a restrictive soil horizon limits root development or when the exploitable soil depth is smaller than the maximum rooting depth. The root deepening rate is described by the shape factor, but once the effective rooting depth reaches the restrictive soil horizon, the expansion is slowed down or even halted depending on the permeability of the soil horizon (soil profile characteristic). Below the restrictive soil horizon, the root zone expansion is normal again, and no longer restricted. However, due to the delay in expanding, the effective rooting depth can no longer reach its maximum value (Fig. 2.10f9).

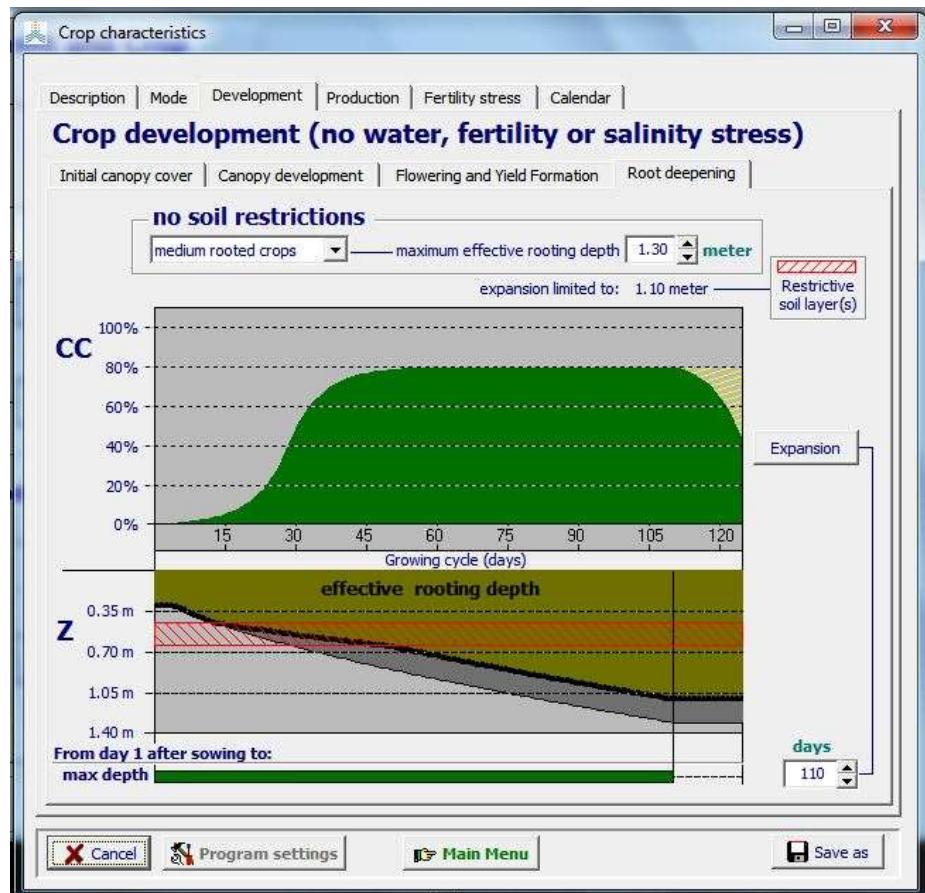


Figure 2.10f9 – Effect of a restrictive soil layer on root development

2.10.7 Tabular sheet: Evapotranspiration

- Coefficients

Crop coefficient for maximum transpiration ($Kc_{Tr,x}$)

Crop transpiration from a well water soil is proportional to the effective canopy cover (CC). The proportional factor is the coefficient for maximum transpiration ($Kc_{Tr,x}$). It is the crop coefficient when canopy cover is complete (CC = 1) and without stresses. $Kc_{Tr,x}$ is conservative and approximately equivalent to the basal crop coefficient at mid-season of FAO Irrigation and Drainage Paper 56 but only for cases of full CC.

After the time required to reach the maximum canopy cover (CC_x) under optimal conditions and before senescence, the canopy ages slowly and undergoes a progressive though small reduction in transpiration and photosynthetic capacity. This is simulated by reducing $Kc_{Tr,x}$ by a constant and very slight fraction per day (Fig. 2.10g1).

In the ‘Evapotranspiration’ tabular sheet, the crop transpiration coefficient (Kc_{Tr}) is plotted from sowing to maturity (Fig. 2.10g1).

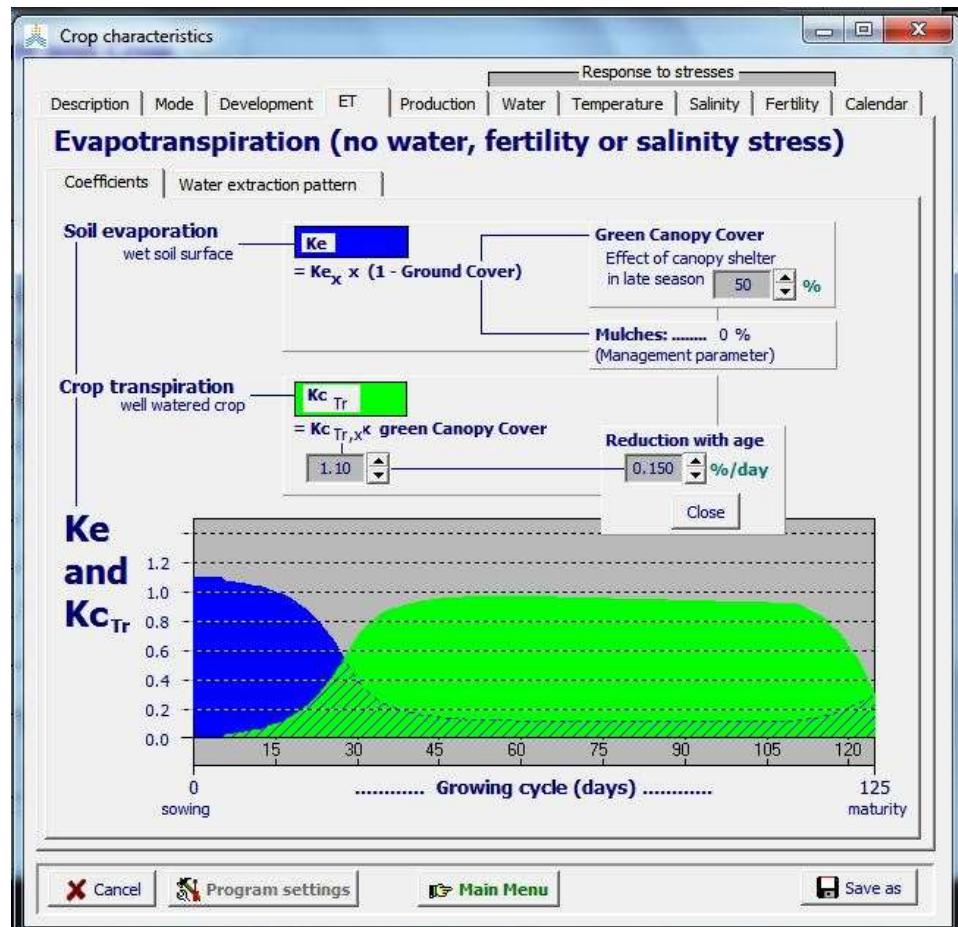


Figure 2.10g1 – Response of the soil evaporation (Ke) and the crop transpiration (Kc_{Tr}) coefficients to canopy development and decline during the growing cycle for non-limiting conditions

Soil evaporation coefficient (Ke_x)

Evaporation from a fully wet soil surface is proportional to the soil surface not covered by the canopy cover ($1 - CC$). The proportional factor is the soil evaporation coefficient for fully wet and unshaded soil surface (Ke_x) which is a program parameter (see 2.10.16 Program settings) with a default value of 1.1. When canopy cover declines (senesces) late in the season as dictated by phenology, or as induced by water, nutrient or salinity stress, soil evaporation remains somewhat reduced by the sheltering effect of the yellow or dead canopy cover. The effect of canopy shelter is parameterized based on whether the senescing canopy retains more or less of its dead leaves.

In the ‘Evapotranspiration’ tabular sheet, the soil water evaporation coefficient (Ke) is plotted from sowing to maturity (Fig. 2.10g1).

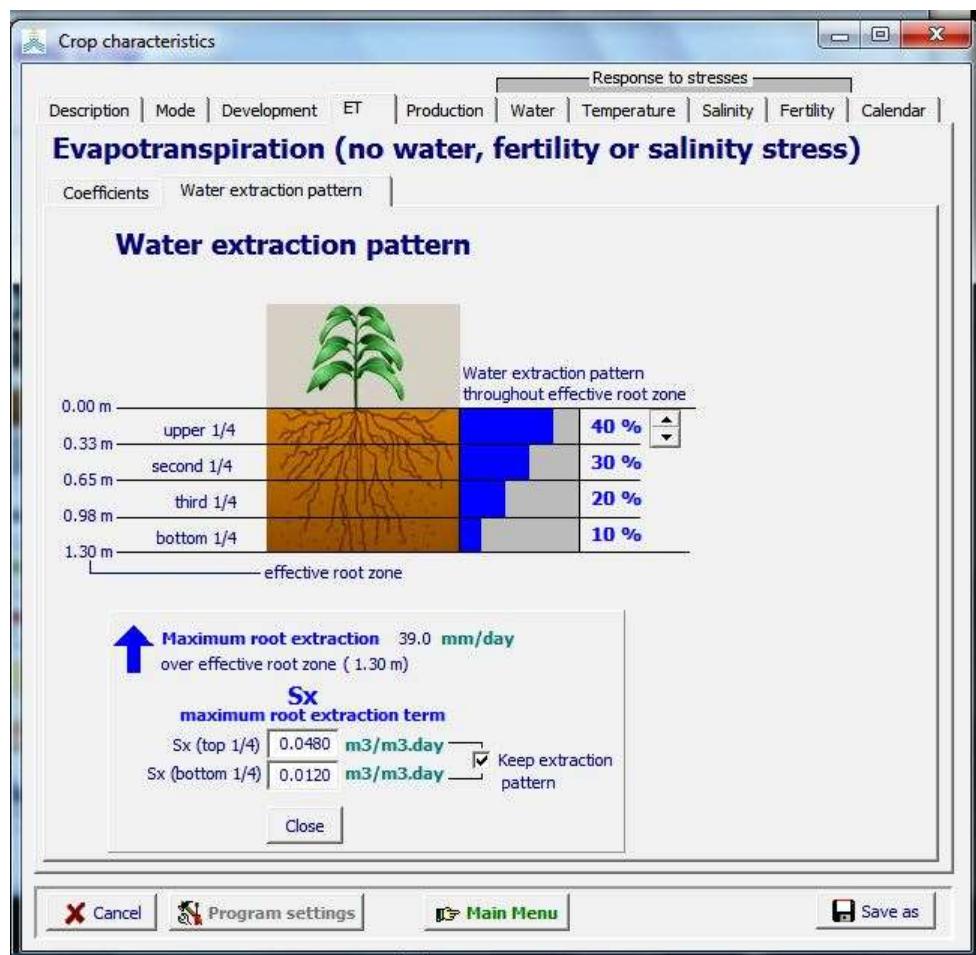


Figure 2.10g2 – Derived maximum extraction terms (S_x) at the top and bottom of the root zone after the specification of the water extraction pattern and the maximum root extraction

- **Water extraction pattern**

The root water extraction from the soil profile is governed by the actual soil water content and the maximum amount of water (S_x) that can be extracted by the roots per unit of bulk volume of soil, per unit of time (m^3 water per m^3 soil per day). Distinction is made between the (Fig. 2.10g2):

- maximum root extraction in top quarter of the root zone;
- maximum root extraction in bottom quarter of the root zone

which are both non-conservative crop parameters, and can be altered by the user. S_x at the top of the soil profile is generally different from S_x at the bottom of the root zone. The range and default values for S_x are given in Table 2.10g.

Table 2.10g – The range and default values for the maximum root extraction at the top ($S_x(\text{top } \frac{1}{4})$) and bottom ($S_x(\text{bottom } \frac{1}{4})$) quarter of the root zone for various maximum rooting depths (Zx)

| Variable | Range S_x $\text{m}^3(\text{water}) \text{ per } \text{m}^3(\text{soil}) \text{ per day}$ | Default S_x | Condition for Zx |
|-----------------------------------|--|---|------------------|
| $S_x(\text{top } \frac{1}{4})$ | 0.030 – 0.060 | 0.048 | $Zx \leq 2$ |
| | | $0.030 + 0.018 \frac{4 - Zx}{2}$ | $2 < Zx \leq 4$ |
| $S_x(\text{bottom } \frac{1}{4})$ | 0.001 – 0.060 | $S_{x_{(\text{top } \frac{1}{4})}} \frac{P_4}{P_1}$ | - |

By specifying the water extraction pattern throughout the root zone, and values for the S_x at the top and bottom quarter of the root zone, AquaCrop derives the S_x values for different depths in the root zone and displays the maximum root extraction rate of a well-developed crop (Fig. 2.10g2).

If a restricted expansion of the root zone is the result of limitations in the soil profile (such as the presence of a restrictive soil horizon), new roots still continue to be formed. Since the expansion of the root zone is limited or inhibited, the new formed roots concentrate above the restrictive soil layer. This result in an increase of S_x at the bottom of the root zone and alters the root distribution (water extraction pattern) in the top soil (Fig. 2.10g3).

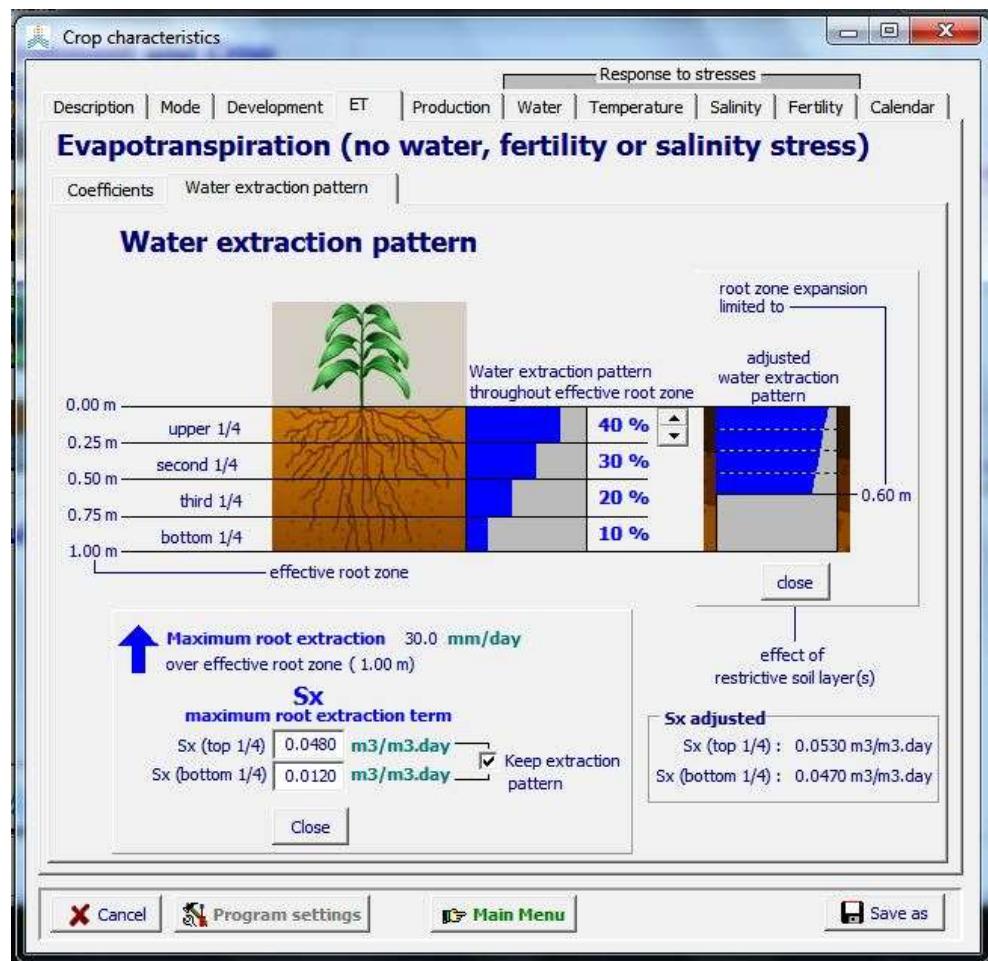


Figure 2.10g3 – Maximum water extraction pattern (root distribution) when maximum rooting depth of 1 meter is reached, and the adjusted pattern in the soil profile when a layer at 0.6 m blocks completely the further development of the root zone as displayed in the ‘ET’ tabular sheet of the *Crop characteristics* menu.

2.10.8 Tabular sheet: Production

- Crop water productivity normalized for climate and CO₂ (WP*)**

To simulate biomass and yield, the water productivity normalized for climate and air CO₂ concentration (WP*) is required. WP* is a conservative parameter. For use with crop species without calibrated WP*, general ranges are provided by AquaCrop for C3 and C4 species. If the harvestable organ is rich in oil and/or proteins, WP* after the beginning of flowering must be reduced over the yield formation period, by multiplying it by an adjustment factor entered by the user (Fig. 2.10h1).

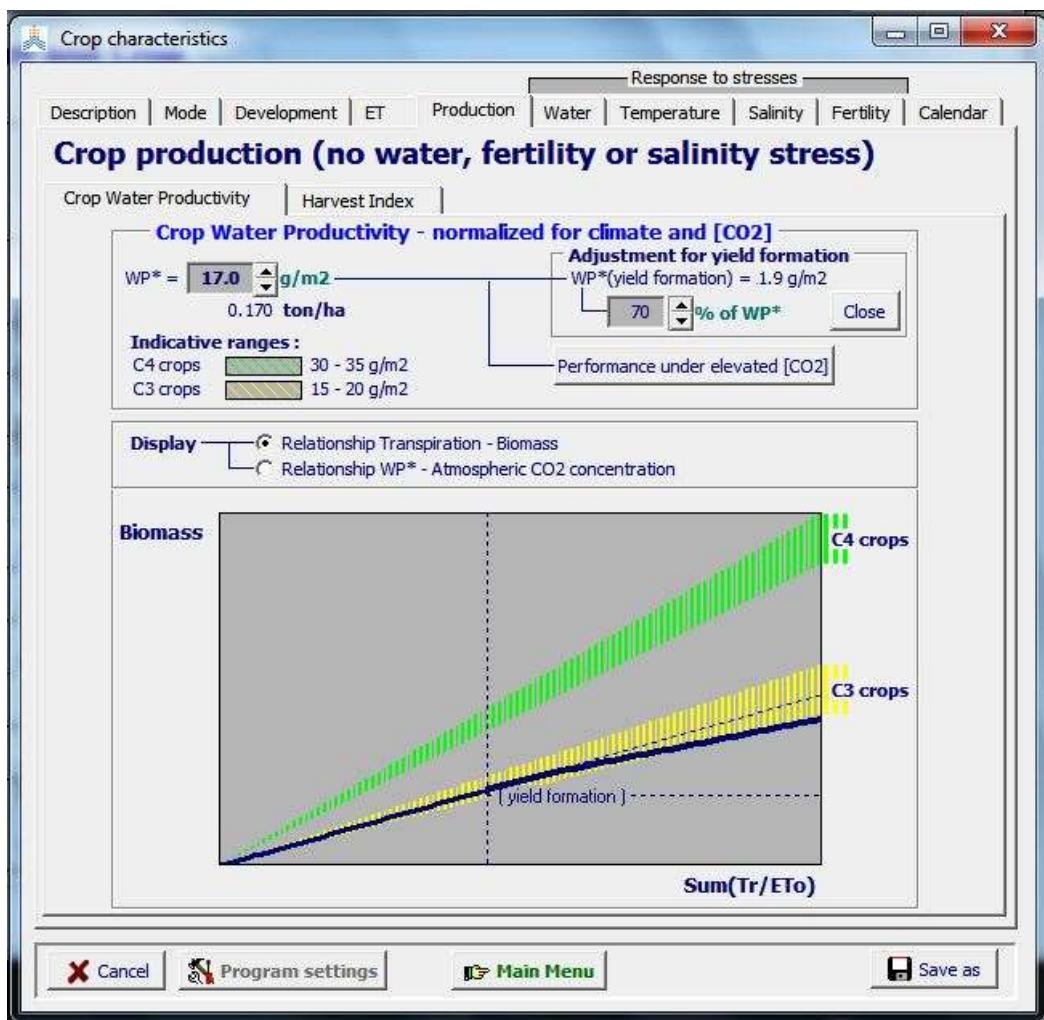


Figure 2.10h1 – The water productivity normalized for climate and atmospheric CO₂ and its adjustment if the harvestable organs are rich in oil and/or proteins

- Performance under elevated atmospheric CO₂ concentration**

WP* is adjusted when running a simulation with an atmospheric CO₂ concentration different from the reference value (i.e. 369.41 ppm measured at Mauna Loa, Hawaii at the year 2000). The adjustment is obtained by multiplying WP* with a correction coefficient as discussed in Chapter 3 (Section 3.11 ‘Dry above-ground biomass’). The theoretical adjustment might not be entirely valid when (i) soil fertility is not properly adjusted to the higher productivity under elevated CO₂ concentration, and/or (ii) the sink capacity of the current crop variety is yet not able to take care of the elevated CO₂ concentration. The performance of the crop under elevated atmospheric CO₂ concentration can be adjusted by the user by altering its sink strength in accordance with the expected soil fertility management and the cultivar (Fig. 2.10h2). Ranges for indicative values for sink strengths are given in Table 2.10h.

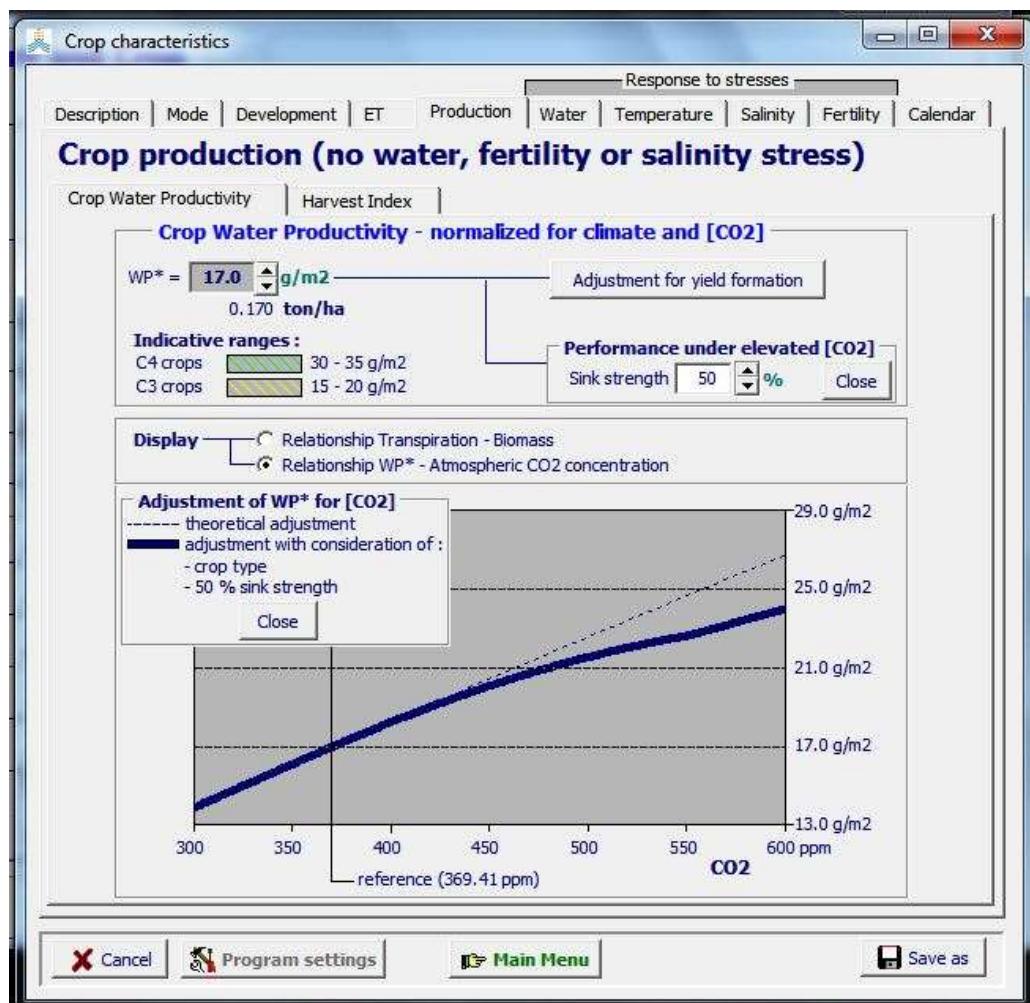


Figure 2.10h2 – The water productivity adjusted to atmospheric CO₂ concentration by considering crop type and crop sink strength

Table 2.10h – Range of indicative values for sink strength for 10 crops available in the database of AquaCrop (Vanuytrecht et al., 2011)

| Crop | Class and indicative value range for sink strength |
|--|--|
| Cereals: Maize (<i>Z. mays</i> L.), Rice (<i>Oryza sativa</i> L.), Wheat (<i>Triticum aestivum</i> L.) Sunflower (<i>Helianthus annuus</i> L.) | Low (0.00–0.20) |
| Legumes: Soybean (<i>Glycine max</i> (L.) Merr.) | Moderate low (0.20–0.40) |
| Indeterminate growth habit: Tomato (<i>Solanum lycopersicum</i> L.), Quinoa (<i>Chenopodium quinoa</i> Willd.) | Moderate low (0.20–0.40) |
| Woody species: Cotton (<i>Gossypium hirsutum</i> L.) | Moderate high (0.40–0.60) |
| Root and tuber crops: Potato (<i>S. tuberosum</i> L.), Sugar beet (<i>Beta vulgaris</i> L.) | High (0.60–0.80) |
| <p>Based on the analysis of crop responses in FACE environments and knowledge on sink capacity available in the literature, Vanuytrecht et al. (2011) specified indicative values for sink strength for different crop species currently listed in the database of AquaCrop. Proposed values for sink strength of cereals (such as maize, rice, wheat) and sunflower were low because these crops do not show high responsiveness to elevated [CO₂] due to limited sink capacity. Nitrogen-fixing crop species (such as soybean) were attributed with a higher sink strength value because these crops are less prone to nitrogen deficiency that can limit sink strength. Higher sink strength values were proposed for crops with an indeterminate growth habit (such as quinoa, tomato), which have a higher responsiveness to elevated [CO₂]. Crops that are expected to maintain a good source–sink balance, such as woody species (cotton) and tuber crops (potato, sugar beet), got high sink strength values.</p> <p>It must be emphasized that the indicative sink strength values in the Table provide well-considered starting values but are not definitive. For more reflections see Vanuytrecht et al. (2011).</p> | |
| <p>Reference: Vanuytrecht, E., Raes, D., Willems, P. 2011. Considering sink strength to model crop production under elevated atmospheric CO₂. Agricultural and Forest Meteorology 151: 1753– 1762.</p> | |

- **Reference Harvest Index (HI_o)**

The reference Harvest Index (HI_o) is the representative HI reported in the literature for the chosen crop species under non-stress conditions. HI_o is conservative to a fair extent but can be cultivar specific.

Fruit or grain producing crops

Beginning at the start of flowering HI increases linearly after a lag phase until physiological maturity is reached (Fig. 2.10h3). The value reached at maturity under non-stress conditions is taken as HI_o for that species.

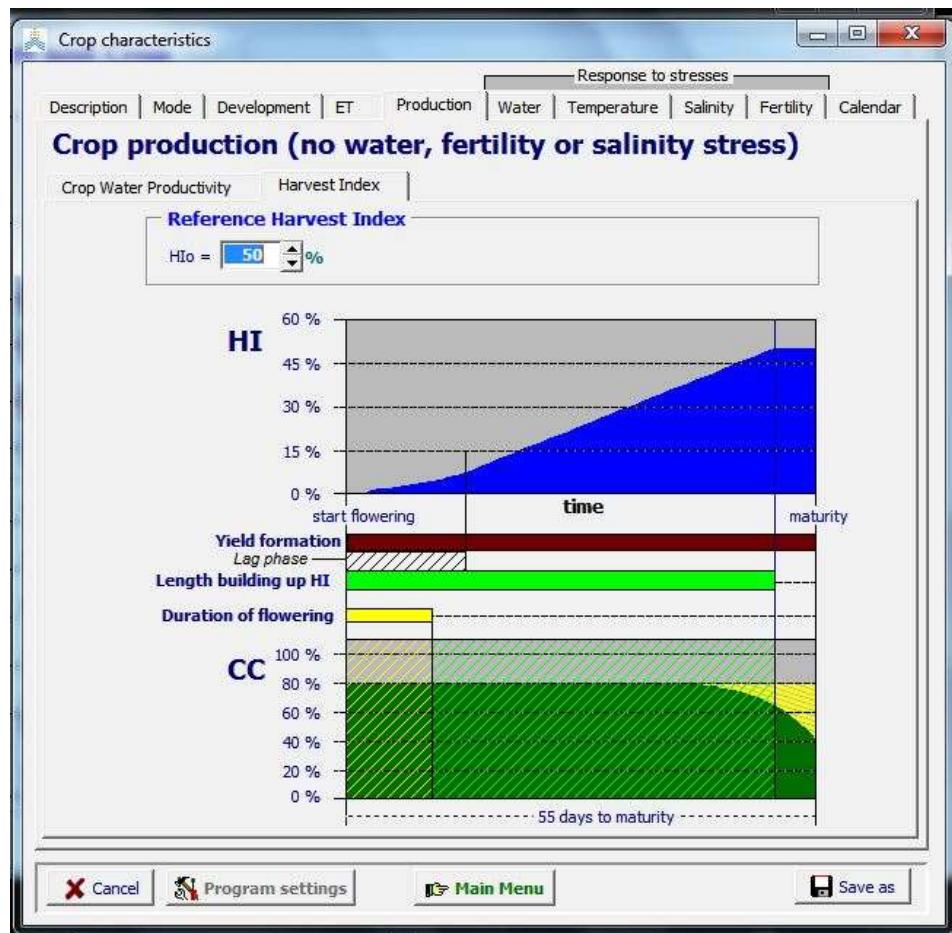


Figure 2.10h3 – Specification of the reference harvest index (HI_o) and the display of the building up of the Harvest Index from flowering to physiological maturity for a fruit or grain producing crop

Root and tubers

Beginning at tuber formation or root enlargement HI increases until physiological maturity (Fig. 2.10h4). The building up of the Harvest Index is described by a logistic function. The value reached at maturity under non-stress conditions is taken as HI_o for that species.

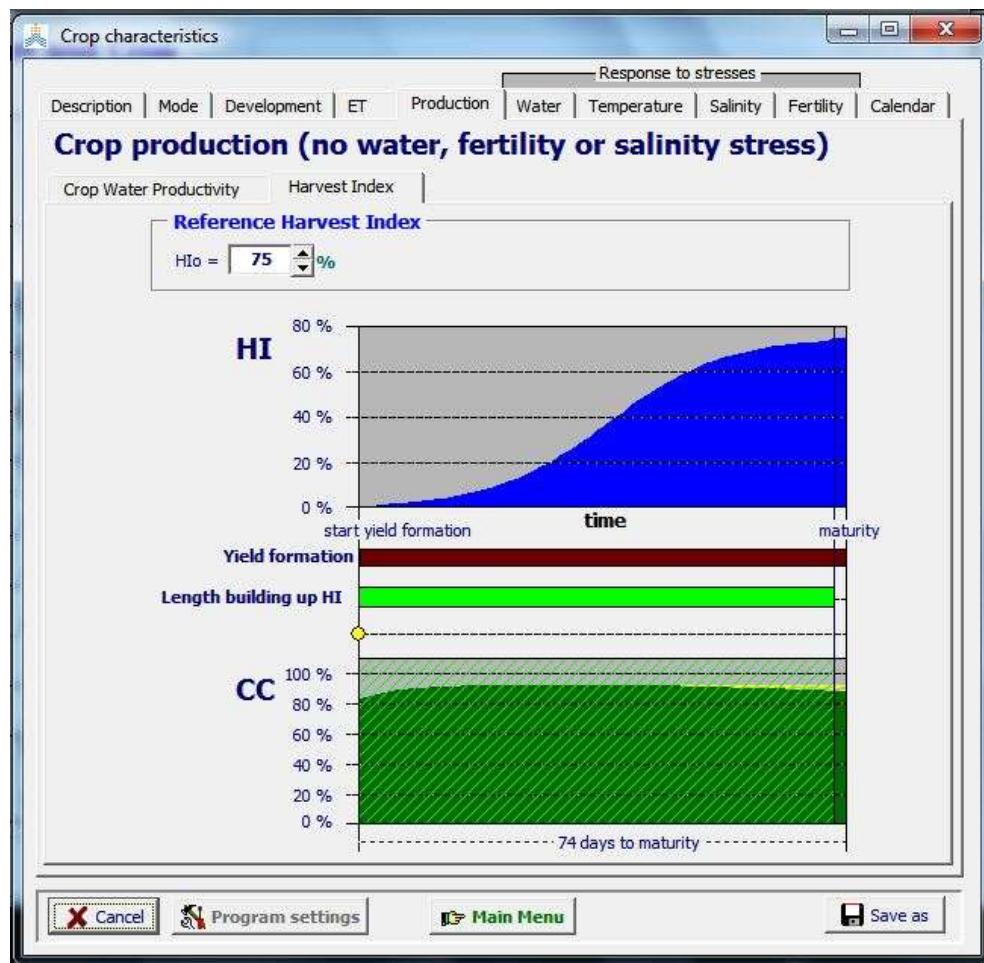


Figure 2.10h4 – Specification of the reference harvest index (HI_o) and the display of the building up of the Harvest Index from the tuber formation or root enlargement to physiological maturity for roots and tubers

Leafy vegetable crops

Beginning at germination, HI increases with a logistic equation till the reference harvest indeed (HIo) is reached (Fig. 2.10h5). For leafy vegetable crops, the time to reach HIo is expressed as a percentage of the growing cycle.

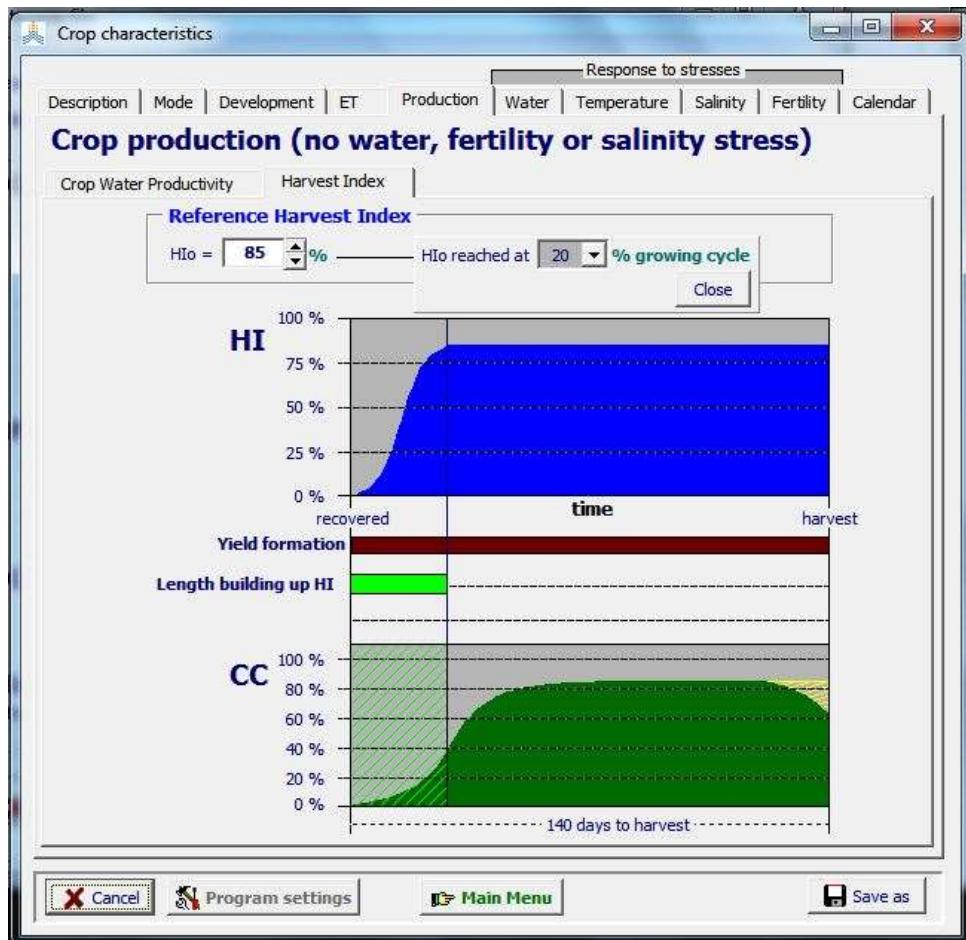


Figure 2.10h5 – Specification of the reference harvest index (HIo) and the time to reach HIo for leafy vegetable crops

2.10.9 Tabular sheet: Water stress

- Canopy expansion, stomatal conductance and early canopy senescence**

Effects of water stress on canopy expansion, stomatal conductance, and early canopy senescence are described by water stress coefficients K_s . Above an upper threshold of soil water depletion in the root zone, water stress is not considered and K_s is 1. Below a lower threshold, the stress is at its full effect and K_s is 0 (Fig. 2.10i1). The user can specify in the corresponding menus threshold values and curve shape, or can select a category graded for relative resistance to water stress.

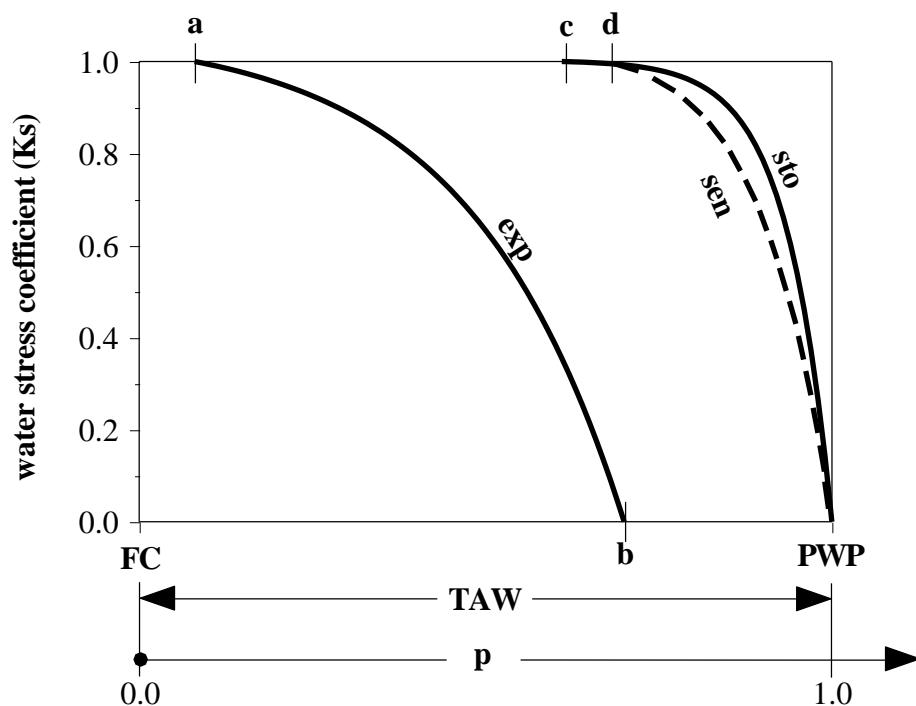


Figure 2.10i1 – Examples of the variation of the water stress coefficient for leaf expansion (exp), stomatal conductance (sto) and canopy senescence (sen) for various soil water depletions in the root zone

Thresholds: The thresholds are expressed as a fraction (p) of the Total Available soil Water (TAW). TAW is the amount of water a soil can hold between field capacity (FC) and permanent wilting point (PWP) in the root zone. For leaf and hence canopy growth, the lower threshold is above PWP ($p < 1$), whereas for stomata and senescence the lower threshold is fixed at PWP ($p = 1$).

Shape of K_s curve: Between the upper and lower thresholds the shape of the K_s curve determines the magnitude of the effect of soil water stress on the process. The shape can be linear or convex (Fig. 2.10i2). Tests so far suggest that the thresholds and shapes of

these curves may be conservative, at least to a fair degree. The shape factor can range from +6 (strongly convex) to 0 (linear).

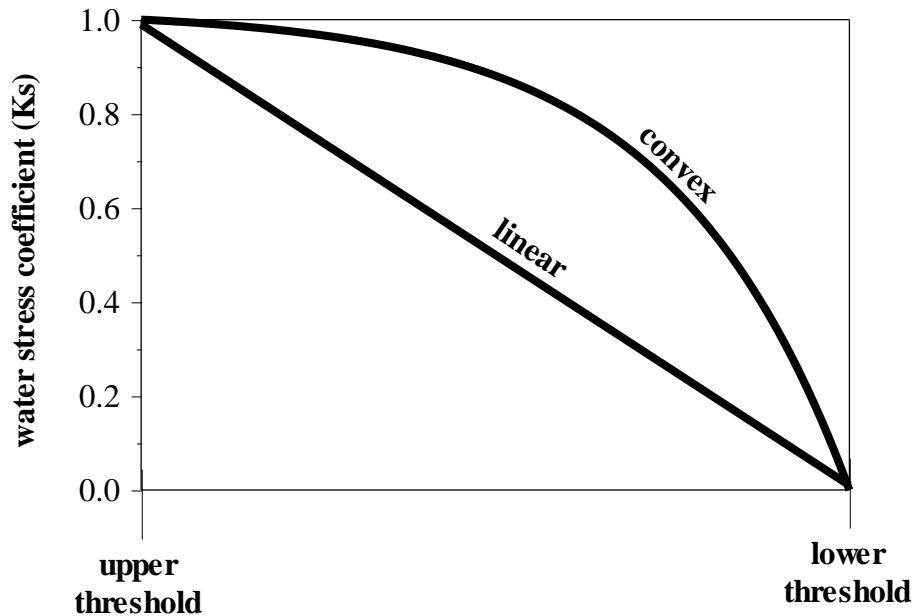


Figure 2.10i2 – Convex and linear shapes of the Ks curve

Adjustment by ET_o : Generally leaf and plant water status are partially dependent on transpiration rate, being lower for higher rate of transpiration. AquaCrop simulate this effect indirectly by adjusting the Ks curve according to ET_o . The specified soil water depletion factors (p) are for a reference evaporative demand of $ET_o = 5 \text{ mm/day}$, and the p is adjusted at run time for different levels of ET_o . The shaded bands in the corresponding displays (Fig. 2.10i3), on the two sides of the curved line indicate the range of the evaporative demand adjustments as dictated by ET_o . The adjustment is not considered if the correction for ET_o is switched off.

Canopy expansion: Leaf growth by area expansion (expansive growth) and therefore canopy development are the highest in sensitivity to water stress among all the plant processes described by the model. The user specifies the effect of water stress on leaf expansion growth by selecting a sensitivity class (Tab. 2.10i1, Fig. 2.10i3) or by specifying values for an upper and lower soil water depletion thresholds (p):

- $p(\text{upper})$: The fraction of the Total Available soil Water (TAW) that can be depleted from the root zone before leaf expansion starts to be limited;
- $p(\text{lower})$: when this fraction of TAW is depleted from the root zone, there is no longer any leaf expansion growth (reduction of 100 %).

Table 2.10i1 – Classes and corresponding default values for the soil water depletion fractions for canopy expansion

| Class Sensitivity to water stress | Soil water depletion fraction for canopy expansion (p_{exp}) | |
|--------------------------------------|---|-------------------|
| | $p(\text{upper})$ | $p(\text{lower})$ |
| extremely sensitive to water stress | 0.00 | 0.35 |
| sensitive to water stress | 0.10 | 0.45 |
| moderately sensitive to water stress | 0.20 | 0.55 |
| moderately tolerant to water stress | 0.25 | 0.60 |
| tolerant to water stress | 0.30 | 0.65 |
| extremely tolerant to water stress | 0.35 | 0.70 |

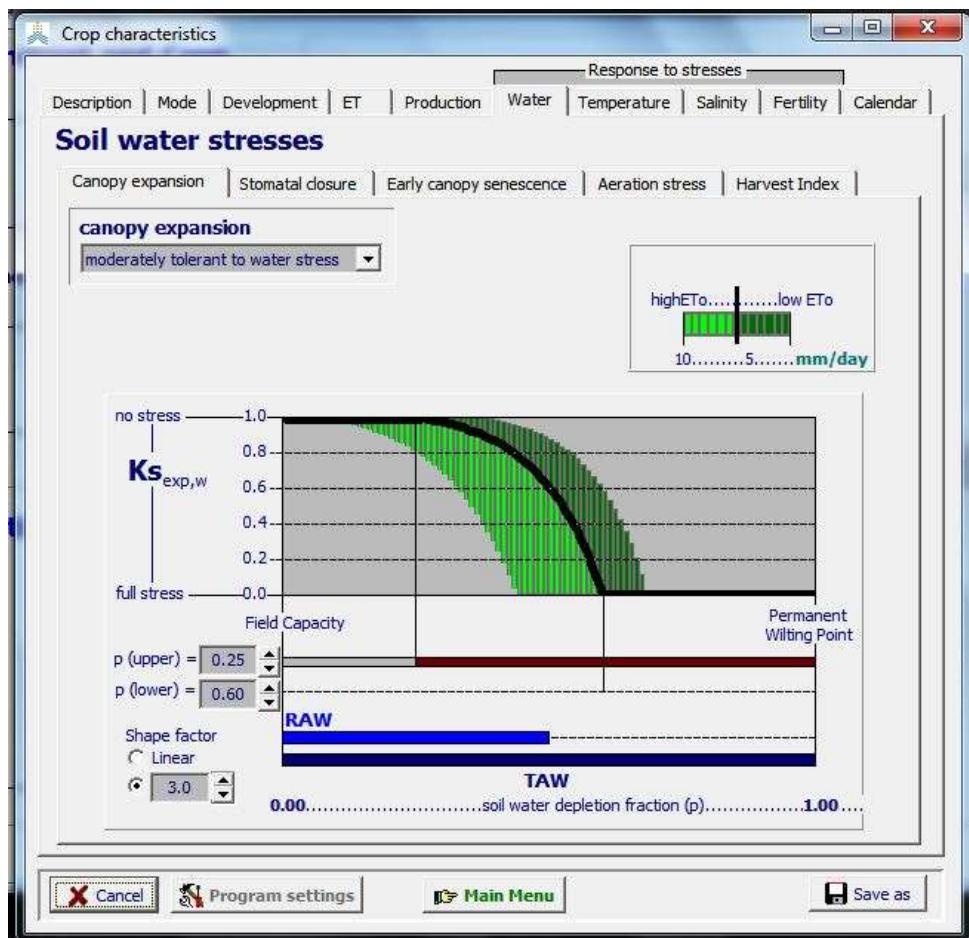


Figure 2.10i3 – Specification of the upper and lower thresholds and the shape of the K_s curve for the effect of water stress on canopy expansion ($K_{s\text{exp},w}$)

Stomatal closure: Stomata have been shown to be much less sensitive to water stress in comparison to leaf expansive growth. The user specifies the effect of water stress on crop transpiration by selecting a sensitivity class (Table 2.10i2) or by specifying a value for the upper soil water depletion thresholds (p):

- p(upper): which determines the Readily Available soil Water (RAW). RAW is the maximum amount of water that a crop can extract from its root zone without inducing stomatal closure and reduction in crop transpiration;
- p(lower): which is fixed at 1.0 (i.e. TAW is completely depleted). When the fraction p(lower) is depleted from the root zone, the soil water content is at permanent wilting point and crop transpiration becomes zero.

Table 2.10i2 – Classes and corresponding default values for the upper threshold of soil water depletion for stomatal closure

| Class Sensitivity to water stress | Upper threshold of soil water depletion for stomatal closure (p_{sto}) | |
|--------------------------------------|---|---------------|
| | Default value | Range |
| extremely sensitive to water stress | 0.25 | 0.10 ... 0.29 |
| sensitive to water stress | 0.45 | 0.30 ... 0.49 |
| moderately sensitive to water stress | 0.55 | 0.50 ... 0.59 |
| moderately tolerant to water stress | 0.65 | 0.60 ... 0.67 |
| tolerant to water stress | 0.70 | 0.68 ... 0.72 |
| extremely tolerant to water stress | 0.75 | 0.73 ... 0.90 |

Early canopy senescence: Under moderate to severe water stress conditions, leaf and canopy senescence is triggered, thereby reducing the transpiring foliage area. The user specifies the effect of water stress on canopy senescence by selecting a *sensitivity class* (Tab. 2.10i3) or by specifying a value for the upper soil water depletion thresholds (p):

- p(upper): The fraction of the Total Available soil Water (TAW) that can be depleted from the root zone before canopy senescence is triggered;
- p(lower): which is fixed at 1.0 (TAW is completely depleted). When the fraction p(lower) is depleted from the root zone, the soil water content is at wilting point and canopy senescence is at full speed.

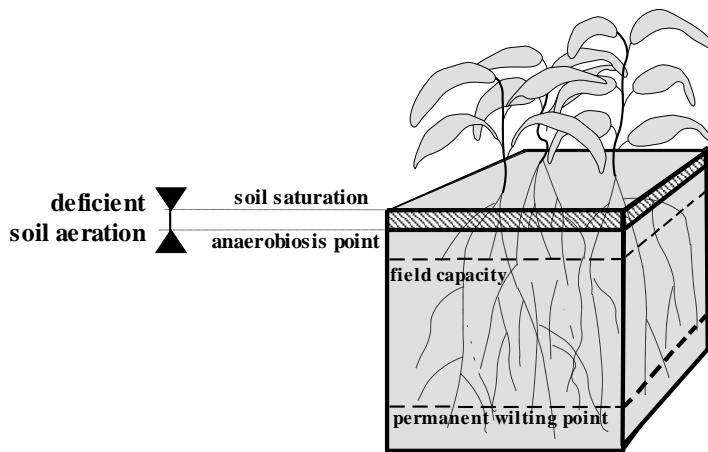
Early canopy senescence is likely to be depended on the nitrogen nutrition of the crop. When nitrogen is more limiting the crop is expected to be more sensitive.

Table 2.10i3 – Classes and corresponding default values for the upper threshold of soil water depletion for canopy senescence

| Class Sensitivity to water stress | Upper threshold of soil water depletion for canopy senescence (p_{sen}) | |
|--------------------------------------|--|---------------|
| | Default value | Range |
| extremely sensitive to water stress | 0.35 | 0.00 ... 0.39 |
| sensitive to water stress | 0.45 | 0.40 ... 0.49 |
| moderately sensitive to water stress | 0.55 | 0.50 ... 0.59 |
| moderately tolerant to water stress | 0.65 | 0.60 ... 0.69 |
| tolerant to water stress | 0.75 | 0.70 ... 0.75 |
| extremely tolerant to water stress | 0.80 | 0.76 ... 0.98 |

■ Aeration stress

Water logging causes stress that affects crop development and growth, except for the case of aquatic species such as rice. When the soil water content in the root zone rises above the anaerobiosis point (Figure 2.10i5), the aeration of the root zone will be deficient, resulting in a decrease of crop transpiration.



**Figure 2.10i5 – Zone (dark area) of restricted soil water extraction
as a result of deficient soil aeration**

The aeration stress is specified by a Ks coefficient. At soil saturation (upper threshold) the stress is at its full effect and Ks is 0. Below a lower threshold of soil water content, water stress is not considered and Ks is 1. The lower threshold is the soil water content below saturation at which poor aeration no longer limits transpiration. Between the upper and lower thresholds the shape of the Ks curve is linear (Fig. 2.10i6). The user specifies the sensitivity of the crop to water logging by selecting an aeration stress class (Tab. 2.10i4) or by specifying the anaerobiosis point (volume percent below soil saturation).

Table 2.10i4 – Classes, corresponding default values, and ranges for aeration stress

| Class | anaerobiosis point (volume % below saturation) | |
|--------------------------------------|---|-----------|
| | default | range |
| not stressed when water logged | 0 | 0 |
| very tolerant to water logging | - 2 vol% | 1 ... 3 |
| moderately tolerant to water logging | - 5 vol% | 4 ... 6 |
| sensitive to water logging | - 10 vol% | 8 ... 12 |
| very sensitive to water logging | - 15 vol% | 13 ... 15 |

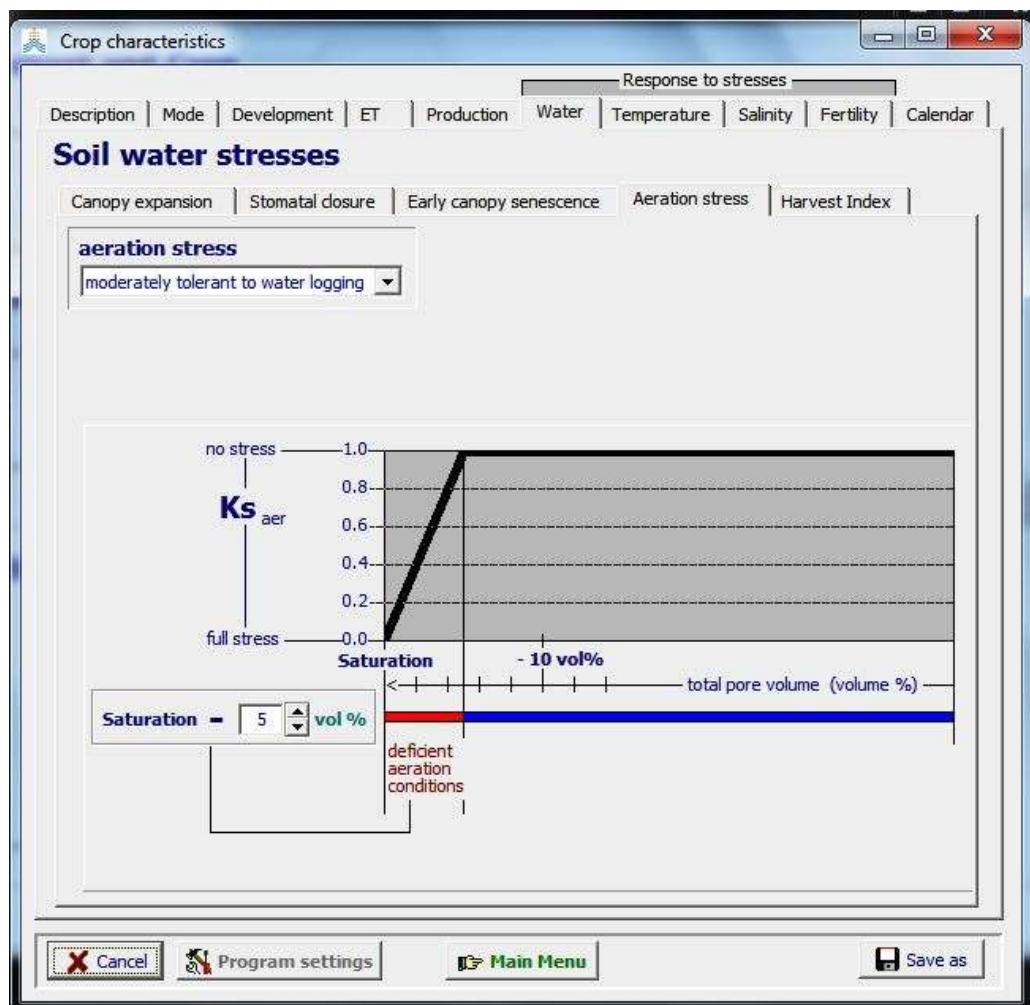


Figure 2.10i6 – Specification of the soil water content below saturation at which poor aeration no longer limits transpiration

- **Harvest Index**

Water stress may alter HI, either positively or negatively, in several ways, depending on timing, severity and duration of the stress.

Before flowering: Pre-anthesis water stress limiting vegetative growth may have positive effects on the Harvest Index. The user specifies the maximum increase that should be considered (Fig. 2.10i7) or select a class graded for the effect of pre-anthesis water stress (Tab. 2.10i5).

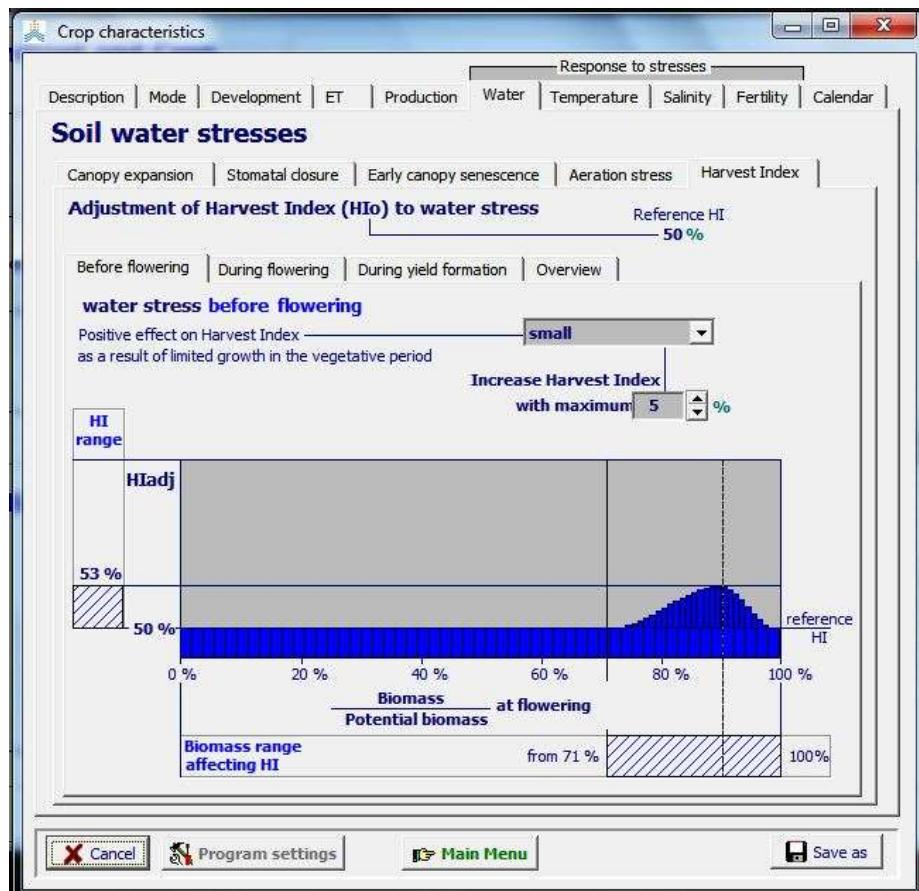


Figure 2.10i7 – Positive effect on Harvest Index of pre-anthesis water stress affecting biomass production

Table 2.10i5 – Classes graded for the maximum positive effect of pre-anthesis stress on HI

| Class | percent increase of HI |
|-------------|------------------------|
| None | 0 % |
| Small | 4 % |
| Moderate | 8 % |
| Strong | 12 % |
| Very strong | 16 % |

During flowering: When stress is **very severe** and inhibits pollination directly, the effect on HI is negative for a given class of excessive potential fruits, and its magnitude is set by a water stress coefficient (K_s). The threshold for the failure of pollination, expressed as a fraction (p) of TAW, is lower (stronger stress level) than the threshold for the effect for stomatal closure and triggering of senescence. The water stress coefficient $K_{s, pol}$ decreases linear from 1 to 0 between the upper threshold (p_{pol}) and lower threshold (permanent wilting point). The user specifies the soil water depletion (p) at the threshold or selects a class graded for relative resistance to drought (Fig. 2.10i8, Tab 2.10i6).

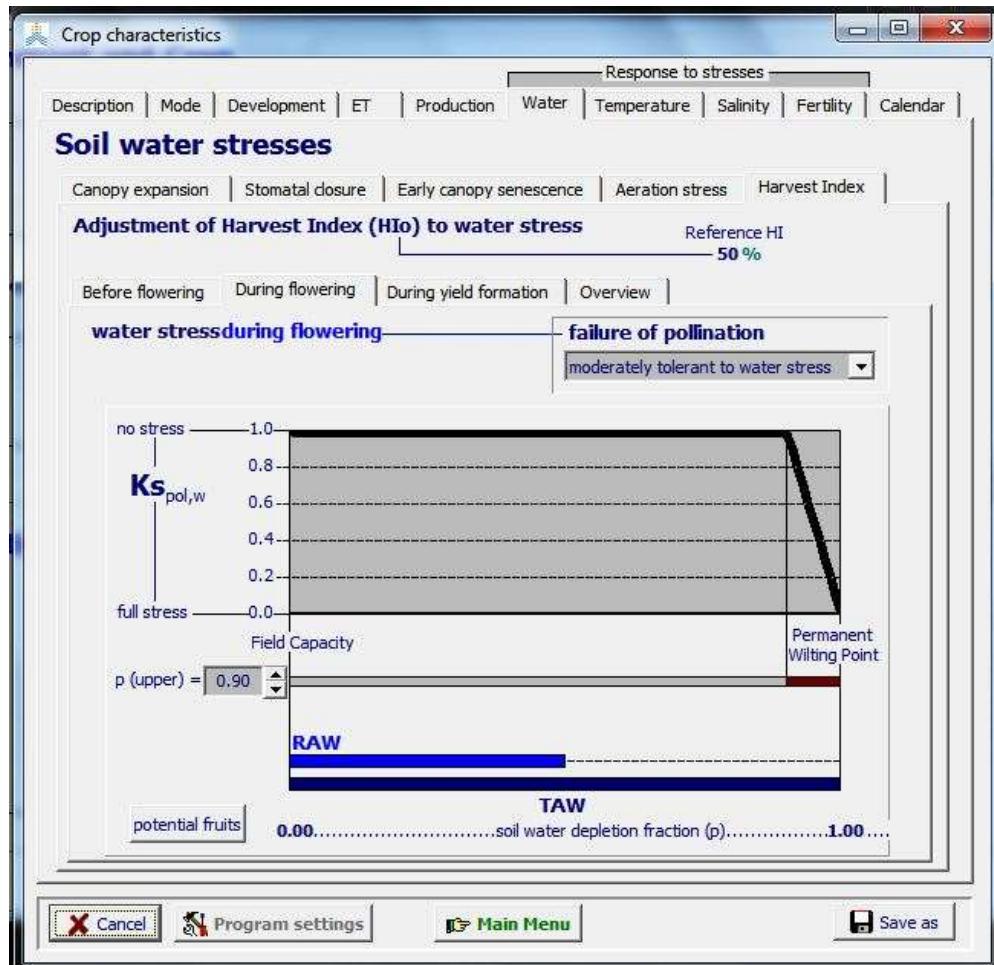


Figure 2.10i8 – Specification of the upper thresholds for the effect of water stress on failure of pollination

During yield formation: The effect of water stress during yield formation can be positive or negative depending on the severity of the stress:

- One adjustment is for the competition between vegetative and reproductive growth after flowering begins, linked to K_s for leaf growth and with positive stress effect on HI. The magnitude of this effect as a function of K_s is set by a coefficient “ a ”, increasing as “ a ” diminishes (Tab. 2.10i7);

- When stress is severe enough to cause substantial stomata closure and reduction in photosynthesis, the effect on HI is assumed to be negative and linked to Ks for stomata. The magnitude of this effect is set by coefficient “b”, with the negative effect on HI being accentuated as “b” decreases (Tab. 2.10i8).

Table 2.10i6 – Classes, corresponding defaults values, and ranges for the soil water depletion factor (p) for failure of pollination

| Class Sensitivity to water stress | Soil water depletion fraction (p) for failure of pollination | |
|--------------------------------------|---|---------------|
| | Default value | Range |
| extremely sensitive to water stress | 0.76 | 0.75 ... 0.77 |
| sensitive to water stress | 0.80 | 0.78 ... 0.82 |
| moderately sensitive to water stress | 0.85 | 0.83 ... 0.86 |
| moderately tolerant to water stress | 0.88 | 0.87 ... 0.90 |
| tolerant to water stress | 0.92 | 0.91 ... 0.93 |
| extremely tolerant to water stress | 0.95 | 0.94 ... 0.99 |

Table 2.10i7 – Classes, corresponding defaults values, and ranges for the “a” coefficient (positive stress effect on HI)

| Class Sensitivity to water stress | “a” coefficient | |
|--------------------------------------|-----------------|---------------|
| | Default value | Range |
| None | - | - |
| small | 4 | 3 ... 40 |
| moderate | 2 | 1.5 ... 2.9 |
| strong | 1 | 0.75 ... 1.40 |
| very strong | 0.7 | 0.50 ... 0.70 |

Table 2.10i8 – Classes, corresponding defaults values, and ranges for the “b” coefficient (negative stress effect on HI)

| Class Sensitivity to water stress | “b” coefficient | |
|--------------------------------------|-----------------|-------------|
| | Default value | Range |
| none | - | - |
| small | 10 | 7.1 ... 20 |
| moderate | 5 | 4.1 ... 7.0 |
| strong | 3 | 1.6 ... 4.0 |
| very strong | 1 | 1.0 ... 1.5 |

In addition to the Ks value, the user specifies the extent of excessive potential fruits (Fig. 2.10i9). When conditions are favorable, crops pollinate many more flowers and set more fruits than needed for maximum yield. The excessive young fruits are aborted as the older fruits grow. The extent of reduction in HI caused by extreme temperature or severe water stress occurring during pollination time depends partly on the extent of this excess in potential reproductive bodies. The excess is specified by selecting one of the classes ranging from very small to large (Tab. 2.10i9).

Table 2.10i9 – Classes and corresponding default values for excess of potential fruits

| Excess of potential fruits | Excess of fruits |
|----------------------------|------------------|
| Very small | 20 |
| small | 50 |
| medium | 100 |
| large | 200 |
| very large | 300 |

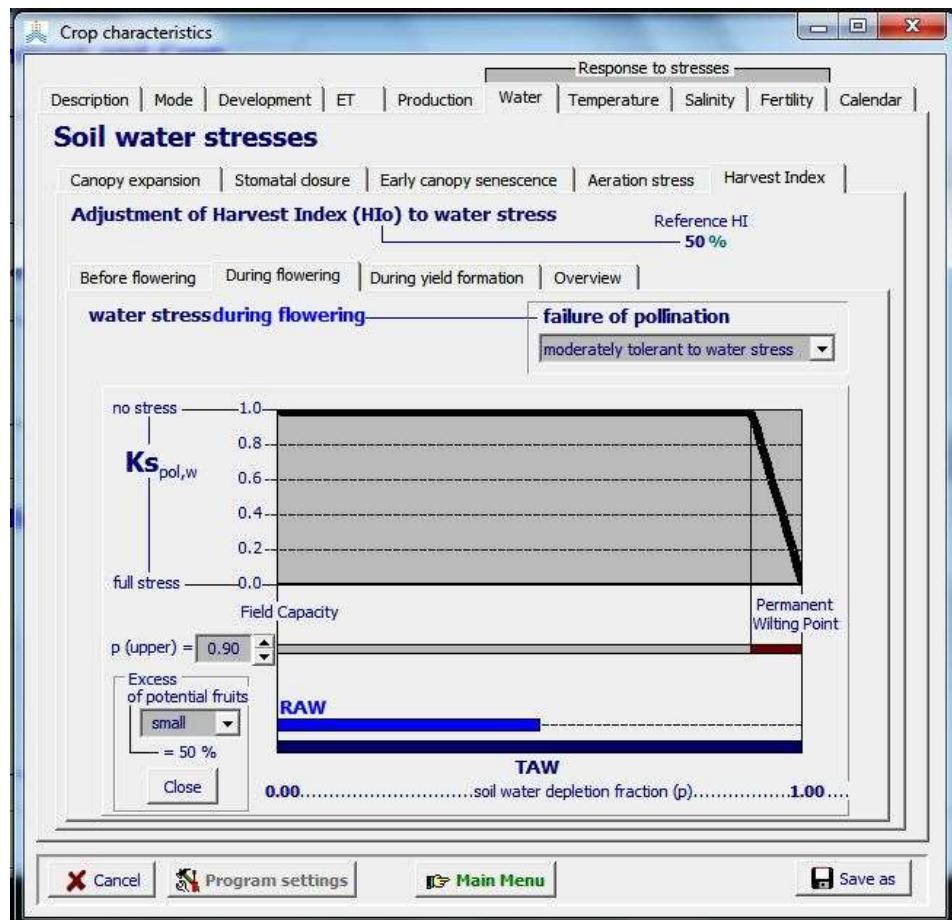


Figure 2.10i9 – Specification of the extent of excessive potential fruits

The combined effect of water stress during yield formation is displayed in the corresponding tab sheet (Fig. 2.10i10).

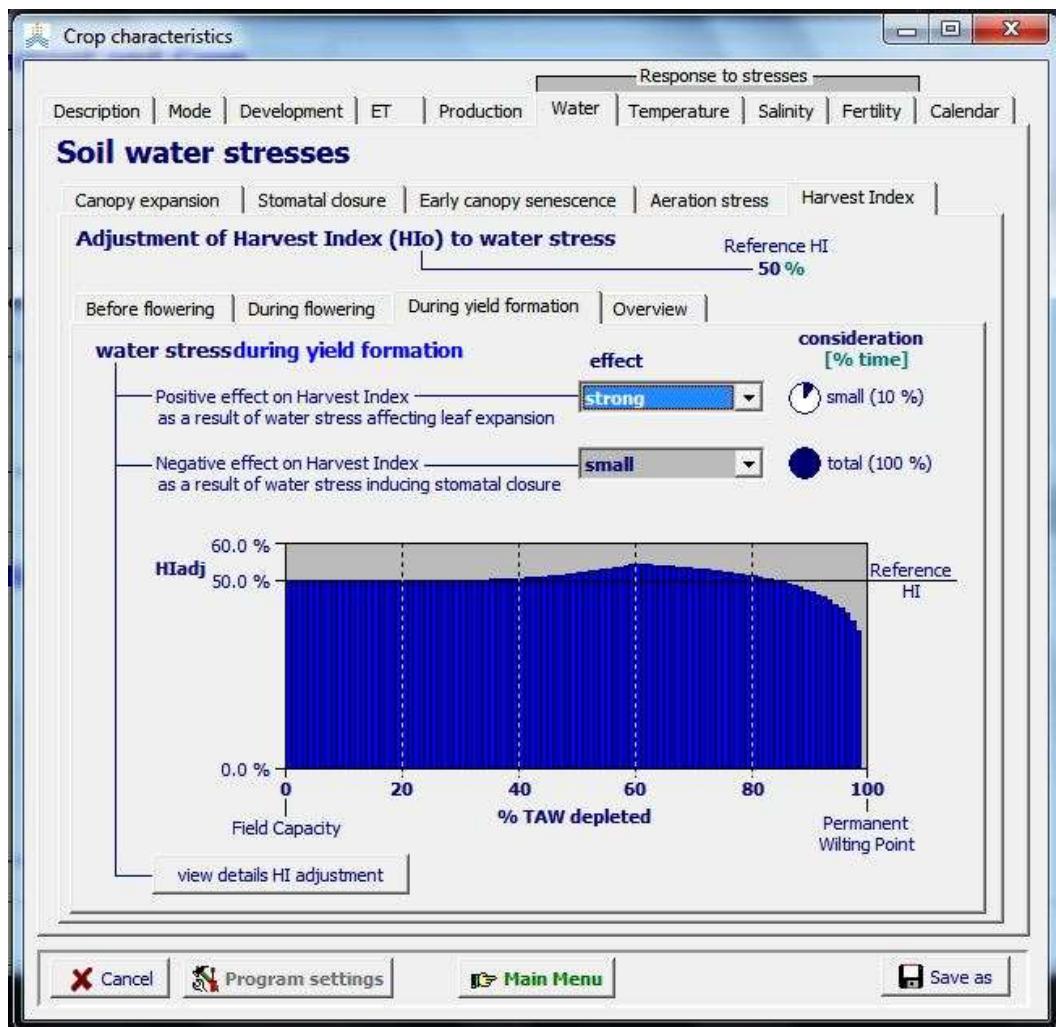


Figure 2.10i10 – Effect on Harvest Index of post-anthesis water stress for various degrees of root zone depletion (% TAW depleted)

By selecting the <view details HI adjustment> command, the user can study the individual and combined effect on the Harvest Index of water stress during yield formation in the *Adjustment of Harvest Index* menu (Fig 2.10i11 and 2.10i12). The individual and combined effect on HI can be displayed for various root zone depletions and evaporative demands.

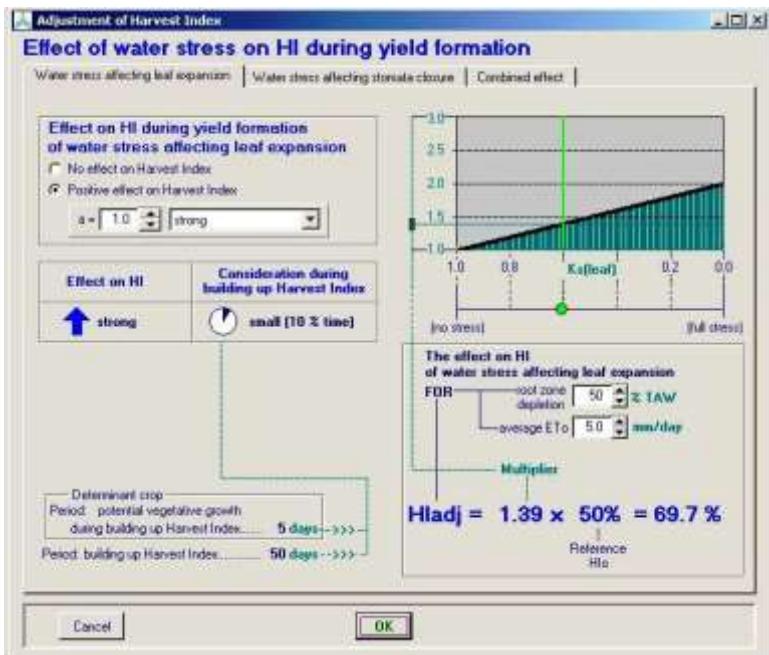


Figure 2.10i11

Positive effect on Harvest Index of water stress during the period of potential vegetative growth for the selected:

- (i) “a” coefficient,
- (ii) root zone depletion,
- (iii) evaporative demand

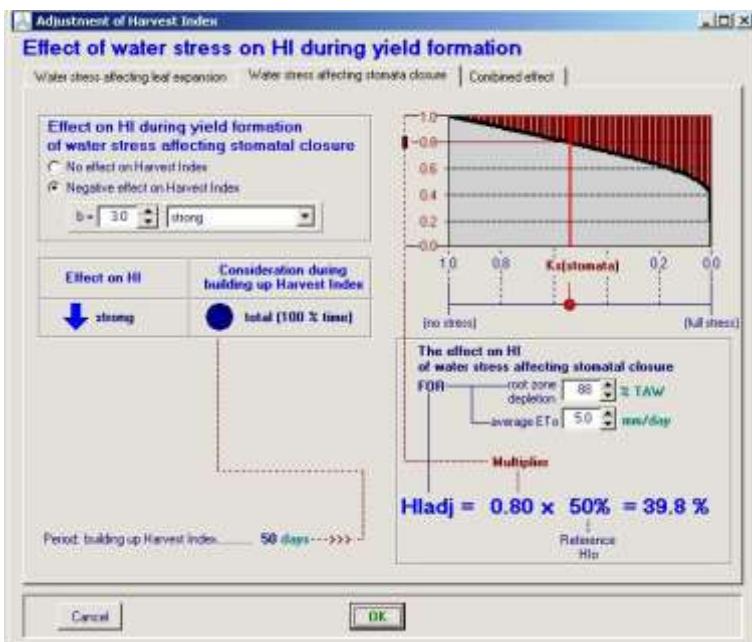


Figure 2.10i12

Negative effect on Harvest Index of water stress during the building up of the Harvest Index for the selected:

- (i) “b” coefficient,
- (ii) root zone depletion,
- (iii) evaporative demand

Overview: After combining the various effects on HI on water stress, the adjusted Harvest Index should remain smaller than a pre-set maximum. In the folder presenting the overview of water stress effects on Harvest Index, the user can adjust the maximum allowable increase (Fig. 2.10i13).

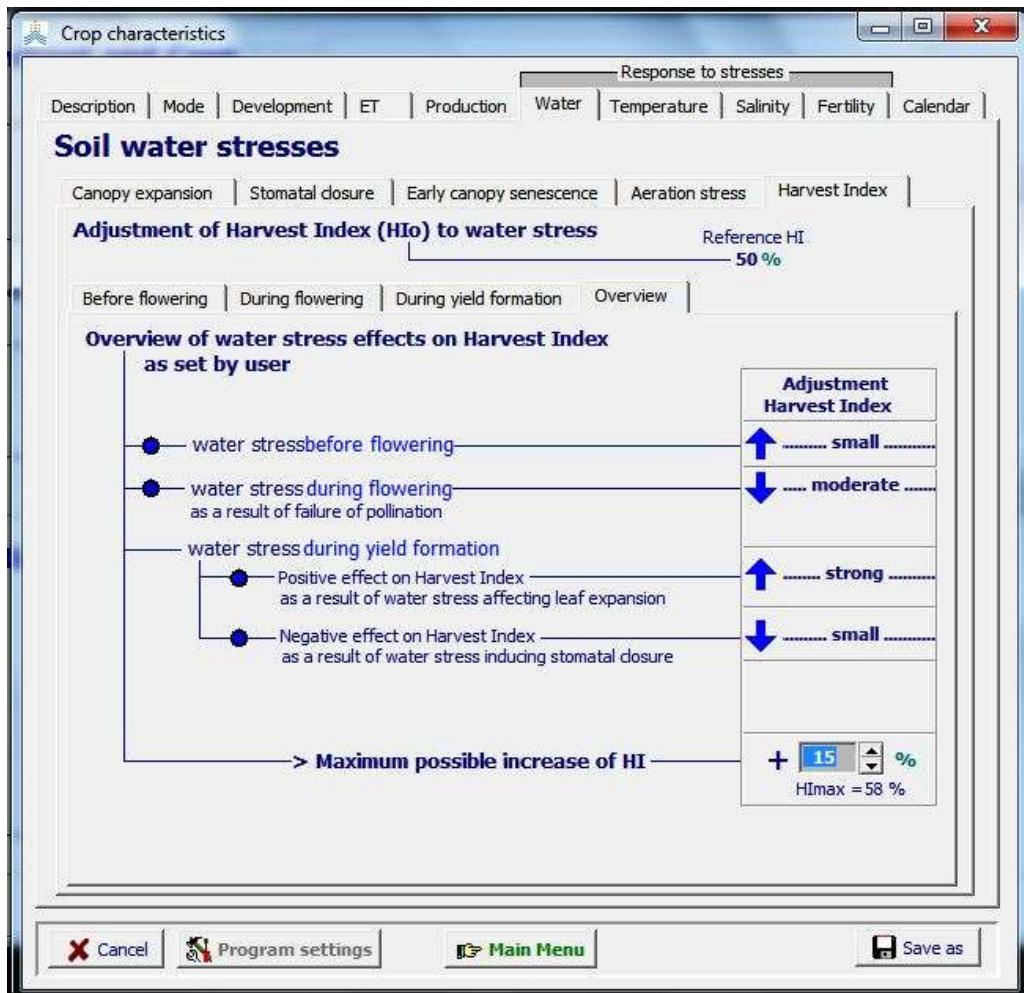


Figure 2.10i13 – Combined effect of water stress on harvest index

2.10.10 Tabular sheet: Temperature stress

In AquaCrop air temperature affects crop development. The effects of temperature stress affecting biomass production and pollination are described by temperature stress coefficients (K_s) which varies between 0 (full effect of stress) and 1 (no effect).

■ Crop development

In the ‘Crop development’ sheet of the ‘Temperature’ stress tabular sheet, the base and upper thresholds temperatures for canopy development can be updated (Fig. 2.10j1). The corresponding growing degrees for each day of the temperature file, or for the length of the growing cycle, are displayed.

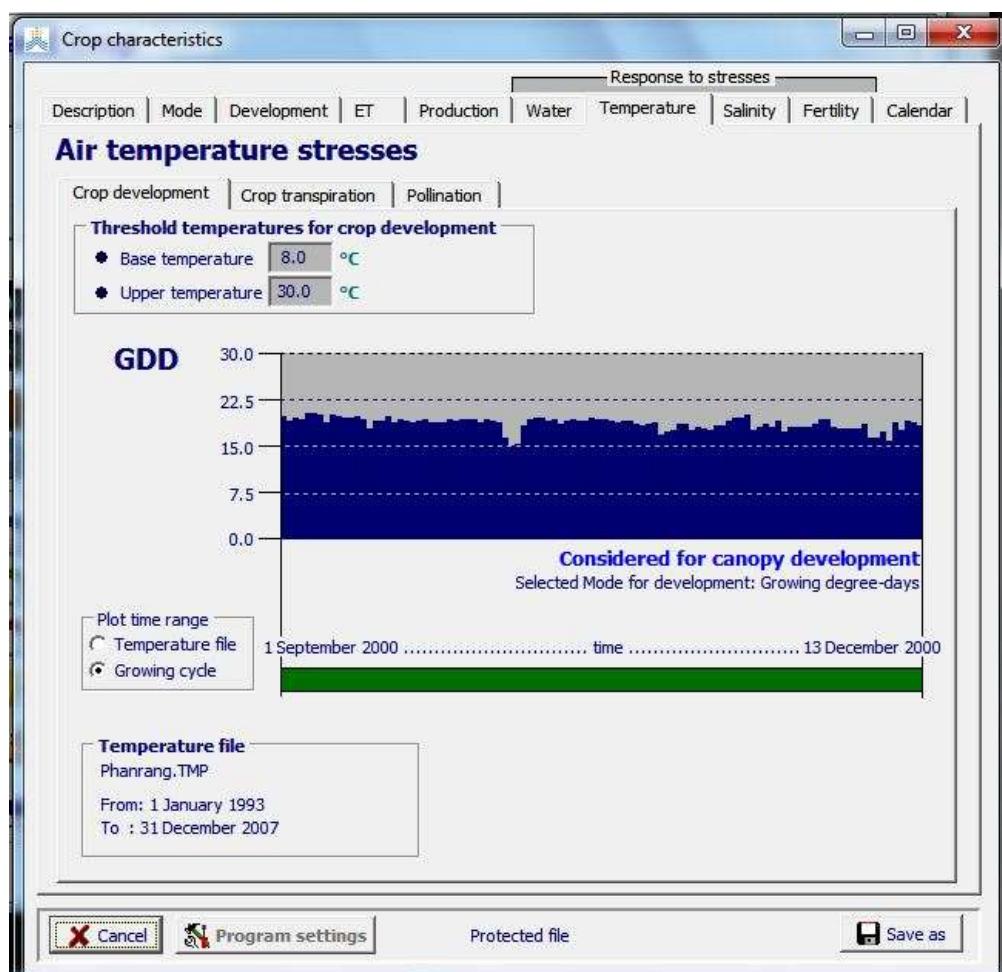


Figure 2.10j1 – The Base and Upper threshold temperatures for crop development in the ‘Crop development’ sheet of the ‘Temperature’ stress tabular sheet, and the corresponding growing degrees in Phanrang (Vietnam)

- **Crop transpiration**

Low temperatures can cause stress that affects crop development and growth. AquaCrop considers the impact of low temperature in two ways. One is by using GDD as the clock, accounting for effects on phenology and canopy expansion and decline rate. In addition, it is necessary to account for the more direct effect of cold stress on crop transpiration (reduction in stomatal conductance at low temperature). The latter is specified by a K_s coefficient, which varies between 1 and 0 between an upper threshold and a lower threshold defined in terms of growing degrees per day (Fig. 2.10j2). The lower threshold is fixed at 0 °C-day. Between the upper and lower threshold the shape of the K_s curve is logistic.

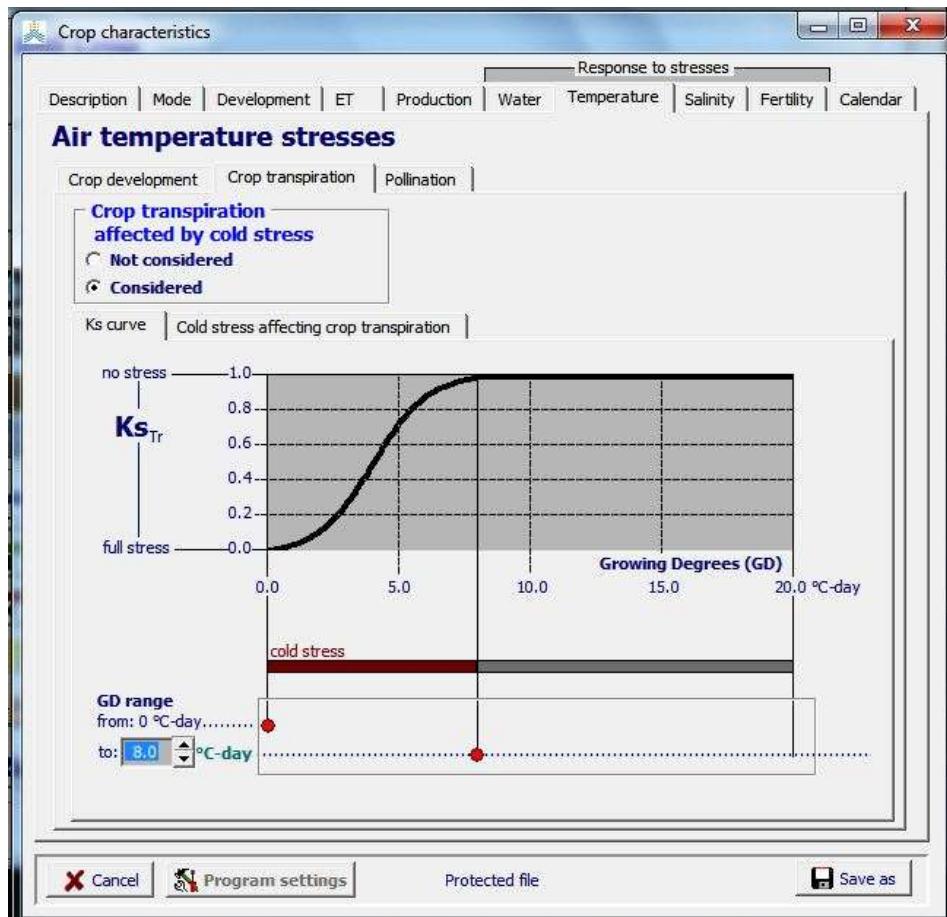


Figure 2.10j2 – The temperature threshold (expressed in growing degree-days) for crop transpiration in the ‘Crop transpiration’ sheet of the ‘Temperature’ stress tabular sheet

Additionally the percentage of cold stress affecting the crop transpiration can be displayed for each day of the temperature file, or for the length of the growing cycle (2.10j3).

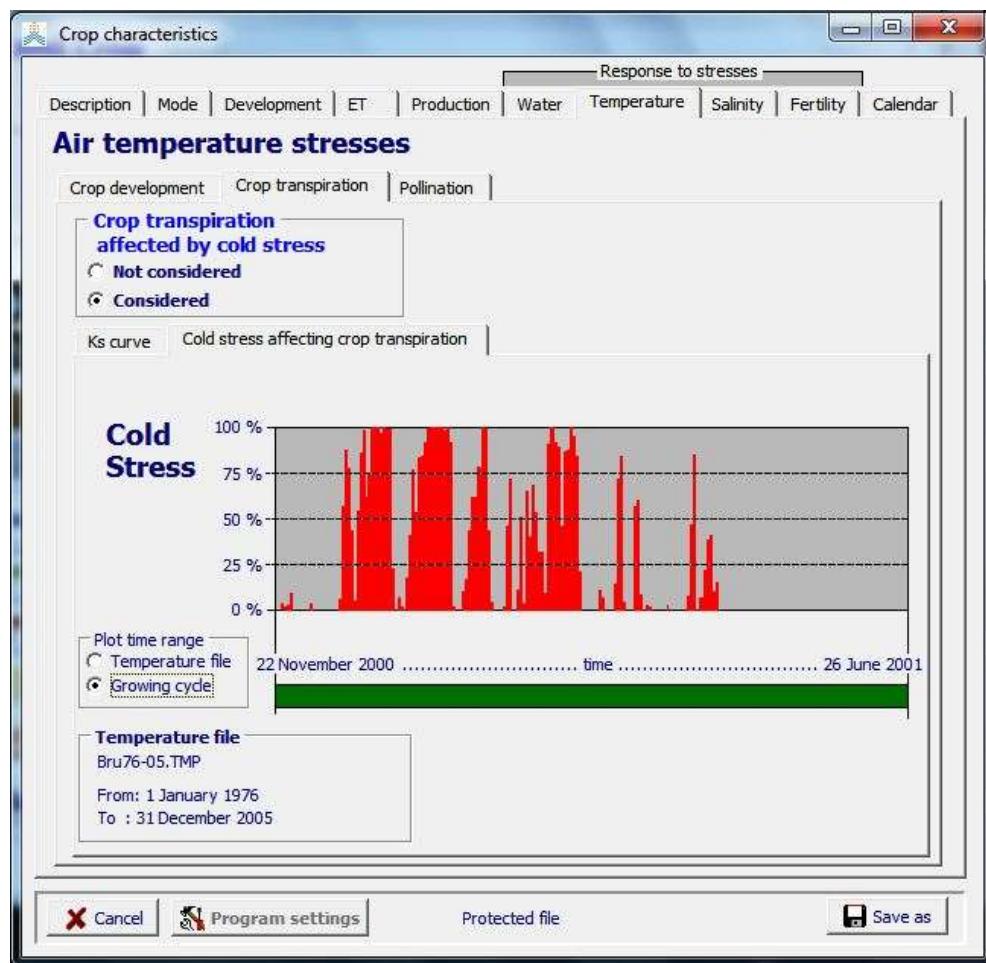


Figure 2.10j3 – The percentage of cold stress in Brussels (Belgium) during the growing cycle for the specified temperature threshold for crop transpiration

- Pollination

Cold and heat stress might affect pollination. The temperature stress is specified by a K_s coefficient, which varies from 0 to 1 between threshold temperatures. For the cold stress K_s is 0 at the lower threshold and 1 at the upper temperature threshold. For the heat stress K_s is 1 at the upper threshold and 0 at the lower threshold temperature (Fig. 2.10j4). Between the upper and lower thresholds the shapes of the K_s curves are logistic.

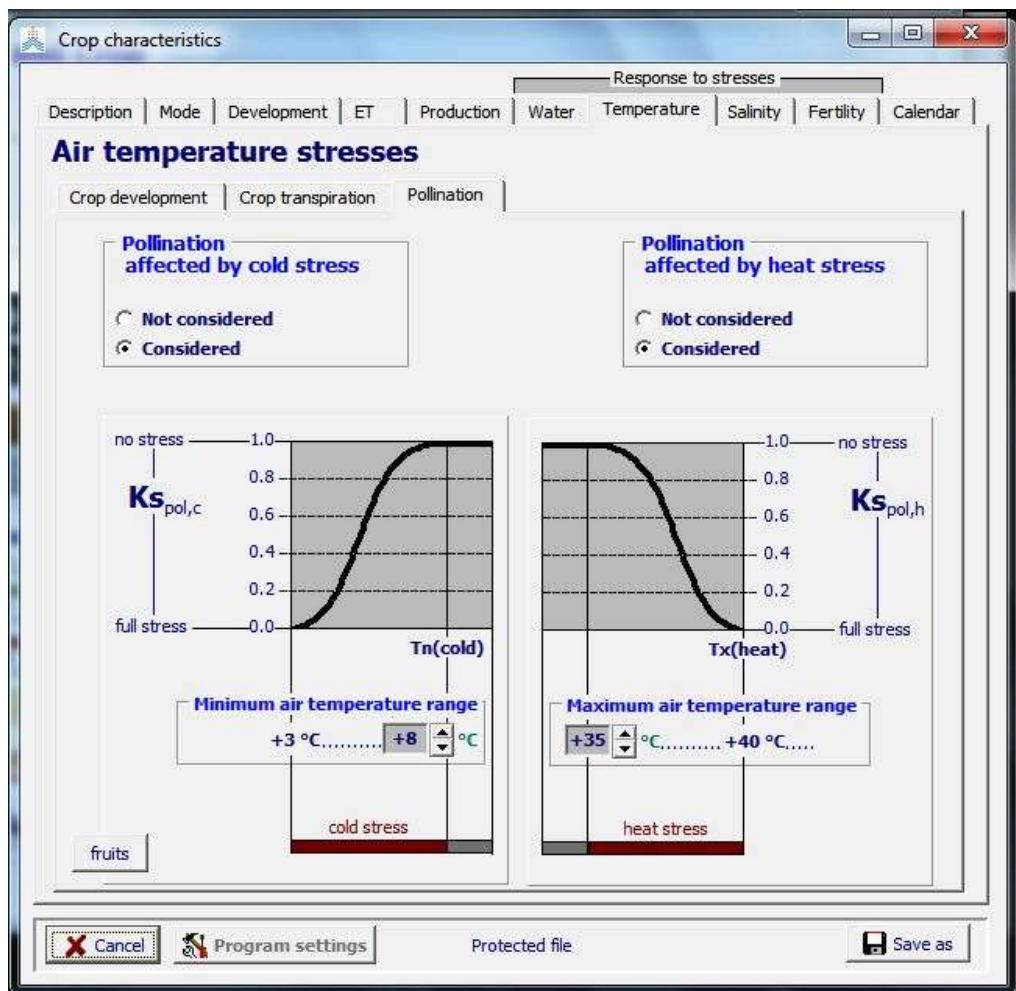


Figure 2.10j4 – Specification of the thresholds for cold and heat stress on pollination

Only the upper threshold for the minimum air temperature ($T_{n,cold}$) and the lower threshold for the maximum air temperature ($T_{x,heat}$) at which pollination starts to fail are crop parameters. $T_{n,cold}$ can range from 0 to +15 °C and $T_{x,heat}$ from +30 to +45 °C. In AquaCrop it is assumed that full stress is reached ($K_s = 0$) at 5 °C below (cold stress) or above (heat stress) the specified threshold air temperature.

2.10.11 Tabular sheet: Soil fertility stress

Although the crop response to soil fertility stress is based on fundamental concepts, it is at present described by a qualitative assessment. Mineral nutrient stress, particularly the lack of nitrogen, can (i) reduce canopy expansion, resulting in a slower canopy development and (ii) the maximum canopy cover that can be reached (CC_x), resulting in a less dense canopy. In addition, under long-term stress, (iii) CC normally undergoes steady decline once the adjusted CC_x is reached at mid season. Further-on (iv) soil fertility stress reduces the water productivity (WP*).

■ Display of the effects of soil fertility stress

If the crop response is calibrated for soil fertility stress, the user can see the effect of various stress levels in the **Crop characteristics** menu: No stress, mild stress, moderate stress, and severe stress (Fig. 2.10k1 and 2.10k2).

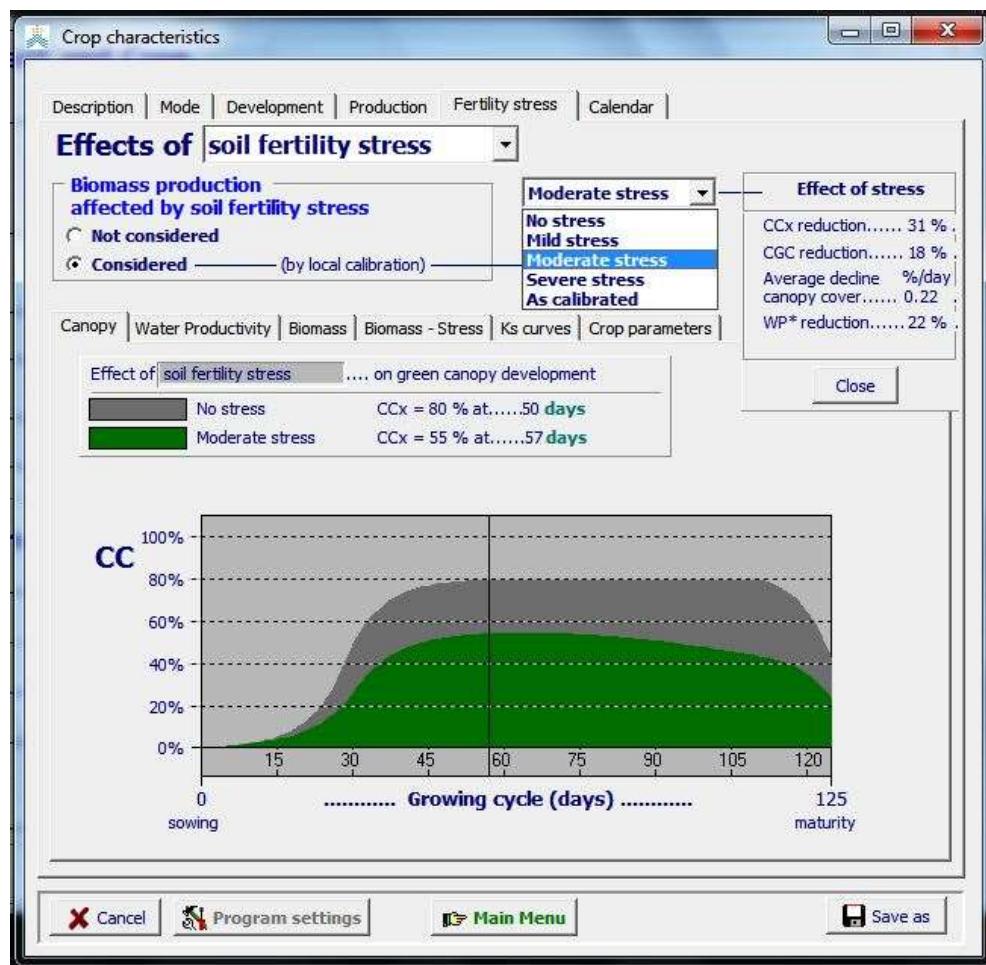


Figure 2.10k1 – The effect of moderate soil fertility stress on canopy development

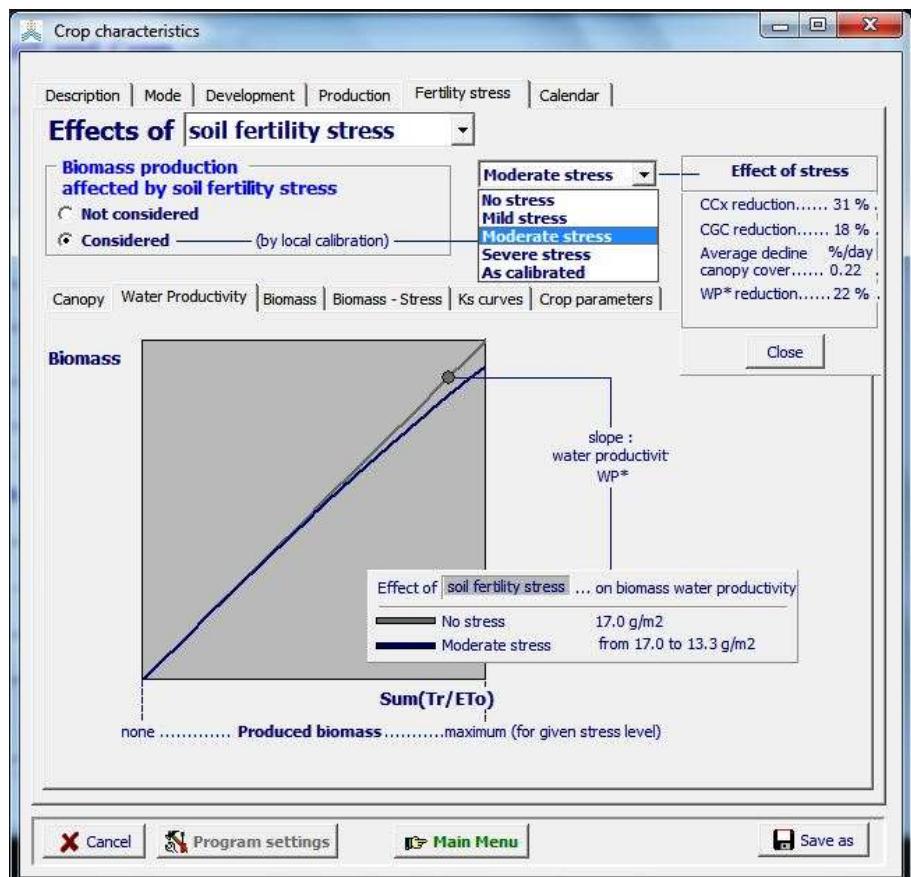


Figure 2.10k2 – The effect of moderate soil fertility stress on biomass production

- **Calibration of the crop response**

Calibration of the crop response to soil fertility stress is done in the *Crop characteristic* menu (See 2.10.12 Calibration for soil fertility stress).

- **Simulation of the effect of soil fertility stress**

To simulate the effect of soil fertility stress the user has to specify one of the categories of the soil fertility stress in the *Field management* menu (Tab. 2.10k).

Table 2.10k – Crop characteristics and specification of field management

| | |
|--|---|
| | <p>Crop characteristics: How does the crop responds to soil fertility stress ?</p> |
| | <p>Field management: What is the soil fertility level in the field ?</p> |

2.10.12 Calibration for soil fertility stress

Since the crop response is specific to the type of stress and the environment in which the crop develops, the crop response to soil fertility stress cannot be described with conservative crop parameters, but needs to be calibration for each specific case.

- **Reference and Stressed field**

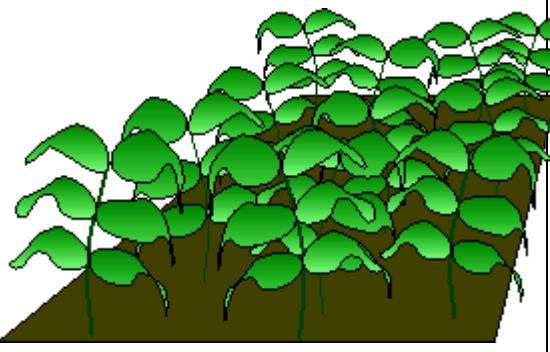
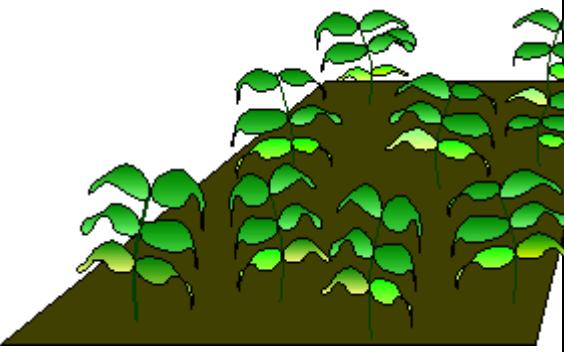
| | |
|--|--|
|  |  |
| Reference field <ul style="list-style-type: none">- well watered field- no soil fertility stress | Stressed field <ul style="list-style-type: none">- well watered field- soil fertility stress |
| Observations: B_{ref} and CC_{ref} | Observations: B_{stress} and CC_{stress} |

Figure 2.10m1 – The calibration of crop response to soil fertility stress is based on field observations of differences in Biomass production (B) and green Canopy Cover (CC) between a Reference and Stressed field

The calibration, which is done in the *Crop characteristic* menu, requires access to observed green Canopy Cover (CC) and biomass production (B) in two well watered fields: one with and the other without soil fertility stress. The field with no stress is regarded as the ‘Reference field’, while the field with limited soil fertility is denoted as the ‘Stressed field’. The fields are well watered to avoid the effect of soil water stress on crop development and production. The calibration requires that the crop in the Stressed field shows a well noted response to the limited soil fertility (Fig. 2.10m1). The calibration consists in linking an observed reduction in total above ground biomass (B) in a Stressed field with the soil fertility stress in that field.

- **Crop response to soil fertility stress**

The observed reduction in biomass is the result of an integration of effects of the stress on several processes. The soil fertility stress affects

- green canopy development (CC) and hence indirectly crop transpiration (Tr). The effect of the soil fertility stress on CC consists:
 - reduced canopy expansion resulting in a slower canopy development
 - reduced maximum canopy cover that can be reached (CC_x) resulting in a less dense canopy
 - steady decline of CC once the adjusted CC_x is reached at mid season.
- the biomass water productivity (WP*).

In Table 2.10m the stress coefficients (K_s) and decline coefficient (f) used for the simulation of the crop response to soil fertility stress are listed.

Table 2.10m – Stress coefficients for simulating crop response to soil fertility stress

| Coefficient | Description | Target crop parameter |
|--|---|--|
| For simulating the effect of both soil fertility and soil salinity stress | | |
| $K_{Sexp,f}$ | Stress coefficient for canopy expansion | Canopy Growth Coefficient (CGC) |
| K_{SCCx} | Stress coefficient for maximum canopy cover | Maximum canopy cover (CC_x) |
| $f_{CDecline}$ | Stress decline coefficient of the canopy cover | Canopy Cover (CC) once maximum canopy cover has been reached |
| For simulating the effect of soil fertility stress | | |
| K_{SWP} | Stress coefficient for biomass water productivity | Biomass water productivity (WP*) |

- The effect of soil fertility stress on biomass is not considered (not calibrated)

The calibration process

Protected crop files (provided by FAO), do not consider the effect of soil fertility stress on biomass, and need to be calibrated before the effect can be simulated (Fig. 2.10m2).



Figure 2.10m2 – Display in the *Crop characteristics* menu of a crop for which the effect of soil fertility stress on biomass is not considered

By selecting ‘Considered’ on the tab sheet in the *Crop characteristics* menu (Fig. 2.10m2), AquaCrop will display the *Calibration soil fertility stress* menu in which the calibration can be started (Fig. 2.10m3).

In the ‘Field observations’ tab sheet of the *Calibration soil fertility stress* menu (Fig. 2.10m3), the user specifies (with reference to Fig. 2.10m1) the observations as surveyed in the Stressed field:

- the observed relative Biomass production, by selecting a class (varying from ‘near optimal’ to ‘very poor’) or by specifying the observed relative biomass ($100 B_{\text{stress}}/B_{\text{ref}}$); The semi-quantitative approach of AquaCrop requires the user to specify the soil fertility level, expressed as the relative biomass (B_{rel}) that can be expected in a fertility-stressed field compared to that for a reference field in non-water-stressed conditions. The B_{rel} can readily be obtained from farmers, from experimental fields or from agricultural statistics relating to local crop production. The approach integrates the effects of various soil nutrients (and not merely nitrogen) and mineralization processes without a requirement for vast amounts of input data, for initialization of the soil

nutrient conditions, or for elaborate parameterization (Van Gaelen, H., Tsegay, A., Delbecque, N., Shrestha, N., Garcia, M., Fajardo, H., Miranda, R., Vanuytrecht, E., Abrha, B., Diels, J., Raes, D. 2015. A semi-quantitative approach for modelling crop response to soil fertility: Evaluation of the AquaCrop procedure. Journal of Agricultural Science,153(7): 1218-1233.);

2. the observed Maximum canopy cover (CCx) , by selecting a class (varying from ‘close to reference’ to ‘very strong reduced’) or by specifying the observed CCx (CCx_{stress});
3. the observed Canopy decline in the season once CCx is reached, by selecting a class (varying from ‘small’ to ‘strong’).

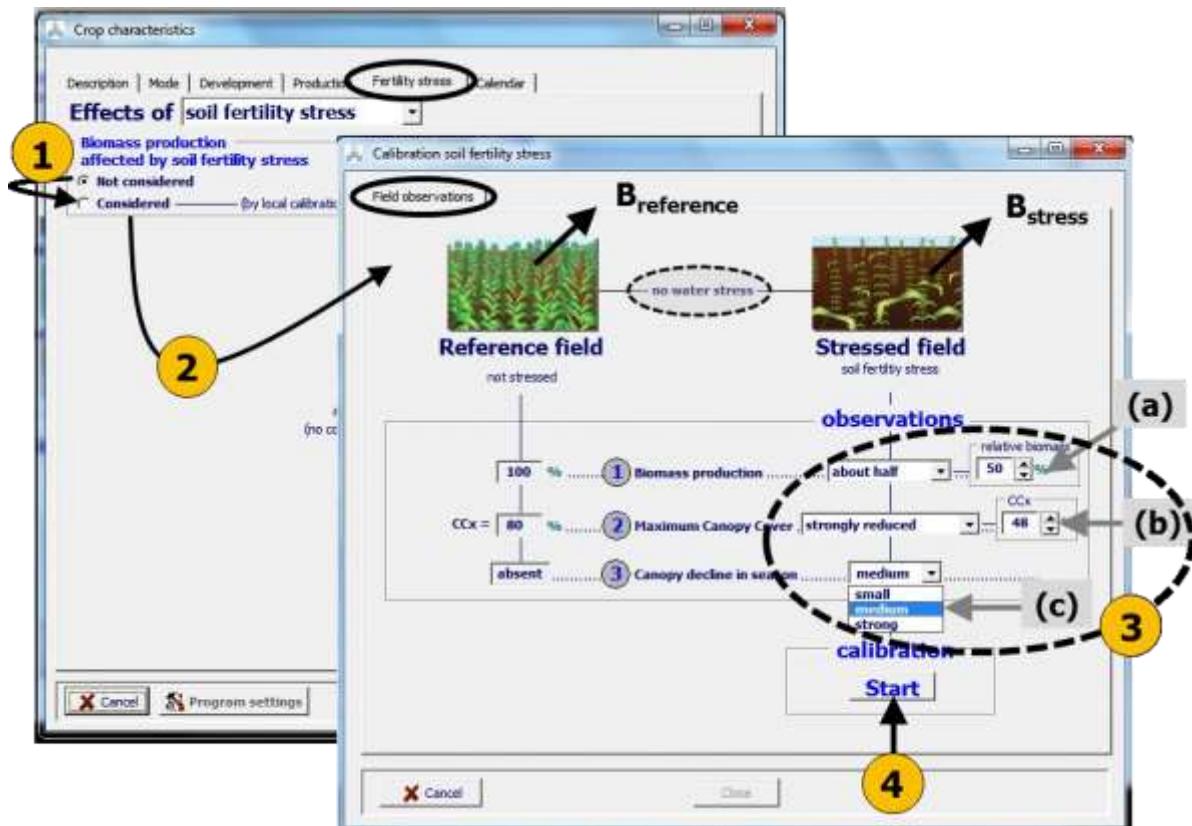


Figure 2.10m3 – (1) By selecting ‘Considered’ in the ‘Fertility-stress’ tabular sheet, (2) the ‘Field observations’ tabular sheet of the *Calibration soil fertility stress* menu becomes available in which the user (3) specifies the observed or expected (a) relative biomass production, (b) maximum canopy cover and (c) canopy decline in season in a stressed field and (4) launches the calibration for soil fertility stress.

By clicking on the <Start> button in the ‘Field observations’ tab sheet of the *Calibration soil fertility stress* menu (Fig. 2.10m3), AquaCrop selects values for the stress coefficients ($K_{Sexp,f}$, K_{SCC_x} , K_{SWP} , $f_{Decline}$) and alters as such the simulated green canopy cover (CC), and biomass water production (WP*) for the Stressed field.

By trying different values for the various stress coefficients, and by respecting the specified observations (Fig. 2.10m3), AquaCrop calculates for each set of stress coefficients, the corresponding CC_{stress} and Biomass production (B_{stress}) until the simulated relative biomass production is equal to the observed relative production in the Stressed field. The results are displayed in the ‘Crop response to soil fertility stress’ tab sheet (Fig. 2.10m4).

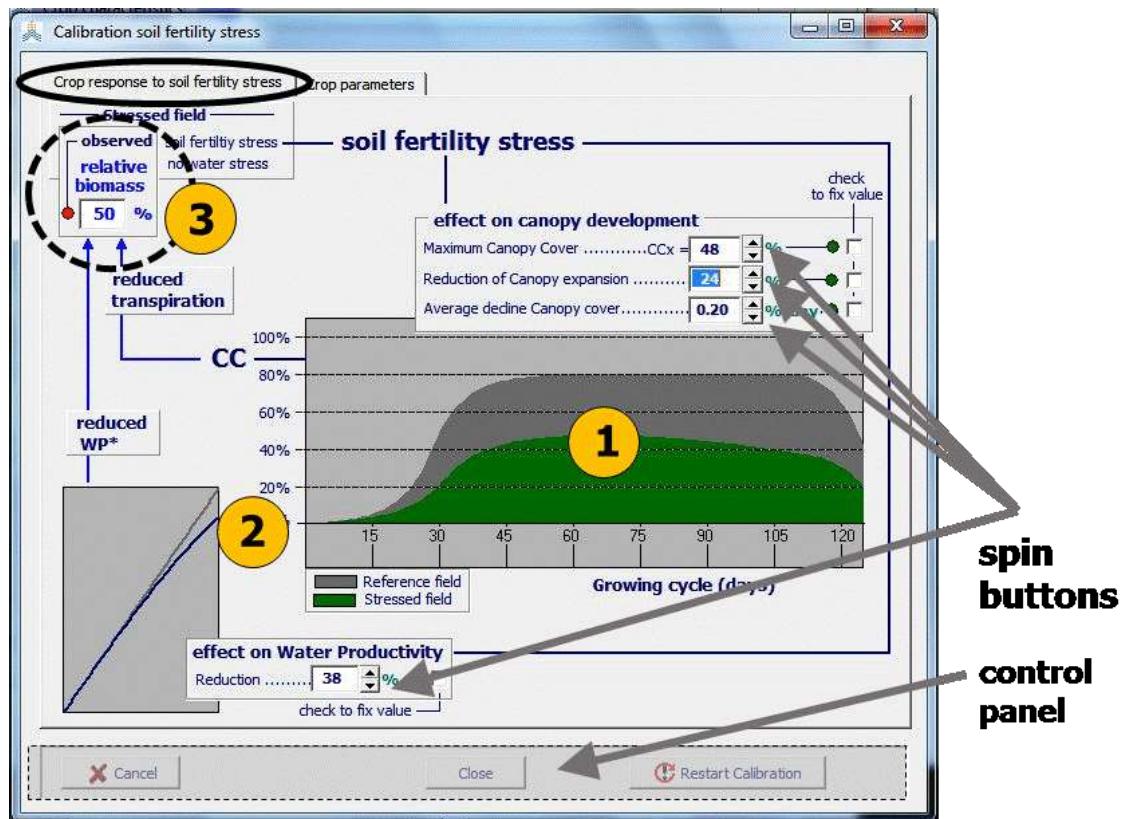


Figure 2.10m4 – The ‘Crop response to soil fertility stress’ tabular sheet of the *Calibration soil fertility stress* menu in which the effect of soil fertility stress (1) on canopy cover and (2) on the decline of WP* during the season, is plotted and is fine-tuned by means of the four spin buttons and (3) by respecting the specified relative biomass

In the ‘Crop parameters’ tab sheet of the *Calibration soil fertility stress* menu, the reduction in Canopy development and biomass Water Productivity (WP*) are displayed. The corresponding simulated relative Biomass production, the 4 Ks-curves and the Crop parameters (adjusted to the stress) can be consulted as well in their respectively tab-sheet (Fig. 2.10m5).

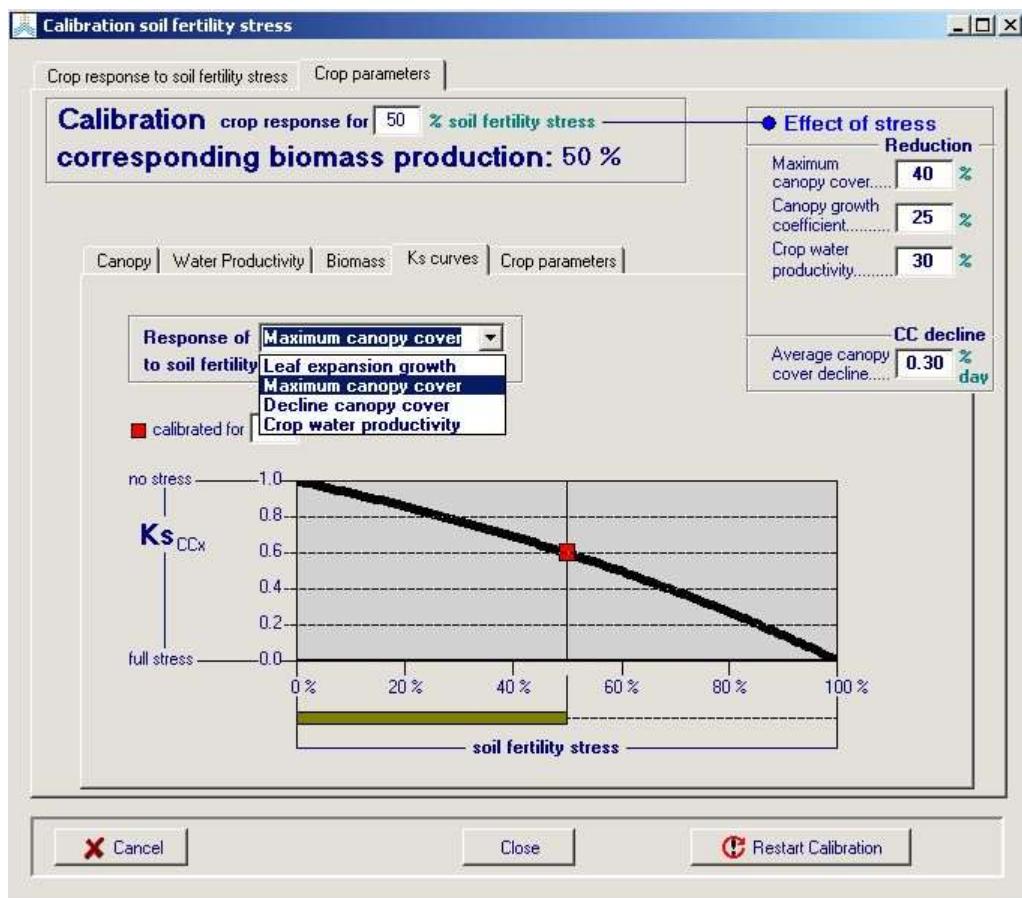


Figure 2.10m5 – The Ks curve for Maximum canopy cover as displayed in the tab-sheet ‘Ks-curves’ of the *Calibration soil fertility stress* menu

The calibration determines the shape of the 3 Ks-curves and of the decline coefficient (f). The shape is given by the values of Ks or f, at 3 different levels of stress:

1. For non-limiting soil fertility (not affecting biomass production), the stress is 0 % and the 3 soil fertility stress coefficients (Ks) are 1, and the decline coefficient ($f_{CDecline}$) is zero;
2. When the soil fertility stress is complete (100% stress), crop production is no longer possible and the Ks coefficients are zero and the decline coefficient ($f_{CDecline}$) is at its maximum rate i.e. 1 % per day;
3. The stress in the Stressed field is defined as:

$$stress = 100 (1 - B_{rel}) \quad (\text{Eq. 2.10m})$$

where B_{rel} is the ratio between the observed biomass in the stressed and reference field ($B_{rel} = B_{stress}/B_{ref}$). By considering the effect on its target parameter (CCx, CGC, WP*, and canopy decline), the corresponding values for Ks and f are obtained for the defined stress level. For example, if B is reduced in the Stressed field by 50 % ($B_{stress} = 0.5 B_{ref}$)

and CC_x by 40 % ($CC_{x\text{stress}} = 0.6 CC_{x\text{ref}}$), $K_s CC_x$ is 0.6 at the soil fertility/salinity stress of 50 % (Fig. 2.10m5).

Once a curve is calibrated, the K_s corresponding to other soil fertility/salinity stresses can be obtained from the curves. With reference to Fig. 2.10m5, CC_x will be reduced by 20 % ($K_s CC_x = 0.80$ or $CC_x = 0.8 CC_{x\text{ref}}$) for a soil fertility stress of 27 %, and by 60 % ($K_s CC_x = 0.40$ or $CC_x = 0.4 CC_{x\text{ref}}$) for a stress of 69 %.

Fine tuning

The user can fine tune the calibration by altering in the ***Calibration soil fertility stress*** menu (Fig. 2.10m4): (i) the maximum canopy cover (CC_x), (ii) the reduction of canopy expansion, (iii) the average decline of the Canopy cover, or (iv) the reduction in biomass water productivity (WP^*). Changing one of the above reductions will alter the reductions of the other parameters since AquaCrop always looks for the equilibrium between the simulated and observed relative biomass production in the Stressed field. By clicking on one or more of the 4 check boxes, the user can fix the value of one or more parameters (Fig. 2.10m4).

By clicking on the **<Restart calibration>** button key in the command panel of the ***Calibration soil fertility stress*** menu, the user returns to the ‘Field observation’ tab sheet (Fig. 2.10m3).

- **The effect of stress on biomass is considered (calibrated)**

Relationship between Biomass and soil fertility stress

For crop files where the effect of soil fertility stress on biomass is considered, AquaCrop displays in the ***Crop characteristics*** menu the effect on canopy development, biomass water productivity, and biomass production for several stress levels (mild up to severe stress). In the menu the relationship between Biomass and soil fertility stress is displayed as well (Fig. 2.10m6). The relationships are obtained by:

- (i) considering for various soil fertility stress levels the individual effect on CC_x , CGC , canopy decline, and WP^* , as described in each of the K_s curves (Fig. 2.10m5); and
- (ii) calculating by considering the stress coefficients, the corresponding canopy development, and reduction in relative biomass production by assuming no water stress. The effect of the each considered soil fertility stress level on CC_x , on CGC , on canopy decline, and on WP^* are described in the individual calibrated K_s and reduction curves (Fig. 2.10m5). Since the shapes of the K_s curve are not identical, and the effect of stress on WP^* increases when the canopy cover increases, the B-stress relationship is not linear (Fig. 2.10m6).

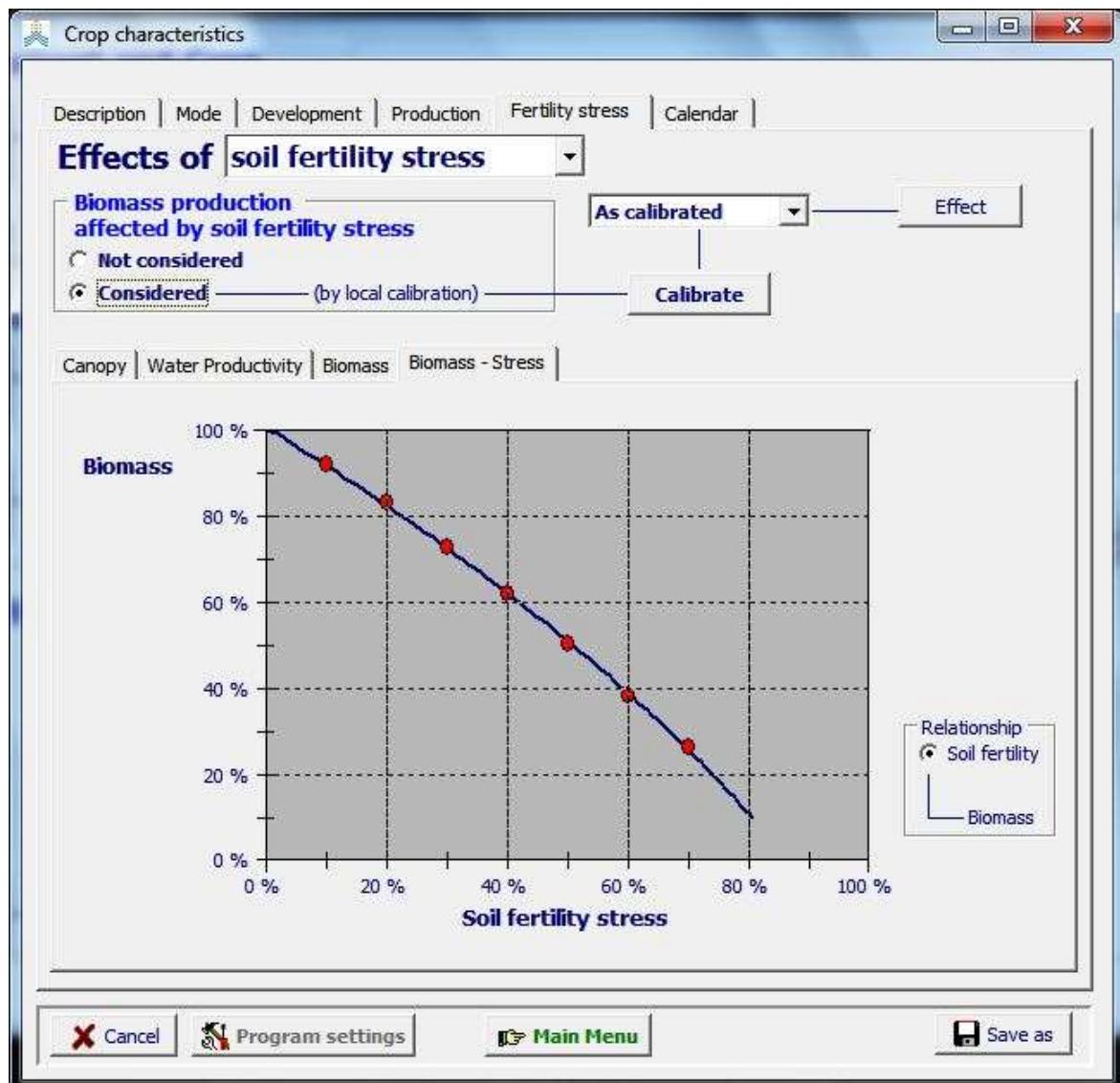


Figure 2.10m6 – Display of the relationship between Biomass and soil fertility stress in the ‘Biomass-Stress’ tab-sheet of the *Crop characteristics* menu.

Fine tuning

For crop files where the effect of soil fertility stress on biomass is considered, the calibration can be fine-tuned by clicking on the <Calibrate> button key in the *Crop characteristics* menu which will display the *Calibration soil fertility stress* menu (Fig. 2.10m4 and 2.10m5).

By clicking on the <Restart calibration> button key in the control panel of the *Calibration soil fertility stress* menu, the user returns to the ‘Field observation’ tab sheet (Fig. 2.10m3).

2.10.13 Tabular sheet: Soil salinity stress

- Crop response to soil salinity stress**

When the crop response to salinity stress is set at ‘Not considered’ in the *Crop characteristics* menu, AquaCrop will still simulate the building up of salts in the root zone, but will not consider the effect of soil salinity stress on the crop. When ‘Considered’ is selected, AquaCrop displays the tabular sheets in which the salt tolerance and crop response can be selected (Fig. 2.10n1).

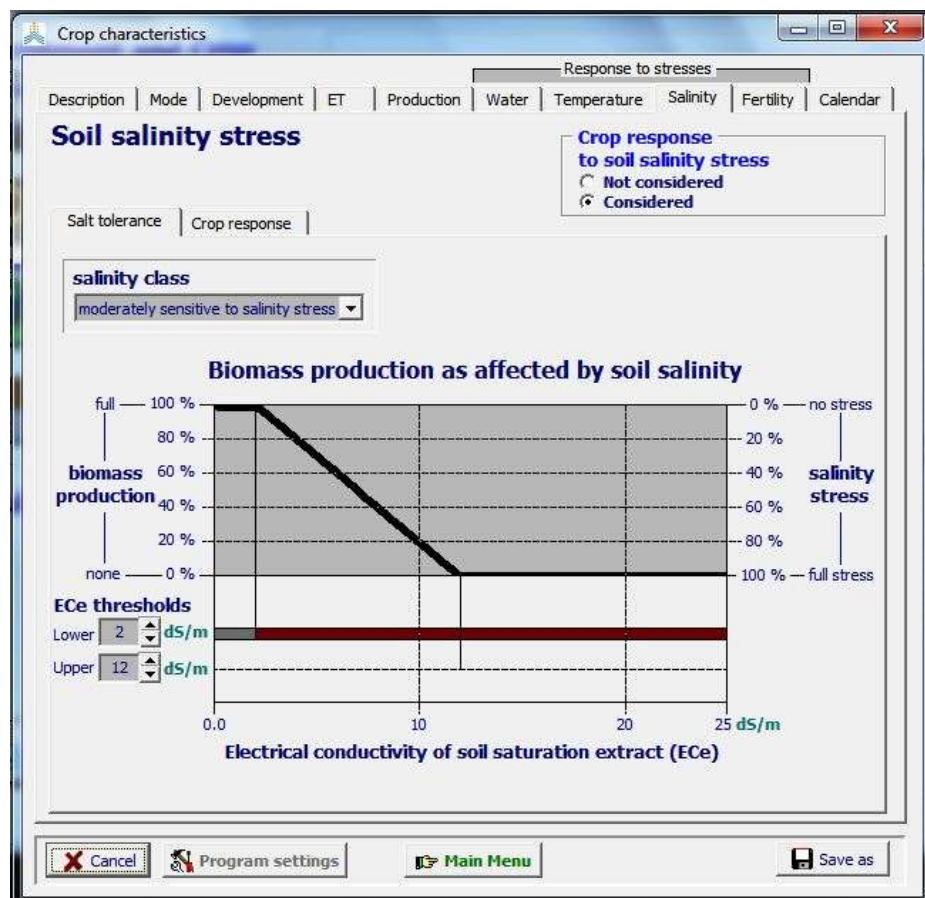


Figure 2.10n1 – Specification of the upper and lower thresholds of the electrical conductivity of soil saturation extract (ECe) with the corresponding salinity class, and the display of the ‘Biomass – ECe’ relationship in the ‘Salt tolerance’ tab sheet.

- ‘Salt tolerance’ tabular sheet

The salt tolerance of the crop determines the maximal biomass production that can be obtained in a salt affected root zone (Fig. 2.10n1). For the selected tolerance, AquaCrop derives from the ‘Biomass – ECe’ relationship, the maximal biomass production (expressed as a percentage) that still can be reached if no other stresses affect the production (no soil fertility, water, air temperature and/or weed stresses). The average electrical conductivity of the saturation soil-paste extract (ECe) from the root zone is the indicator for soil salinity. Soil salinity stress varies between 0% (with full biomass production) and 100% (resulting in no biomass production).

The user specifies the effect of soil salinity stress by selecting a sensitivity class (Tab. 2.10n) or by specifying values for the lower and upper threshold for soil salinity in the root zone (Fig. 2.10n1). The thresholds for ECe, which are crop specific and conservative crop parameters, are expressed in deciSiemens per meter (dS/m). Indicative values for various crops, are given in Annex III. Distinction is made between:

- the lower threshold (ECe_n) at which soil salinity stress starts to affect biomass production, and;
- the upper threshold (ECe_x) at which soil salinity stress has reached its maximum effect and the stress becomes so severe that biomass production ceases.

Table 2.10n – Classes and corresponding default values for the lower (ECe_n) and upper (ECe_x) threshold of soil salinity stress

| Class Sensitivity to salinity stress | Electrical conductivity of the saturated soil-paste extract (ECe) in dS/m | |
|---|---|---------|
| | ECe_n | ECe_x |
| extremely sensitive to salinity stress | 0 | 6 |
| sensitive to salinity stress | 1 | 8 |
| moderately sensitive to salinity stress | 2 | 12 |
| moderately tolerant to salinity stress | 5 | 18 |
| tolerant to salinity stress | 7 | 25 |
| extremely tolerant to salinity stress | 8 | 37 |

The reduction in biomass production is the result of a less dense crop, a poor development of the canopy cover, and a partial closure of the stomata. These effects of soil salinity stress are displayed in the ‘Crop response’ tabular sheet. Since the individual effects of salinity stress on crop density, development of the canopy cover and closure of the stomata are not well documented in literature for simulation in AquaCrop, the user can calibrate the crop response to soil salinity stress (Section 2.10.14 ‘Calibration for soil salinity stress’).

- ‘Crop response’ tabular sheet

In the ‘Canopy Cover’ (Fig. 2.10n2) and ‘Stomata closure’ (Fig. 2.10n3) sheets of the ‘Crop response’ tabular sheet, the canopy cover and stomatal closure are displayed for a selected salinity stress (ECe). By altering the ECe value in the sheets, the crop responses to various soil salinity stresses can be displayed. The integrated crop responses results in the biomass production as displayed in the ‘Biomass – ECe’ relationship (Fig. 2.10n1 in the ‘Salt tolerance’ tabular sheet). The biomass production is the maximum that can be obtained when the soil is well-watered.

When the soil is not well-watered, water depletion in the root zone results in an increase of the salt concentration in the remaining soil water. Although root zone depletion does not alter ECe (the indicator for soil salinity), it increases the electrical conductivity of the soil water (ECsw). The stronger the root zone depletion, the larger ECsw, and the more difficult it becomes for the crop to extract water from its root zone. This results in an stronger closure of the stomata when the soil dries out. The stomata closure for various root zone depletions is plotted for the selected salinity stress (ECe) in the ‘Stomatal closure’ tabular sheet (Fig. 2.10n3).

- **Calibration of the crop response**

Calibration of the crop response to soil salinity stress is done in the *Crop characteristic* menu (See 2.10.14 ‘Calibration for soil salinity stress’).

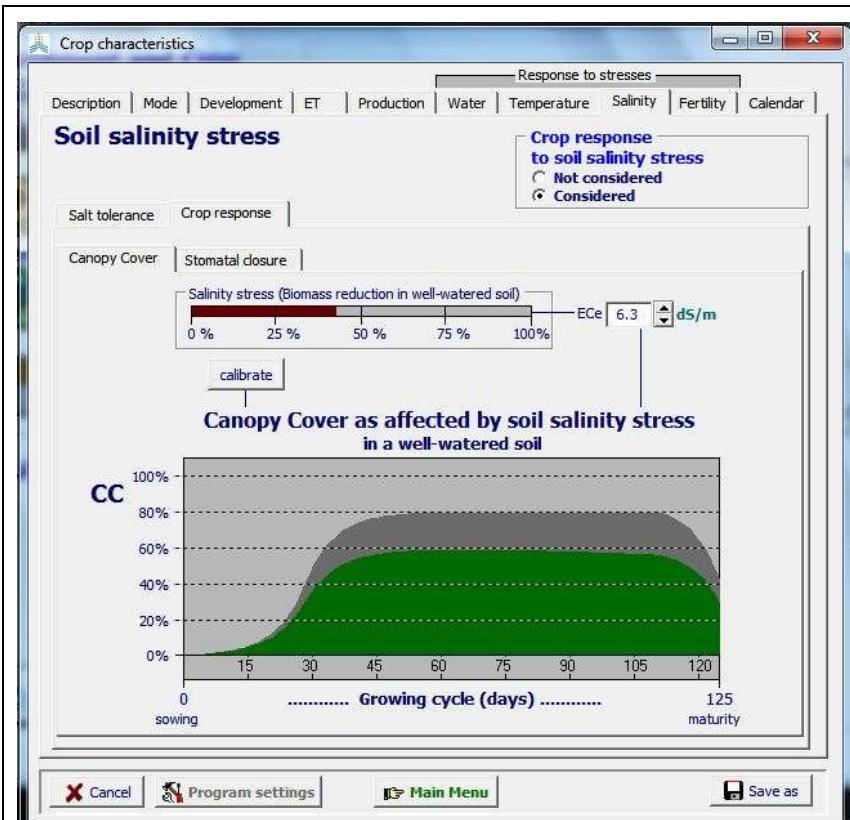


Figure 2.10n2
Development of the Canopy Cover (CC) for a selected soil salinity stress of 43% ($ECe = 6.3 \text{ dS/m}$), resulting in a 43% reduction of biomass production if no other stresses occur (i.e. in a well-watered soil).

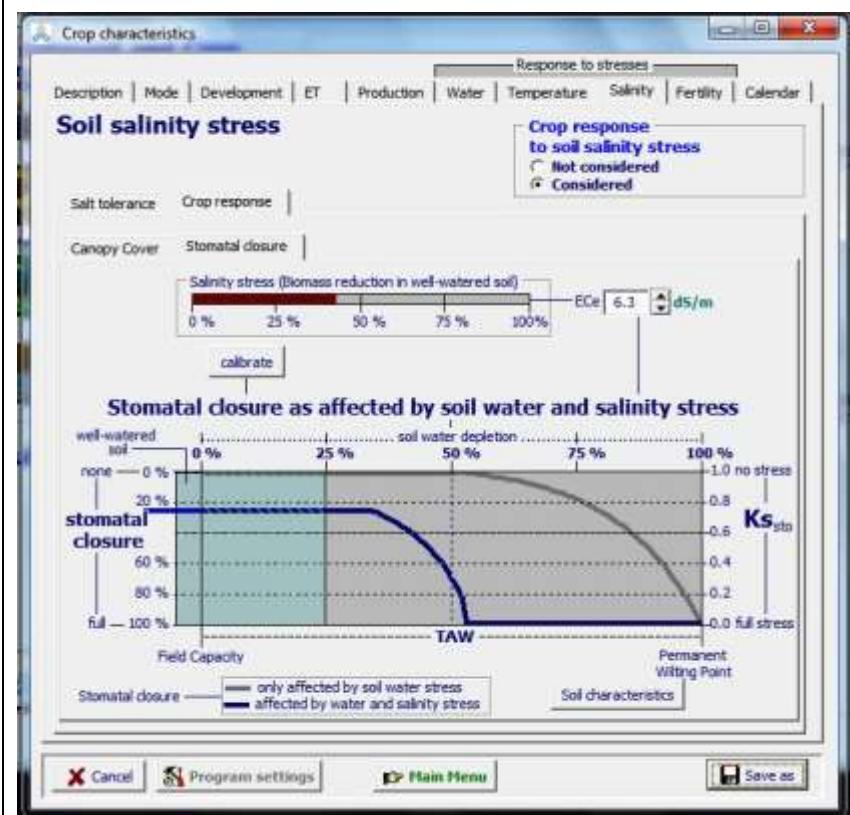


Figure 2.10n3
Stomatal closure for a soil salinity stress of 43% ($ECe = 6.3 \text{ dS/m}$), resulting in a 43% reduction of biomass production in a well-watered soil (shaded part at the left side of the graph).
The additional stomatal closure for various root zone depletions is plotted as well (right side of the graph).

2.10.14 Calibration for soil salinity stress

- **Biomass - ECe relationship**

Between the lower (ECe_n) and upper (ECe_x) threshold of the saturated soil-paste extracts, the shape of the ‘Biomass – ECe’ curve determines the effect of soil salinity on the biomass production in a well-watered soil. A linear shape is assumed (Fig. 2.10n1).

- **Crop response in a well-watered soil**

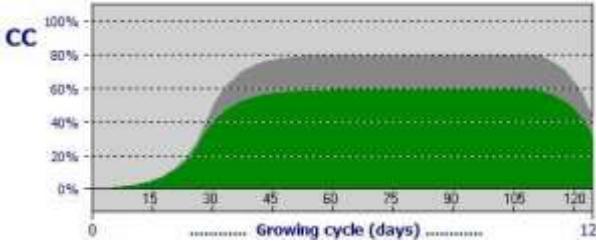
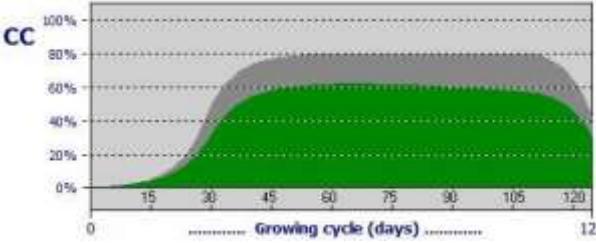
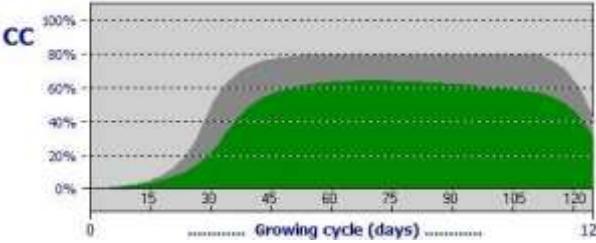
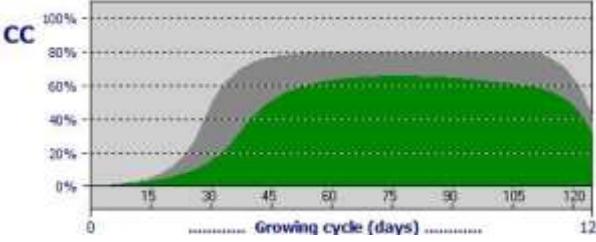
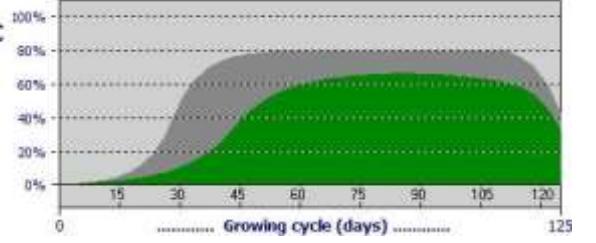
In a well-watered saline soil, and in the absence of any other stresses than salt stress, AquaCrop obtains the relative biomass production from the ‘Biomass – ECe’ relationship (Fig. 2.10n1). The reduction in biomass is the result of the integrated effect of four processes: (i) a slow canopy expansion, (ii) a poor canopy cover, (iii) a decline of the canopy cover during the crop cycle, and (iv) a partial closure of the stomata. Although the total reduction in biomass (i.e. the combined effect) in a well-watered soil is given by the ‘Biomass – ECe’ relationship, the individual effect of salinity stress on the four processes is not sufficient documented for simulation in AquaCrop. The same maximal biomass production can be obtained by assigning various combinations of weights to each of the involved 4 processes of crop response. The calibration process consists in selecting a specific combination.

If the development of the canopy cover is observed in the field, the user can calibrate the effect of salinity stress on the development, in the ‘Canopy Cover’ tabular sheet (Fig. 2.10p2). This is done by selecting a class or percentage of canopy cover distortion (Table 2.10p1). The canopy distortion is expressed with reference to the development of the canopy cover in the absence of any stress (as calibrated in the ‘Development’ tabular-sheet of the *Crop characteristics* menu). For ‘no’ distortion, the effect of salinity stress consists mainly of a reduction of CC_x , which results in a canopy cover which is parallel to the reference development in the non-stressed environment. If a distortion is considered, additional effects of salinity stress on (i) the rate of canopy expansion and (ii) the steady decline of the canopy cover in the season are considered. The stronger the distortion, the stronger the additional effects (Tab. 1.10p1).

In AquaCrop, the percentage of stomata closure in the well-watered-soil is taken as identical to the decline of CC_x . Since the maximum biomass production for a particular soil salinity stress should remain identically for any degree of distortion, a stronger canopy distortion with additional effects on Canopy cover, results automatically in a smaller decline of CC_x (and a smaller degree of stomata closure). If only the reduction of the maximum canopy cover (CC_x) is available from field observations, the plot of the CC_x reduction might be helpful for calibration (Fig. 2.10p3). This plot shows also the percentage of stomatal closure in a well-watered soil.

As long as the soil is well watered (no significant root zone depletion between wetting events) and the ECe (salt stress) remains fairly constant throughout the season, the selection of the distortion of the canopy cover by salinity stress will not have a significant effect on the simulated biomass production (Fig. 2.10p4).

Table 2.10p1 – Classes for Canopy Cover distortion due to salinity stress. The corresponding effect on the canopy cover development is displayed for a salinity stress of 41%.

| Class | Canopy Cover distortion (%) | | Development of the canopy cover under salinity stress (green) with reference to its development in a non-stressed environment (grey) |
|--------------|-----------------------------|----------|--|
| | Default | Range | |
| None | 0 | - |  |
| Moderate | 25 | 1 – 35 |  |
| Intermediate | 50 | 36 – 60 |  |
| Strong | 75 | 61 – 90 |  |
| Very strong | 100 | 91 – 100 |  |

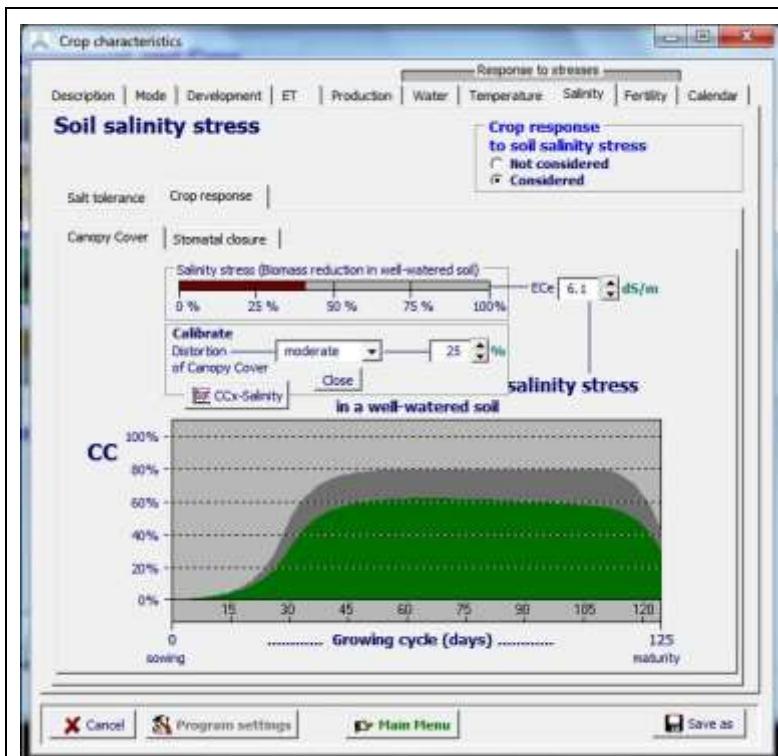


Figure 2.10p2 –The calibration of the effect of salinity stress on the development of the canopy cover in a well-watered soil, consists in selecting a class of canopy distortion or by specifying the percentage of the distortion in the ‘Canopy Cover’ tabular sheet.

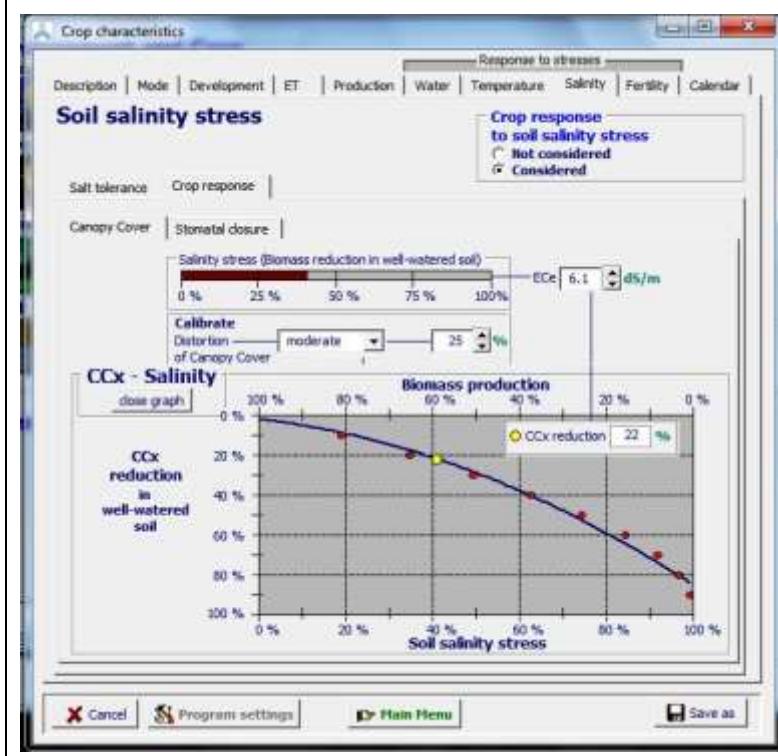


Figure 2.10p3 – Display of the effect of salinity stress on the reduction of the maximum canopy cover (CCx) in a well-watered soil in the ‘Canopy Cover’ tabular sheet. The percentage of stomatal closure in a well-watered soil is considered as identical.

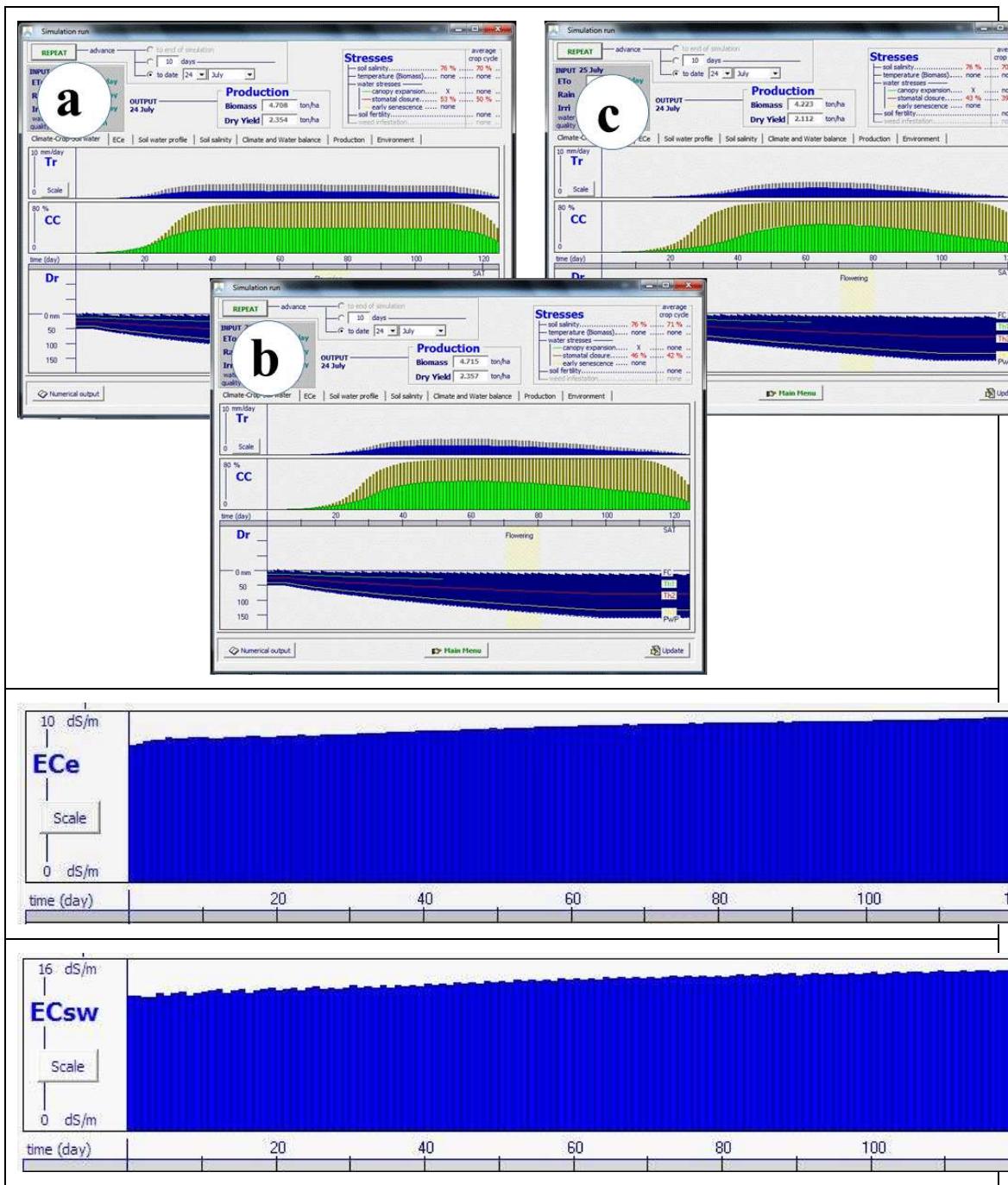


Figure 2.10p4 – Simulation of canopy development (CC) and biomass production and crop yield in a saline soil for (a) no canopy distortion, (b) an intermediate distortion of 50%, and (c) a very strong distortion of 100 %, and the corresponding Electrical Conductivity of the soil saturation extract (ECe) and soil water (ECsw).

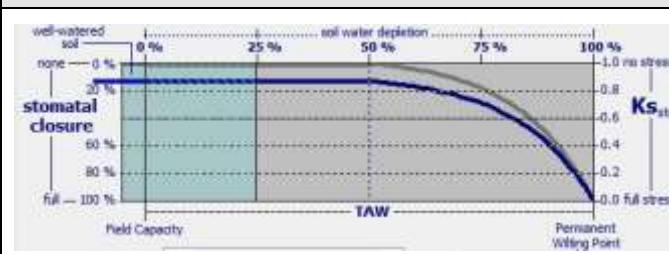
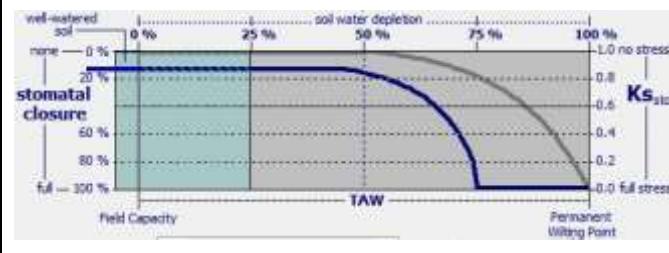
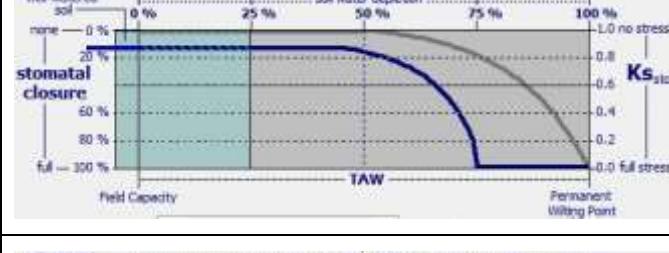
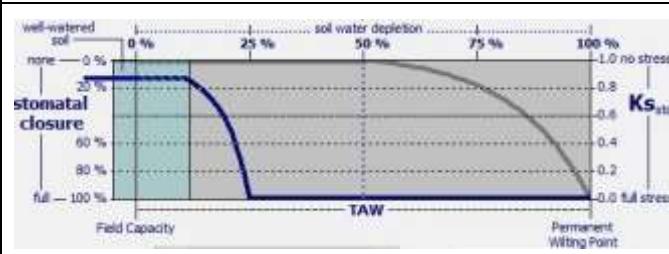
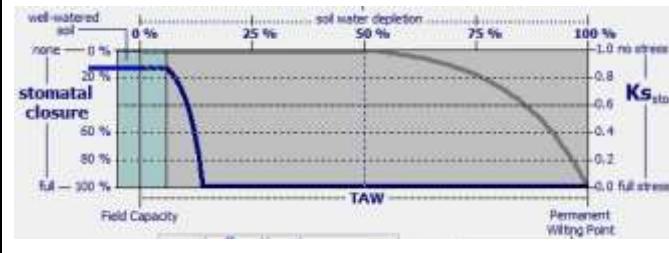
In each of the three simulations presented in Fig. 2.10p4, the salinity stress throughout the season remained fairly constant (70 %) and the biomass production was very similar (about 30 % of the production in the absence of any stress). In this example the loamy soil was well-watered by a very frequent application of water of 3 dS/m by drip irrigation. The crop, which is moderately sensitive to salinity stress ($ECe_n = 2$ dS/m and $ECe_x = 12$ dS/m), received 5 mm of water each time 20% of RAW was depleted. At the start of the simulation process the whole soil profile was at Field Capacity, and soil salinity at 8 dS/m.

- **Crop response when root zone depletion increases the salinity stress**

Due to the root zone depletion between wetting events, salts concentrate in the remaining soil water. Although the depletion does not alter ECe (the indicator for soil salinity), the depletion results in an increase of the electrical conductivity of the soil water (ECsw), stronger osmotic forces and a stronger closure of the stomata. The stronger the root zone depletion, the larger ECsw, and the more difficult it becomes for the crop to extract water from its root zone.

The effect of ECsw on stomatal closure can be calibrated in the ‘Stomatal closure’ tabular sheet (Fig. 2.10p5). This is done by selecting a class or percentage for the effect of ECsw on stomatal closure (Table 2.10p2). Since ECsw depends on the physical characteristics of the soil layer, the soil water content at saturation, field capacity and permanent wilting point, can be displayed (Fig.2.10p6).

Table 2.10p2 – Classes for the response of stomatal closure to the Electrical Conductivity of the soil water (EC_{sw}). In the graphs the stomatal closure for various root zone depletions, for a salinity stress of 25 % and a moderate distortion of the canopy cover (25%), are displayed

| Class | Response (%) to EC _{sw} | | Stomatal closure for various root zone depletion when only affected by soil water stress (grey) and affected by water and salinity stress (blue) |
|--------------------|----------------------------------|-----------|--|
| | Default | Range | |
| None | 0 % | - |  |
| Poor | 75 % | 1 - 80 |  |
| Moderate | 100 % | 81 - 110 |  |
| Strong | 125 % | 111 - 130 |  |
| Very strong | 150 % | 131 - 200 |  |

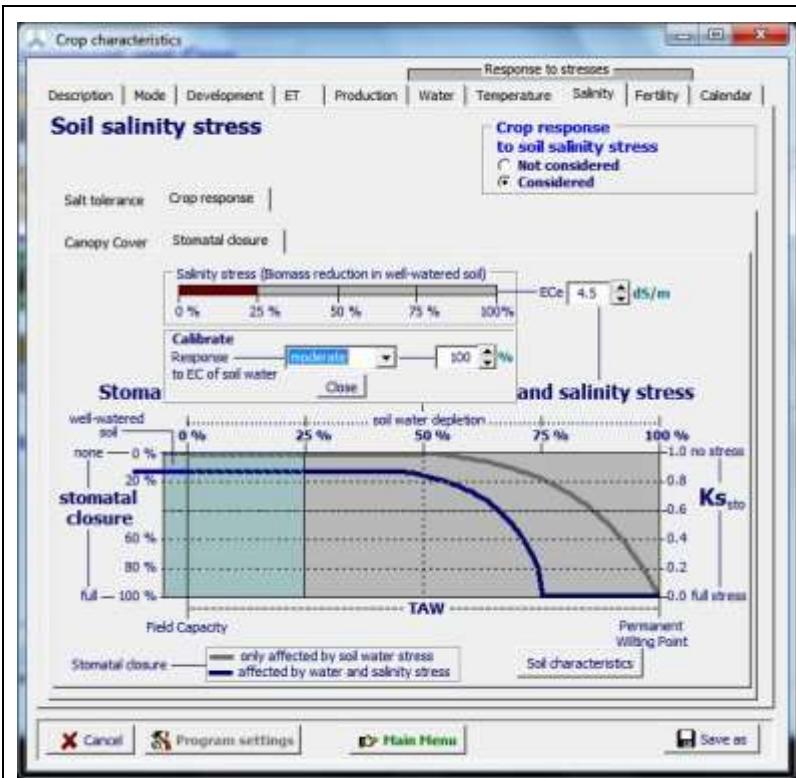


Figure 2.10p5 –The calibration of the effect on stomatal closure of salt concentration in a depleting root zone, consists in selecting a class of the response to the Electrical Conductivity of the soil water (EC_{sw}) or by specifying the percentage of the response in the ‘Stomatal closure’ tabular sheet.

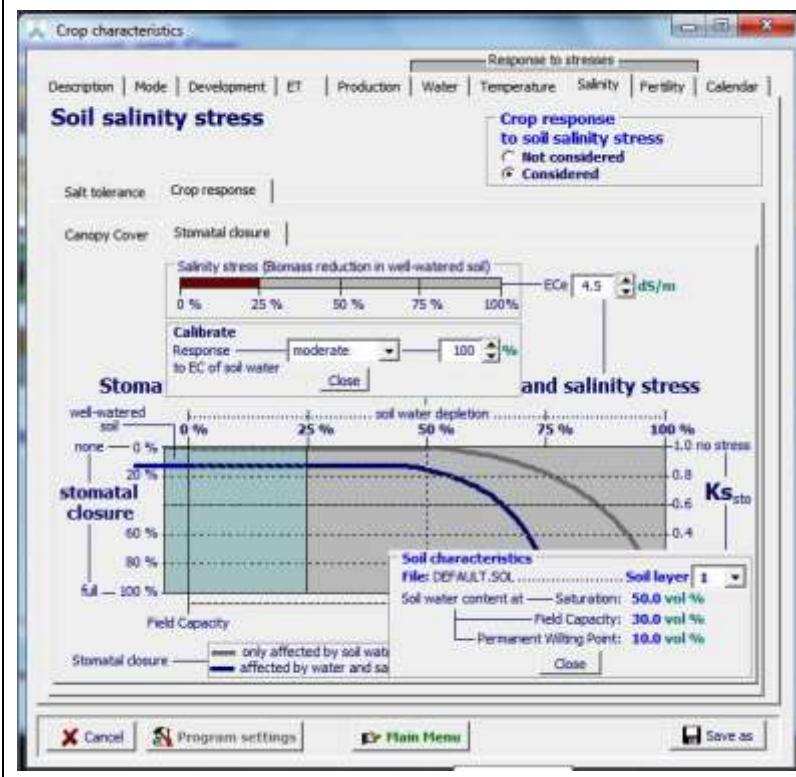


Figure 2.10p6 – Display of the soil physical characteristics of the soil layer for which the response to EC_{sw} is valid.

For a simulation in which the root zone depletion is important between irrigation events, the canopy development, crop production, and salt concentration in the root zone are plotted in Figure 2.10p7.

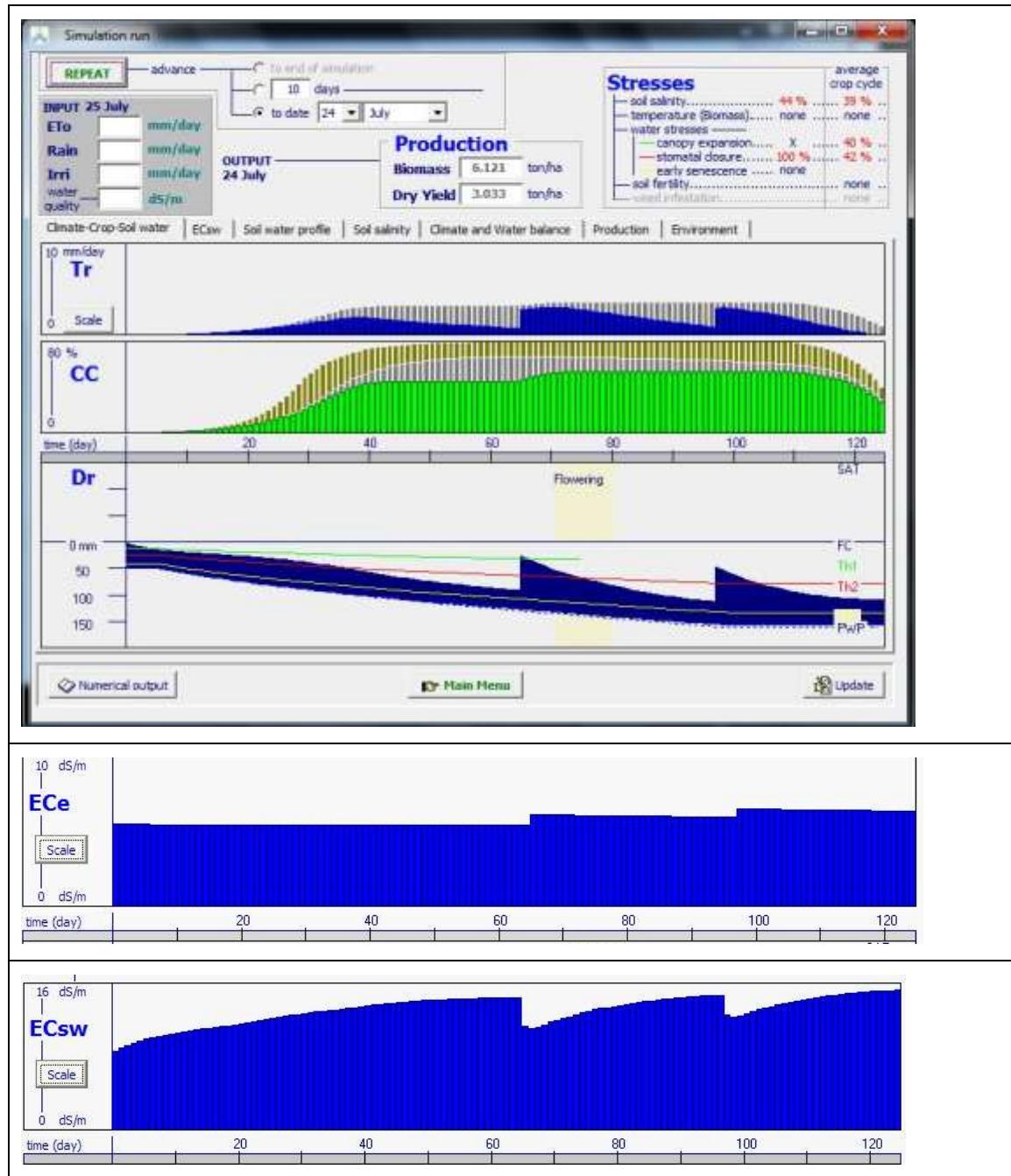


Figure 2.10p7 – Simulation of crop transpiration (Tr) and Canopy Cover (CC) in a saline soil with strong root zone depletions, and the corresponding simulated Electrical Conductivity of the soil saturation extract (ECe) and of the soil water (ECsw). The Canopy Cover that could have been reached in a well-watered soil is displayed in grey. The canopy cover displayed in olive is CC in the absence of any stress

The simulation displayed in Fig. 2.10p7, was run for a crop which is moderately sensitive to salinity stress ($EC_{e_n} = 2 \text{ dS/m}$ and $EC_{e_x} = 12 \text{ dS/m}$). The class for the canopy cover distortion was selected as intermediate (50%) and the class for the response of stomatal closure as affected by the Electrical Conductivity of the soil water (EC_{sw}) was selected as moderate (100%). At the start of the simulation process the whole soil profile was at Field Capacity, and soil salinity (EC_e) at 5.5 dS/m. In the simulation run, the loamy soil received by basin irrigation, two irrigation applications of 65 mm with poor water quality of 4 dS/m. In the simulation, the average salinity stress was only 39 % (EC_e ranging between 5.5 and 6.4 dS/m). Nevertheless the biomass production dropped to 40 % of the reference production due to a strong root zone depletion (up to 150% of RAW) between the two irrigation applications, resulting in serious stress affecting the canopy cover development and the closure of the stomata.

2.10.15 Tabular sheet: Calendar

An overview of the calendar of the growing period is displayed in the Calendar folder of the **Crop characteristics** menu (Fig. 2.10q). The planting date and length of the different growth stages can be adjusted with the help of spin buttons.

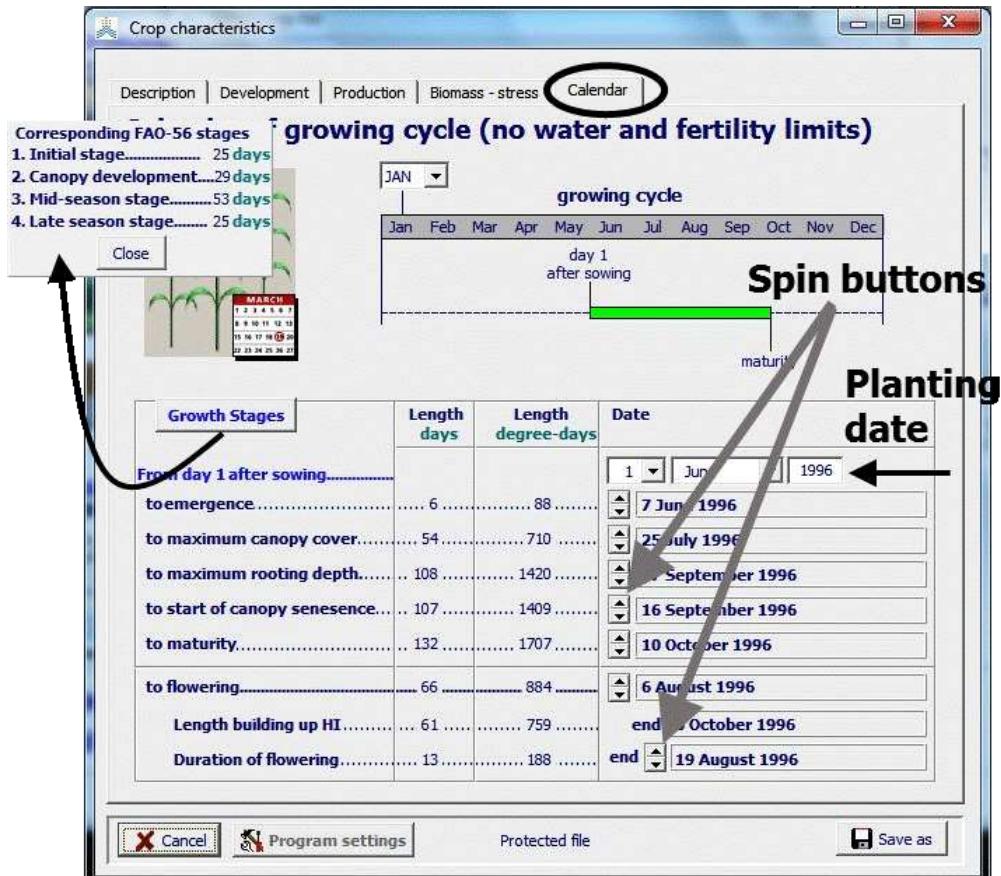


Figure 2.10q – Crop calendar to inspect or update the calendar of the growing cycle with indication of the FAO-56 growth stages

In the calendar the length of crop growth stages can also be displayed. The stages refer to the definitions used in earlier FAO publications (Irrigation and Drainage Papers Nr. 24, 33 and 56) and are:

- The **initial stage** starts at sowing and stops when canopy cover is 10% ($CC = 0.10$);
- The **canopy development stage** starts when the canopy cover is larger than 10 % and stops when 98% of the maximum canopy cover is reached ($CC = 0.98 CC_x$).
- The **mid season stage** starts when the canopy covers reaches $0.98 CC_x$ and stops when canopy senescence begins. The end of the stage is given by the time to reach canopy senescence.
- The **late season stage** starts when the days to senescence are reached and stops at the moment crop maturity is reached, and the crop is ready to be harvested.

In Annex II (Tab. II-1) indicative values for lengths of crop development stages for various planting period and climate regions for common agriculture crops are presented.

2.10.16 Program settings

From the *Crop characteristics* menu the user has access to the program settings listed in Table 2.10r. The effect of the settings on soil evaporation, crop transpiration, canopy expansion and decline, and stresses are explained in the relevant sections of Chapter 3 (Calculation procedures).

Table 2.10r – Program settings affecting soil evaporation, crop transpiration, crop development, production and the effect of water and salinity stresses

| Symbol | Program parameter | Default |
|-----------------------------------|--|---------------|
| f _K K _{ex} | <p><i>Soil evaporation</i></p> <ul style="list-style-type: none"> ▪ Evaporation decline factor for stage II ▪ Soil evaporation coefficient for fully wet and non-shaded soil surface | 4 1.10 |
| - | <p><i>Harvest Index</i></p> <ul style="list-style-type: none"> ▪ Threshold for green canopy cover below which HI can no longer increase due to inadequate photosynthesis (% cover) | 5 % |
| - | <p><i>Germination</i></p> <ul style="list-style-type: none"> ▪ Minimal soil water content required for germination at sowing depth (% TAW) | 20 % |
| Z _o - | <p><i>Root zone</i></p> <ul style="list-style-type: none"> ▪ Starting depth of the root zone expansion curve (% of minimum effective rooting depth) ▪ Shape factor for the curve describing the effect of water stress (relative transpiration) on root zone expansion | 70 % -6 |
| - β | <p><i>Senescence</i></p> <ul style="list-style-type: none"> ▪ Shape factor (exponent a) for an adjustment factor of K_{cbx}, considering the drop in photosynthetic activity of dying crop ▪ Decrease of p(sen) once canopy senescence is triggered (% of p(sen)) | 1 12 % |
| - f _{adj} | <p><i>Stresses</i></p> <ul style="list-style-type: none"> ▪ Aeration stress: Number of days after which deficient aeration is fully effective ▪ Water stress: Adjustment factor for the ETo correction of the soil water depletion (p) (fraction of default FAO-adjustment) | 3 days 1.0 |
| Z _{top} | <p><i>Top soil</i></p> <ul style="list-style-type: none"> ▪ Considered thickness of top soil for the estimate of soil water stress in the top of the soil profile | 10 cm |

2.10.17 Training videos about crop

A set of training modules (MP4 videos) are posted in an ‘AquaCrop Training’ channel of YouTube. The modules about crop are listed in Table 2.10s. For the playlist go to FAO AquaCrop website <http://www.fao.org/nr/water/aquacrop.html>

Table 2.10s – Set of training modules about climate

| Video | Learning objective | Length [min:sec] |
|--|--|------------------|
| 04.1 Crop parameters | Know the required crop parameters | - |
| – Part 1. Type of crop parameters | 06:23 | |
| – Part 2. Tuning of crop parameters | 15:59 | |
| – Part 3. Crop development adjustment to temperature regimes | 08:15 | |
| 04.2 Stress coefficients | Understand the way the stress is simulated | 06:52 |
| 04.3 Crop development | Understand how AquaCrop simulates crop development | 13:23 |
| 04.4 Crop transpiration | Understand how AquaCrop simulates crop transpiration | 09:22 |
| 04.5 Biomass production | Understand how AquaCrop simulates biomass production | 10:59 |
| 04.6 Yield response to water | Understand how AquaCrop simulates yield and adjust the Harvest Index to stresses | - |
| – Part 1. Reference Harvest Index, Period of potential vegetative growth | 07:35 | |
| – Part 2. Stresses affecting yield formation | 17:19 | |
| 04.7 Water productivity | Understand the concept of water productivity | 06:56 |

2.11 Start of the growing cycle

The start of the growing cycle is specified in the **Main menu** (Fig. 2.11a) by

- specifying the date, or
- generating an onset based on rainfall or air temperature.

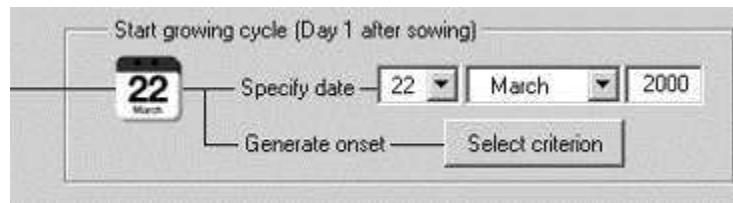


Figure 2.11a – Panel in *Main menu* where the start of the growing cycle is specified

2.11.1 Specified date

The user specifies the first day of the observed or planned start of the growing cycle (i.e. the first day after sowing or planting). If the selected climatic data is linked to a specific year, the start of the growing period is also linked to that year. If the climatic data consists of several years, the start of the growing period occurs in the first year of the climatic data set. The year can be adjusted in the panel.

2.11.2 Generated onset

▪ Onset generated based on rainfall

In rainfed cropping, sowing or planting is typically determined by rainfall events. By clicking on the <Select criterion> commanding the **Main menu**, the **Onset based on rainfall** menu is displayed (Fig. 2.11b). By selecting one or another criterion, the start of the growing cycle is determined by appraising the rainfall data specified in the selected Rain data file. By specifying the first and last day in a ‘Search window’, only rainfall within the specified window is evaluated. The following criteria can be selected to determine the onset of the growing cycle:

- **cumulative rainfall** since the start of the search period is equal to or exceeds the preset value;
- observed **rainfall during a number of successive days** is equal to or exceeds the preset value;
- **10-day rainfall** is equal to or exceeds the preset value;
- **10-day rainfall exceeds** the preset **fraction of the 10-day ETo**.

The last two options are particular useful if only 10-day or monthly rainfall is available.

The first occurrence of the onset date is the first date for which the selected criterion holds. The next 10 occurrences of onset days are displayed when clicking on the <Next days> command. When the start of the rainy season is not certain at the first occurrence of the selected criterion, selecting one of the displayed next occurrences or specifying a more stringent criterion might avoid early canopy senescence and a complete crop failure after germination.

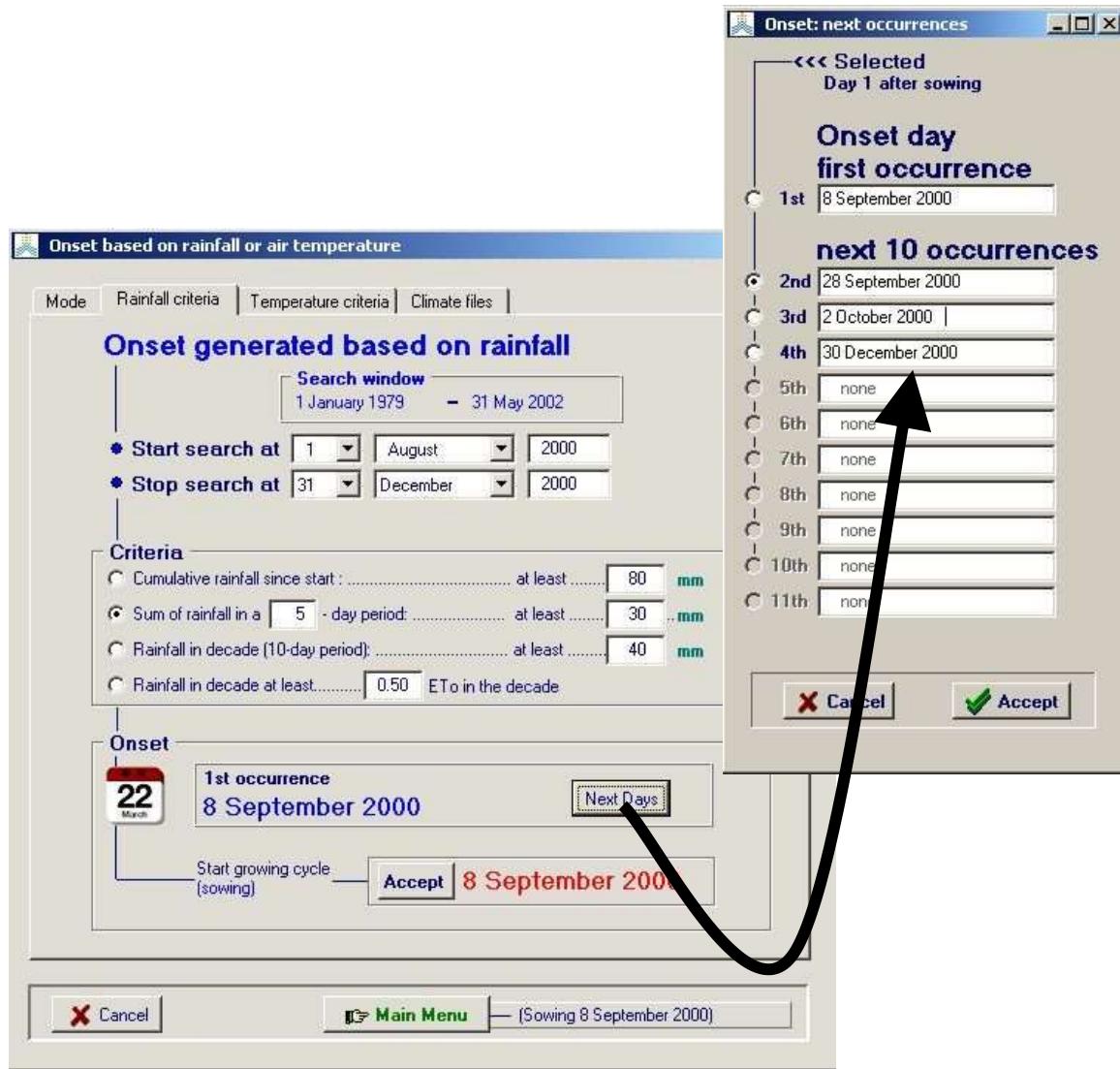


Figure 2.11b – Onset based on rainfall menu where the onset of the growing period is determined by the exceedance of 30 mm of rainfall in a period of 5 successive days, counting from 1 August 2000 (start of the search window)

- **Onset generated based on air temperature**

Climate change is likely to increase the air temperature in many regions. To estimate the planting dates for future years for spring crops in cool climates, AquaCrop offers the possibility to generate the sowing/planting date based on air temperature. By selecting one or another criterion, the likely planting/sowing date is generated by appraising the air temperature data specified in the selected ‘Air temperature’ data file. By specifying the first and last day in a ‘Search window’, only temperature data within the specified window is evaluated (Fig. 2.11c).

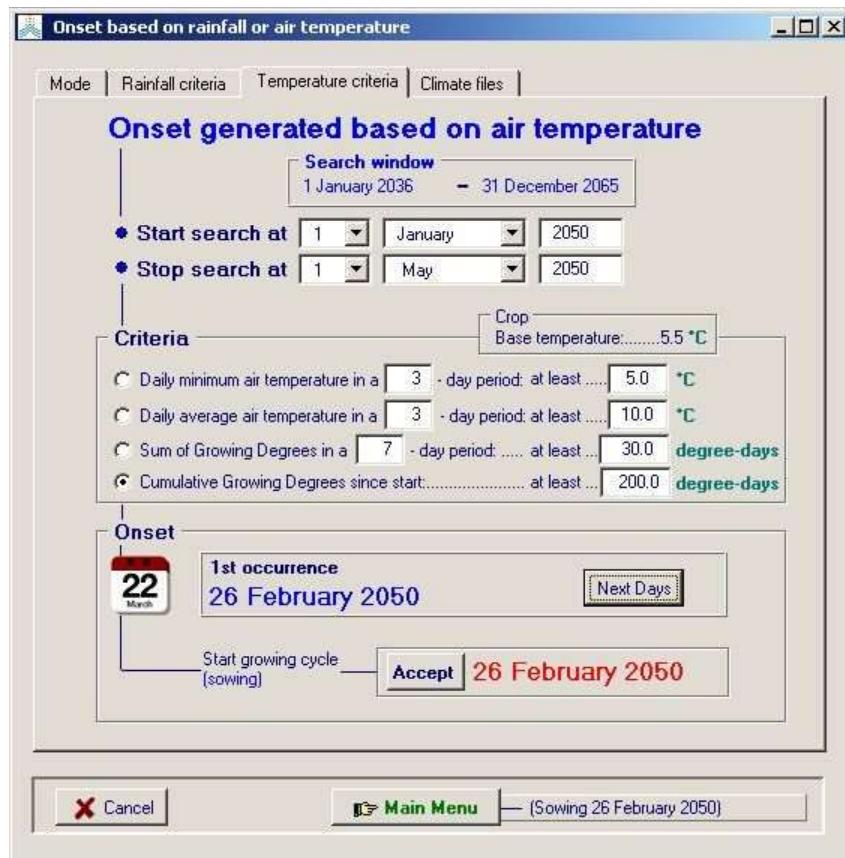


Figure 2.11c – Selection of a temperature criterion in the *Onset based on rainfall or air temperature* menu

The following criteria can be selected to determine the onset of the growing cycle based on air temperature:

- The daily minimum air temperature, in each day of a given number of successive days, is equal to or exceeds a specified minimum air temperature;
- The daily average air temperature, in each day of a given number of successive days, is equal to or exceeds a specified average air temperature;
- The sum of Growing Degrees in a given number of successive days is equal to or exceeds the specified growing degree days;

- The cumulative Growing Degrees since the start of the search period are equal to or exceed the specified growing degree days.

The first occurrence of the onset date is the first date for which the selected criterion holds. The next 10 occurrences of onset days are displayed when clicking on the <Next days> command.

■ **Display climate characteristics**

Information on the air temperature regime, rainfall, and ETo for the selected climate is available when selecting the ‘Display Climate characteristics’ command key in the ‘Climate files’ tabular sheet (Fig. 2.11d).

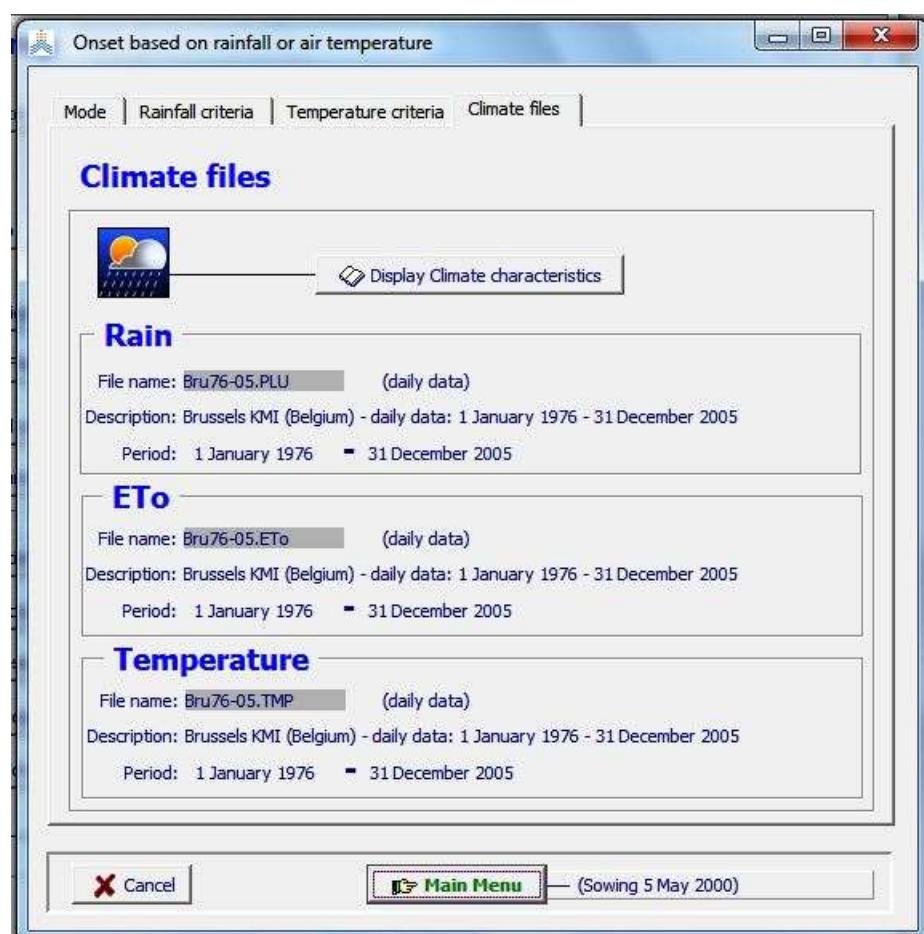


Figure 2.11d – Command key ‘Display Climate characteristics’ in the ‘Climate files’ tabular sheet of the *Onset based on rainfall or air temperature* menu

2.11.3 Training video about the start of the growing season

A set of training modules (MP4 videos) are posted in an ‘AquaCrop Training’ channel of YouTube. The module about the start of the growing season is listed in Table 2.11. For the playlist go to FAO AquaCrop website <http://www.fao.org/nr/water/aquacrop.html>

Table 2.11 – Training modules about the start of the growing cycle

| Video | Learning objective | Length [min:sec] |
|---|--|-----------------------------|
| 06.2 Start of the growing season | Understand how to determine the start of the growing cycle | 06:40 |

2.12 Irrigation management

The selected irrigation management can be displayed in the *Display of irrigation management* menu and updated in the *Irrigation management* menu (Fig. 2.12a). Various irrigation modes can be considered in AquaCrop:

- rainfed cropping (no irrigation in season) – which is the default,
- the determination of Net irrigation water requirement,
- an irrigation schedule by specifying the events to asses an existing irrigation schedule,
- the generation of an irrigation schedule by specifying a time and depth criterion for planning or evaluating a potential irrigation strategy.



Figure 2.12a – The selection of the mode in the *Irrigation management* menu

2.12.1 No irrigation (rainfed cropping)

When selecting this option (which is the default), no irrigations will be generated when running a simulation.

2.12.2 Determination of net irrigation water requirement

When selecting this option, AquaCrop will calculate during the simulation run the amount of water required to avoid (a certain level of) water stress. When the root zone depletion exceeds the specified threshold value (50% of RAW is the default), a small amount of irrigation water will be stored in the soil profile to keep the root zone depletion just above the specified threshold for that day (time step).

The threshold for the allowable root zone depletion can be adjusted (Fig. 2.12b). The thresholds at which leaf expansion growth starts to be hampered, and at which stomatal closure starts to restrict crop transpiration are given as reference for the selected crop.

The total amount of irrigation water required to keep the water content in the soil profile above the specified threshold is the net irrigation water requirement for the period. The net requirement does not consider extra water that has to be applied to the field to account for conveyance losses or the uneven distribution of irrigation water on the field.

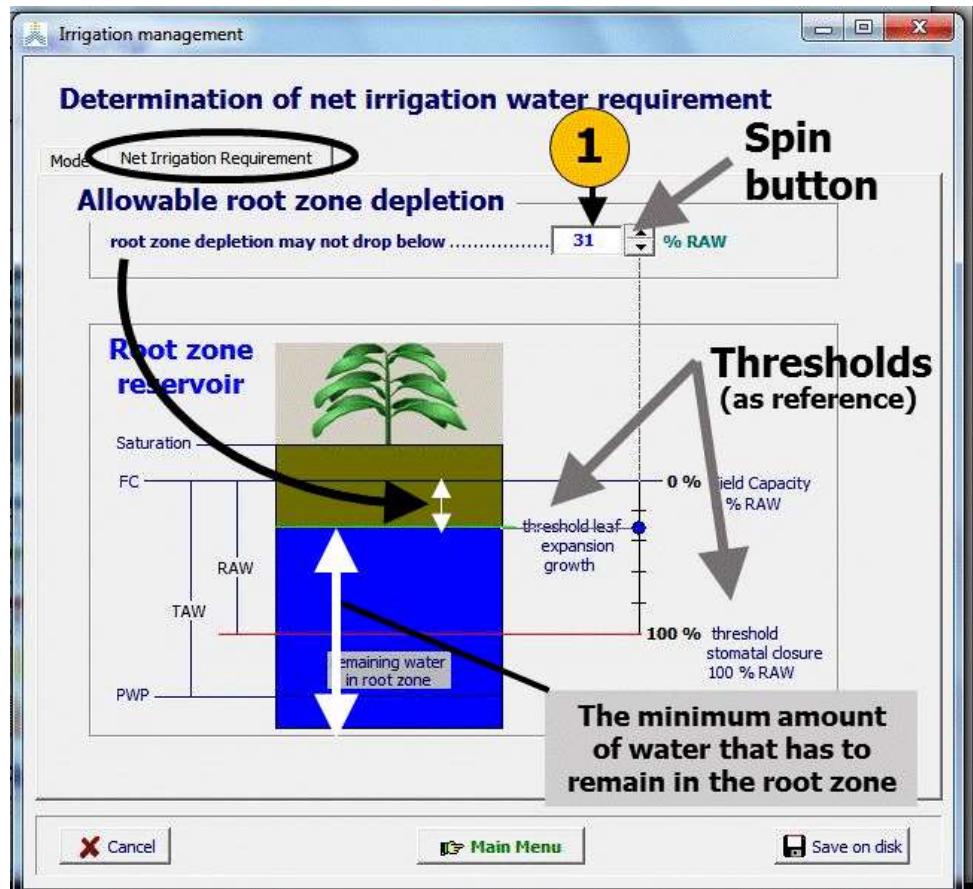


Figure 2.12b – Specified allowable root zone depletion for the determination of the net irrigation requirement in the *Irrigation management* menu

2.12.3 Irrigation schedule (specified events)

The irrigation schedule mode is used to assess an existing irrigation schedule. For each irrigation event the user specifies (Fig. 2.12c):

- **time of application:** The time is entered as days after sowing (DAS) and translated by the program to the corresponding calendar day;
- **application depth:** The irrigation depth refers to the irrigation amount that has infiltrated in the field. Extra water applied to the field to account for conveyance losses or the uneven distribution of irrigation water on the field should not be added;
- **water quality:** The electrical conductivity (EC) of the irrigation water is specified if low quality water was used.

As a reference, the canopy development for the selected crop, and the irrigation events in the season can be plotted.

The performance of the irrigation schedule and crop response can be assessed by examining the results in the **Simulation run** menu. The user can study the simulated and plotted root zone depletion (Dr), canopy development (CC), and crop transpiration (Tr). The simulated biomass (B), crop yield (Y) and ET water productivity (WPET) might give valuable information about the performance of the schedule. By adding/removing irrigation applications, and/or increasing/decreasing irrigation intervals or irrigation application doses, it can be checked if crop yield and WPET can be improved.

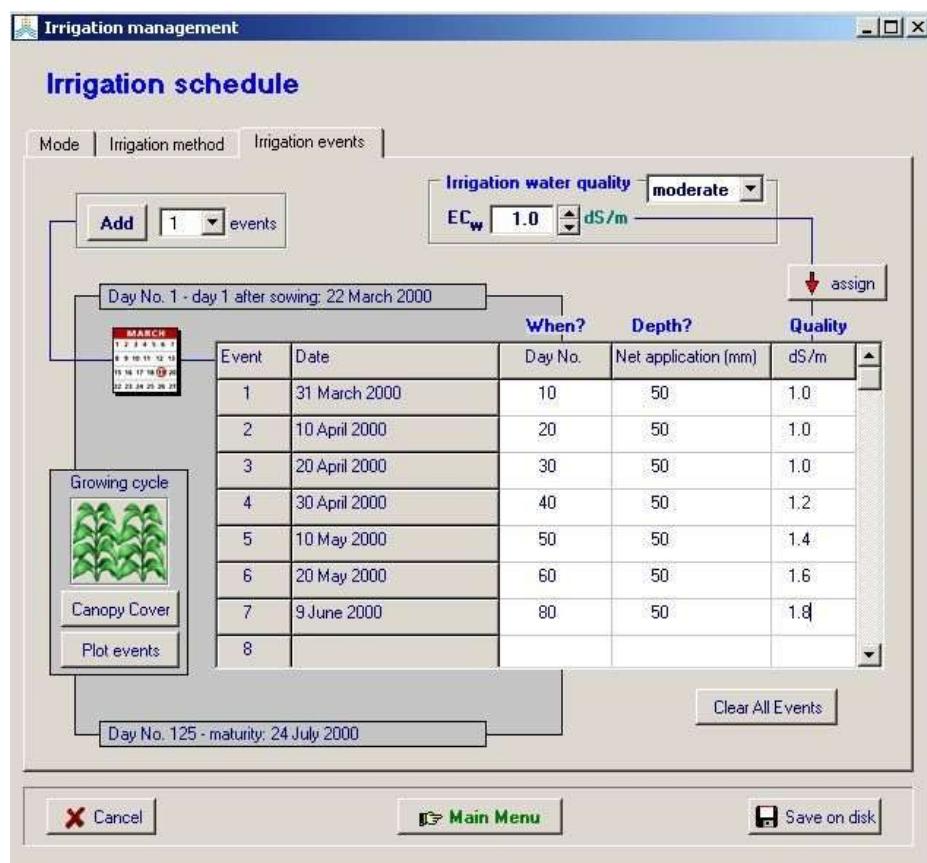


Figure 2.12c – Specification of the time, application depth and water quality for irrigation events

2.12.4 Generation of irrigation schedules

This option is available to generate an irrigation schedule for evaluating or planning purposes of a particular irrigation strategy. At run time irrigations are generated according to the specified time and a depth criterion. The time criterion specifies 'When' an irrigation has to be applied while the depth criterion determines 'How much' water has to be applied. The time and depth criteria with their corresponding parameters that need to be specified are listed in Tables 2.12a and 2.12b. As a reference, the canopy cover and the various thresholds for water stress for the selected crop, can be plotted.

After the selection of the criteria the values linked with the time and depth criteria and water quality have to be specified (Fig. 2.12d). The values specified at a specific day of the cropping period will be valid till the date where another value is specified or to the end of the cropping period when no values at later dates are specified. As such one can adjust the values to crop development or the time in the season. In Figure 2.12e the generated irrigation schedule as defined in Figure 2.11d is presented.

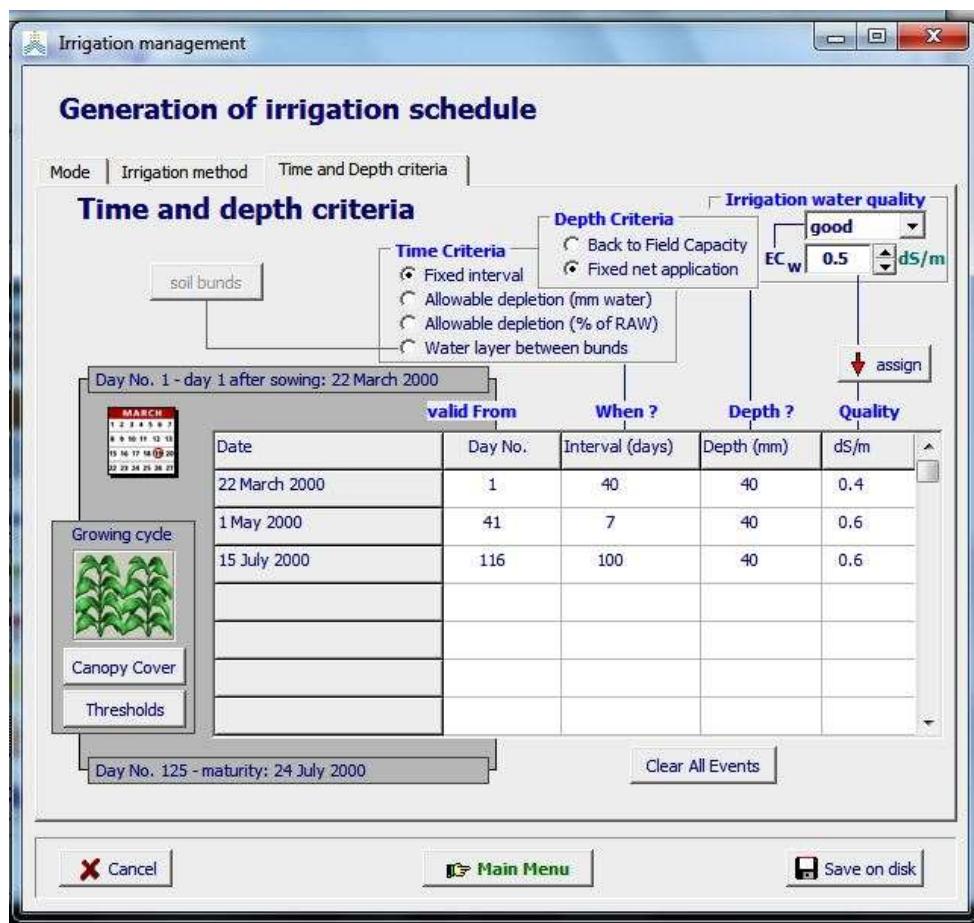


Figure 2.12d – Specifying an irrigation schedule where the fixed irrigation interval (time criterion) varies over the season, while the fixed irrigation application depth (depth criterion) remains constant, and the irrigation water quality deteriorates

| no irrigation | irrigation interval: 7 days applied irrigation amount: 40 mm | no irrigation |
|-----------------------------|---|--------------------------|
| DNr 1 22 March sowing | DNr 41 1 May | DNr 116 15 July |

Figure 2.12e – Generated irrigation schedules as defined in Figure 2.12d

Table 2.12a – Time criteria with corresponding parameter

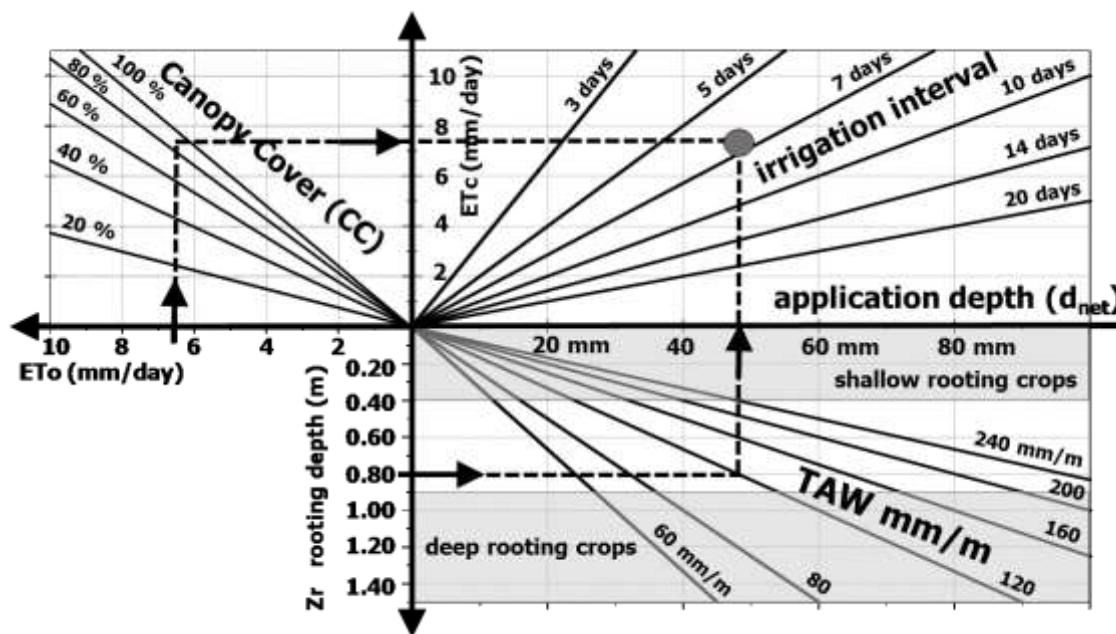
| Criterion | Parameter |
|--------------------------------------|---|
| Fixed interval (days) | Interval between irrigations (for example 10 days). Indicative values are given in Table 2.12c. |
| Allowable depletion (mm water) | Amount of water that can be depleted from the root zone (the reference is soil water content at field capacity) before an irrigation has to be applied (for example 30 mm) |
| Allowable depletion (% of RAW) | Percentage of RAW that can be depleted before irrigation water has to be applied (for example 100 %) |
| Water layer between bunds (mm water) | Threshold for the depth of the surface water layer that should be maintained between the soil bunds (for example 5 mm). An irrigation is generated when the level of the water layer reaches the threshold,. This time criterion is only applicable when ‘Fixed net application’ is the depth criterion |

Table 2.12b – Depth criteria with corresponding parameter

| Criterion | Parameter |
|---|--|
| Back to Field Capacity (+/- extra mm water) | Extra water on top of the amount of irrigation water required to bring the root zone back to Field Capacity. The specified value can be zero, positive or negative: <ul style="list-style-type: none"> ▪ zero : the applied irrigation will bring the soil water content in the root zone at Field Capacity (reached at the end of the day); ▪ positive: an over irrigation is planned for example for leaching purposes (for example + 20 mm); ▪ negative: an under irrigation is planned for example to profit from expected rainfall (for example – 10 mm) |
| Fixed application depth (mm water) | Net irrigation application depth. Indicative values are given in Table 2.12c. |

Table 2.12c – Indicative values for irrigation intervals and application depths

Indicative values for the maximum net application depth and irrigation interval in the absence of rain can be obtained from the figure below by considering the weather conditions (ET₀), crop canopy cover, rooting depth and soil physical characteristics (TAW). The net application depth and corresponding irrigation interval should be adjusted to the local characteristics of the irrigation method and irrigation practices.



Example: For a crop with an effective rooting depth (Z_r) of 0.8 m, cultivated on a sandy loam soil (TAW = 120 mm/m), the maximum net irrigation application depth (d_{net}) is about 48 mm. For a reference evapotranspiration (ET₀) of 6.5 mm/day, and a Canopy Cover (CC) of 90%, the crop evapotranspiration (ET_c) will be 7.5 mm/day. The corresponding irrigation interval will be about 6.5 days.

Assumptions: $d_{net} = (0.5) TAW Zr$ [meter]. The value of 0.5 is a representative threshold for the root zone depletion at which stomata start to close (50 % TAW);

$ET_c = (1.2) CC^* ET_0$ [mm/day]; CC* is CC adjusted for micro-advection effects. The value of 1.2 is a representative value for K_{cTr,x}, but increased to consider soil evaporation.

Characteristics of the irrigation method:

| Irrigation method | Indicative irrigation application depths |
|----------------------|---|
| Surface irrigation | Basin : 50 - 150 mm; Border: 40 - 80 mm; Furrow: 30 - 60 mm. |
| Sprinkler irrigation | Solid set: 30 – 80 mm; Center pivot, linear move and travelling gun: 15 - 35 mm (if infiltration allows: up to 80 mm) |
| Localized irrigation | 5 - 25 mm. |

| Indicative values for TAW (Total Available soil Water) for soil texture classes | | | | | |
|--|------------|-----------|-----------------|------------|-----------|
| Soil class | TAW (mm/m) | | Soil class | TAW (mm/m) | |
| | Mean | Range | | Mean | Range |
| Sand | 70 | 55 – 75 | Sandy clay loam | 120 | 90 – 135 |
| Loamy sand | 80 | 65 – 85 | Clay loam | 160 | 145 – 175 |
| Sandy loam | 120 | 110 – 130 | Silty clay loam | 210 | 195 – 215 |
| Loam | 160 | 155 – 185 | Sandy clay | 120 | 100 – 125 |
| Silt loam | 200 | 170 – 225 | Silty clay | 180 | 175 – 190 |
| Silt | 240 | 225 – 250 | Clay | 150 | 135 – 160 |

2.12.5 Irrigation method

Many types of irrigation systems wet only a fraction of the soil surface. Since only part of the soil surface is wetted, less water evaporates from the soil surface after an irrigation event. By selecting an irrigation method, an indicative value for the fraction of soil surface wetted is assigned (Tab. 2.12d). The user can alter the value if more specific information is available from field observations.

Table 2.12d – Indicative values for the percentage of soil surface wetted for various irrigation methods

| Irrigation method | Soil surface wetted (%) |
|--|-------------------------|
| Sprinkler irrigation | 100 |
| Basin irrigation | 100 |
| Border irrigation | 100 |
| Furrow irrigation (every furrow), narrow bed | 60 – 100 |
| Furrow irrigation (every furrow), wide bed | 40 – 60 |
| Furrow irrigation (alternated furrows) | 30 – 50 |
| Trickle/Drip - Micro irrigation | 15 – 40 |
| Subsurface drip irrigation | 0 |

2.12.6 Irrigation water quality

Since the quality of the irrigation water can alter during the season, it has to be specified for each irrigation event (see Fig. 2.12c and 2.12d). The quality is expressed by the electrical conductivity of the irrigation water (EC_w) in deciSiemens per meter (dS/m). When the quality of the irrigation water remains constant over the crop cycle the constant EC_w can be assigned for all irrigation events. Indicative values for EC_w for various classes of irrigation water are listed in Table 2.11e.

Table 2.12e – Indicative values for the quality classes of the irrigation water (EC_w)

| Range of EC_w Electrical Conductivity (dS/m) | Class Quality of irrigation water |
|---|--------------------------------------|
| 0.0 ... 0.2 | excellent |
| 0.3 ... 1.0 | good |
| 1.0 ... 2.0 | moderate |
| 2.1 ... 3.0 | poor |
| > 3.0 | very poor |

2.12.7 Training videos about irrigation management

A set of training modules (MP4 videos) are posted in an ‘AquaCrop Training’ channel of YouTube. The modules about irrigation management are listed in Table 2.12f. For the playlist go to FAO AquaCrop website <http://www.fao.org/nr/water/aquacrop.html>

Table 2.12f – Set of training modules about irrigation management

| Video | Learning objective | Length [min:sec] |
|--|--|---------------------|
| 05.1 Irrigation management | Know the required irrigation management parameters | - |
| - Part 1. Determination of net irrigation requirement | | 08:56 |
| - Part 2. Evaluation of an irrigation schedule | | 12:11 |
| - Part 3. Generation of an irrigation schedule, Deficit irrigation | | 19:54 |

2.13 Field management

The selected field management can be displayed in the **Display of field management** menu and updated in the **Field management** menu (Fig. 2.13a). Options of soil fertility levels and practices that affect the soil water balance and crop production are specified in this menu.

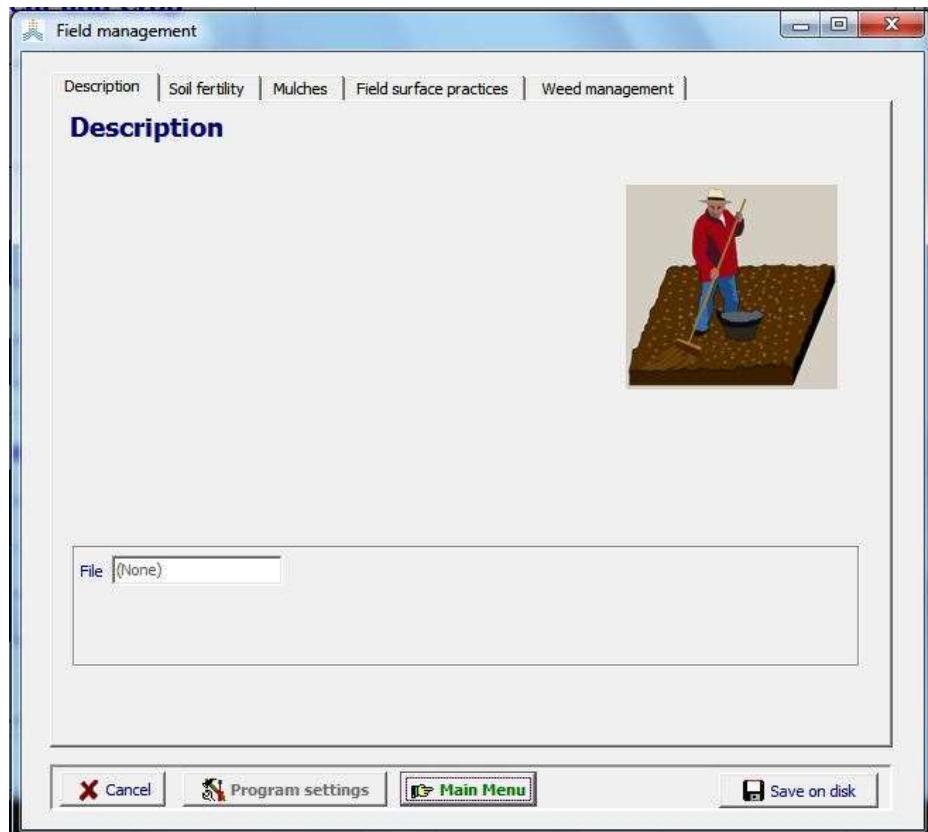


Figure 2.13a – *Field management* menu

2.13.1 Soil fertility

For limited soil fertility, the biomass production declines as result of the effect of soil fertility on (i) canopy development (CC) and hence on crop transpiration and on (ii) biomass water productivity (WP*). The maximum relative biomass production that can be expected as a result of soil fertility stress is specified by (Fig. 2.13b):

- selecting one of the classes ranging from non-limiting to very poor (Tab. 2.13a), or
- specifying directly the relative biomass production in the **Field management** menu.

The relative biomass production ($B_{rel} = B_{stress}/B_{ref}$) refers to the maximum dry aboveground biomass (B_{stress}) that can be expected at the end of the growing season in a field with soil fertility stress with reference to stress-free conditions (B_{ref}). Both B_{stress} and B_{ref} are to be observed in well watered fields (no soil water stress) and free of any other stress factors like weeds, pests, diseases and salinity. B_{stress} can be easily obtained from farmers,

experimental fields or agricultural statistics on local crop production (it is B in a good rainy year with small or none existing water stress during the growing cycle). B_{ref} can be obtained from nearby experimental fields, published potential yield levels, or by applying a full nutrient strip in one part of the farmer's field. Also model simulations can provide an estimation of the biomass levels for the local farming conditions under stress-free conditions.

When running simulations, the crop response on soil fertility will be different if additionally stresses (water, salinity) occur during the season.

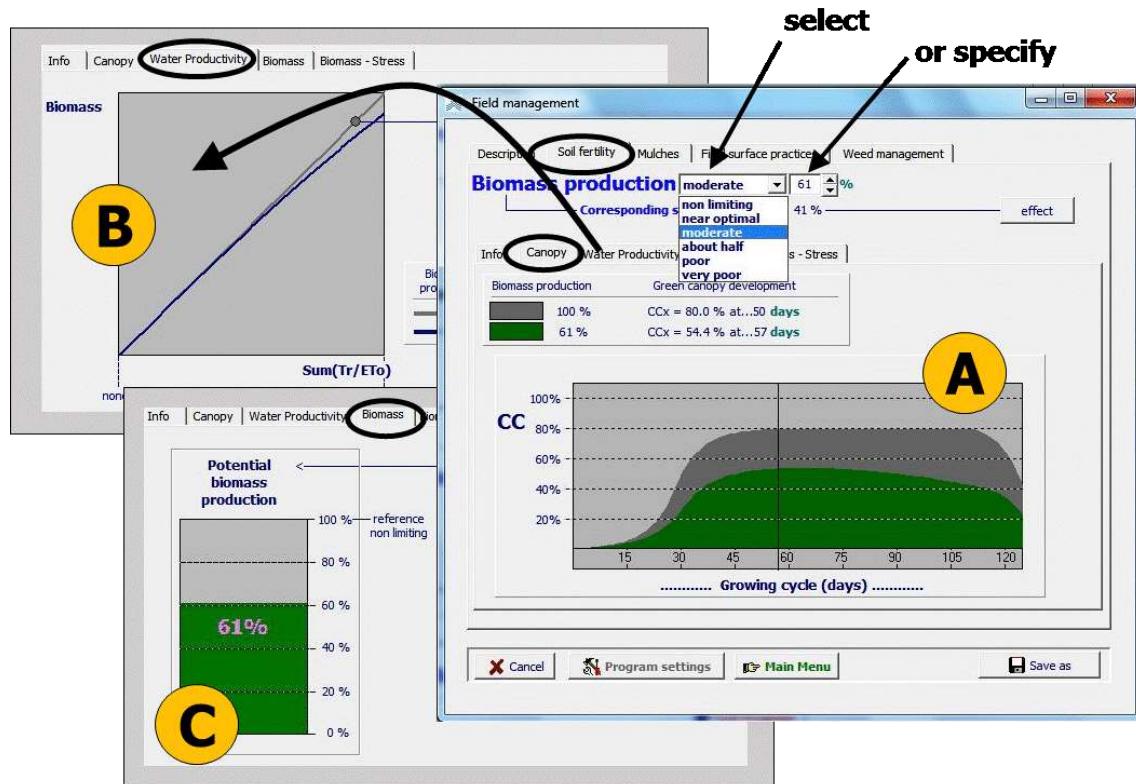


Figure 2.13b – The ‘Soil fertility’ tabular sheet of the *Field management* menu in which the maximum relative dry aboveground biomass that can be expected in the soil fertility stressed field is specified, and the corresponding effect on (A) canopy cover, (B) water productivity, and (C) potential biomass production is displayed in different tabular sheets.

AquaCrop displays for the selected maximum biomass production (i) the canopy development, (ii) the water productivity corresponding to the amount of biomass produced, (iii) the expected maximum biomass production, (iv) the calibrated biomass – stress relationship, and (v) the adjusted values for particular cop parameters (Fig. 2.13b).

Table 2.13a – Classes, corresponding default values, and ranges for soil fertility.

| Class | Default value | Range |
|--------------|---------------|------------|
| Non limiting | 100 % | 99 – 100 % |
| Near optimal | 80 % | 76 – 98 % |
| Moderate | 60 % | 56 – 75 % |
| About half | 50 % | 45 – 55 % |
| Poor | 40 % | 35 – 44 % |
| Very poor | 25 % | 34 – 20 % |

The biomass – stress relationship (Fig. 2.13c), calibrated in the *Crop characteristic* menu, determines the corresponding soil fertility stress and as such the values for the stress coefficients ($K_{S\text{exp},f}$, K_{SWP} , K_{SCCx} , $f_{C\text{Decline}}$).

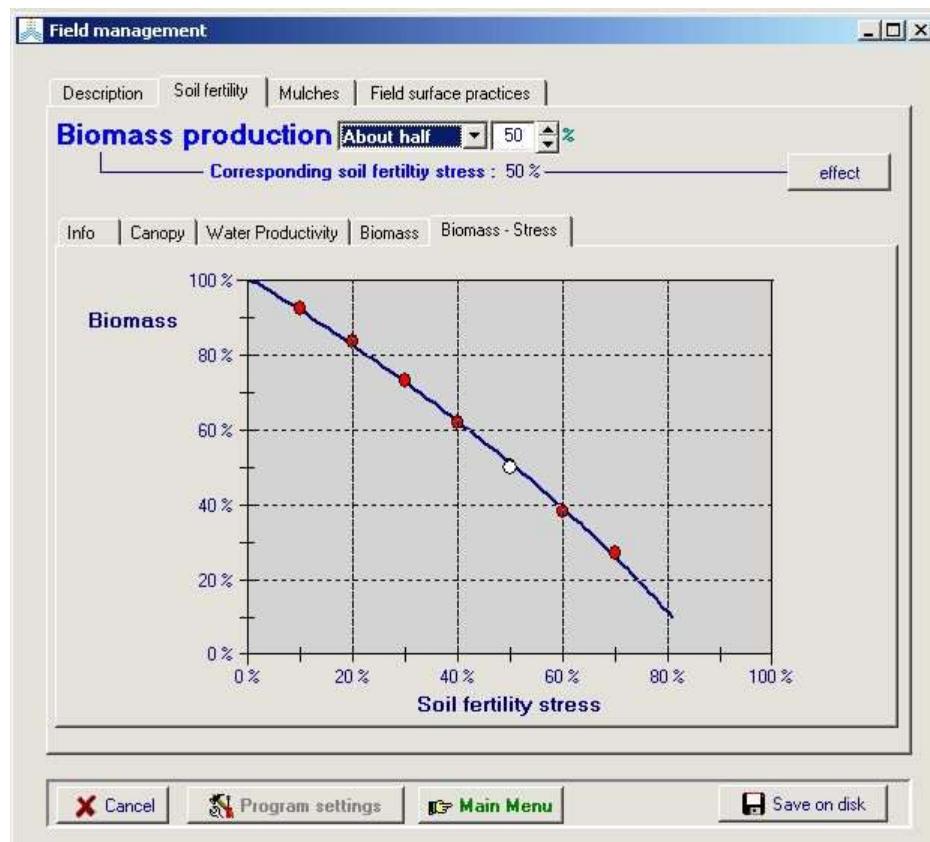


Figure 2.13c - Display of the calibrated Biomass - stress relationship in the *Field management* menu

2.13.2 Mulches

Mulches covering the soil surface will affect soil evaporation. Depending on the type of mulches and the fraction of the soil surface covered, the reduction in soil evaporation might be more or less substantially. The user specifies:

- the degree of soil cover;
 - the type of surface mulches.
- o Synthetic plastic mulches, which reduce completely the evaporation of water from the soil surface (100 %)
 - o Organic mulches, which consists of unincorporated plant residues or foreign material imported to the field such as a straw, and reduce the soil evaporation by 50%,
 - o User specified mulches, for which the reduction in soil evaporation losses needs to be specified by the user.

The corresponding total reduction in soil evaporation and the relative soil evaporation (or soil water evaporation coefficient and crop transpiration coefficient), are displayed (Fig. 2.13d).

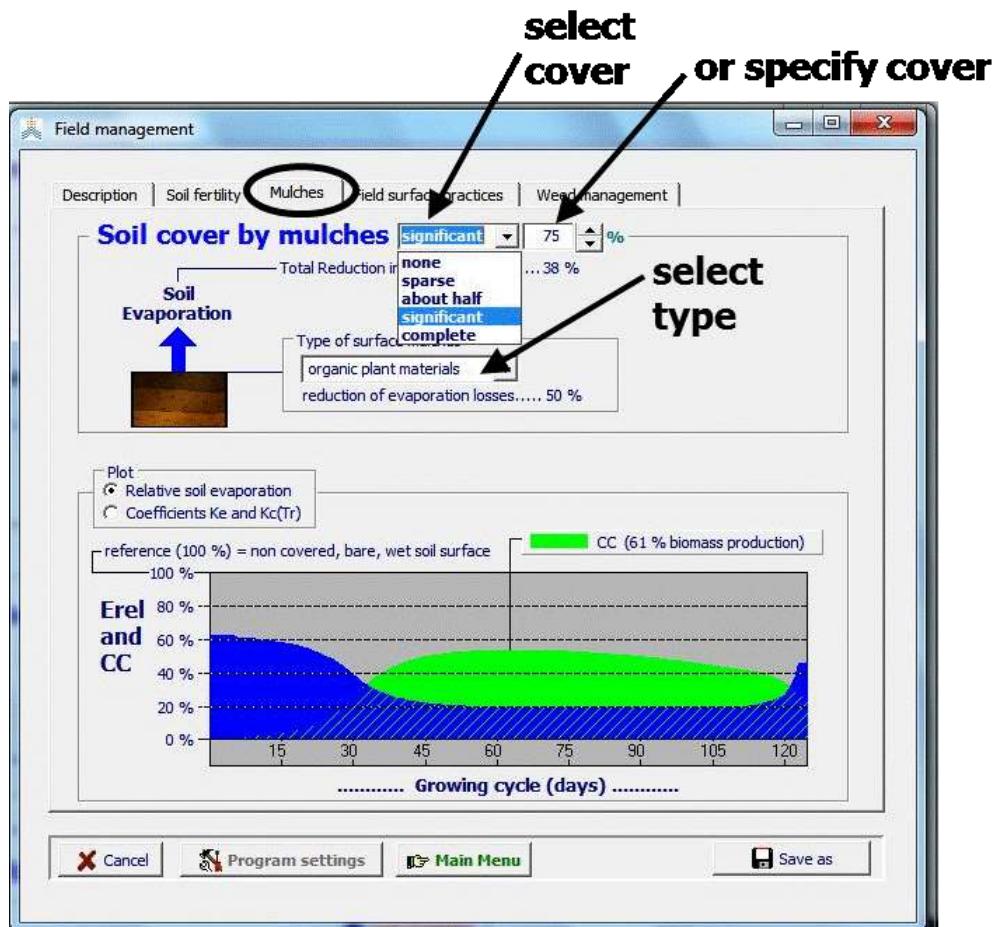


Figure 2.13d – Display of the effect of mulches on soil evaporation

2.13.3 Field surface practices

The part of rainfall lost by surface runoff, is estimated by means of the curve number method (See chapter 3). The Curve number (CN) is based on soil profile characteristics (CN_{soil}), see 2.14 Soil profile characteristics. If field surface practices affect surface runoff, CN_{soil} needs to be adjusted. When characterizing field management, the user can specify if field surface practices:

1. **do NOT affect surface runoff.** Surface runoff is based exclusively on the soil profile characteristic (CN_{soil});
2. **affect surface runoff.** CN_{soil} , which is based on soil profile characteristics, can be adjusted by considering the crop type (if different from ‘small grain’), treatment, and hydrologic conditions (Fig. 2.13e). By selecting the <guide to adjustments> command, indicative values for the percent increase/decrease are displayed in the ***CN adjustment*** menu.(Fig 2.13f);
3. **prevent surface runoff.** Practices, such as tied-ridges and closed-end furrows, will prevent surface runoff;
4. **Soil bunds.** Soil bunds (as is the case in rice paddy fields) not only prevent surface runoff, but store excess water that could not infiltrate during the day. The water remains stored on top of the field between the bunds until all stored water has infiltrated or is lost by soil evaporation. The height of the soil bunds has to be specified in meter.

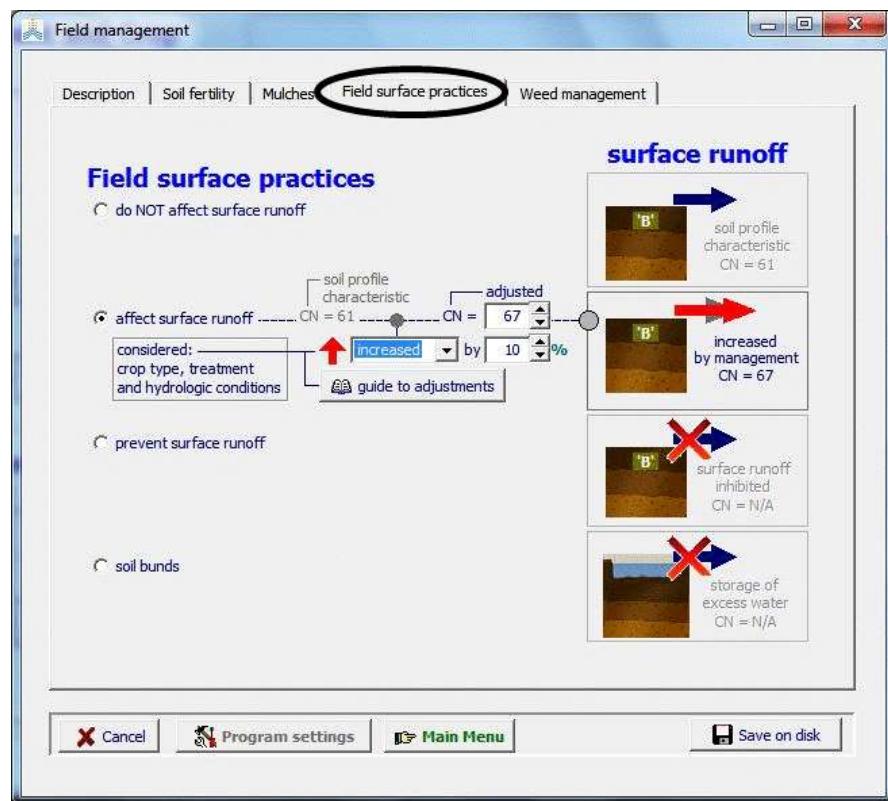


Figure 2.13e – The ‘Field surface practices’ tabular sheet of the *Field management* menu in which the effect of field surface practice on surface runoff is specified.

By selecting the <guide to adjustments> command, indicative values for the percent increase/decrease are displayed in the **CN adjustment** menu (Fig. 2.13f). Values for all hydrologic soil groups are displayed (for reference), but adjustments can only be selected for the group to which the soil profile belongs. Adjustments are available for various treatments, hydrologic conditions (i.e. conditions that affect infiltration and runoff) and for five crop types: (i) row crops, (ii) small grain, (iii) close-seeded or broadcast legumes, (iv) pasture, grassland for grazing, and (v) grassland moved for hay (protected from grazing). The adjustments are based on the CN values provided by the USDA for various hydrologic soil-cover complexes (Tab. 2.13b), and were converted in the percentage increase/decrease by considering the default CN for each of the hydrologic soil group (see 2.14 Soil profile characteristics).

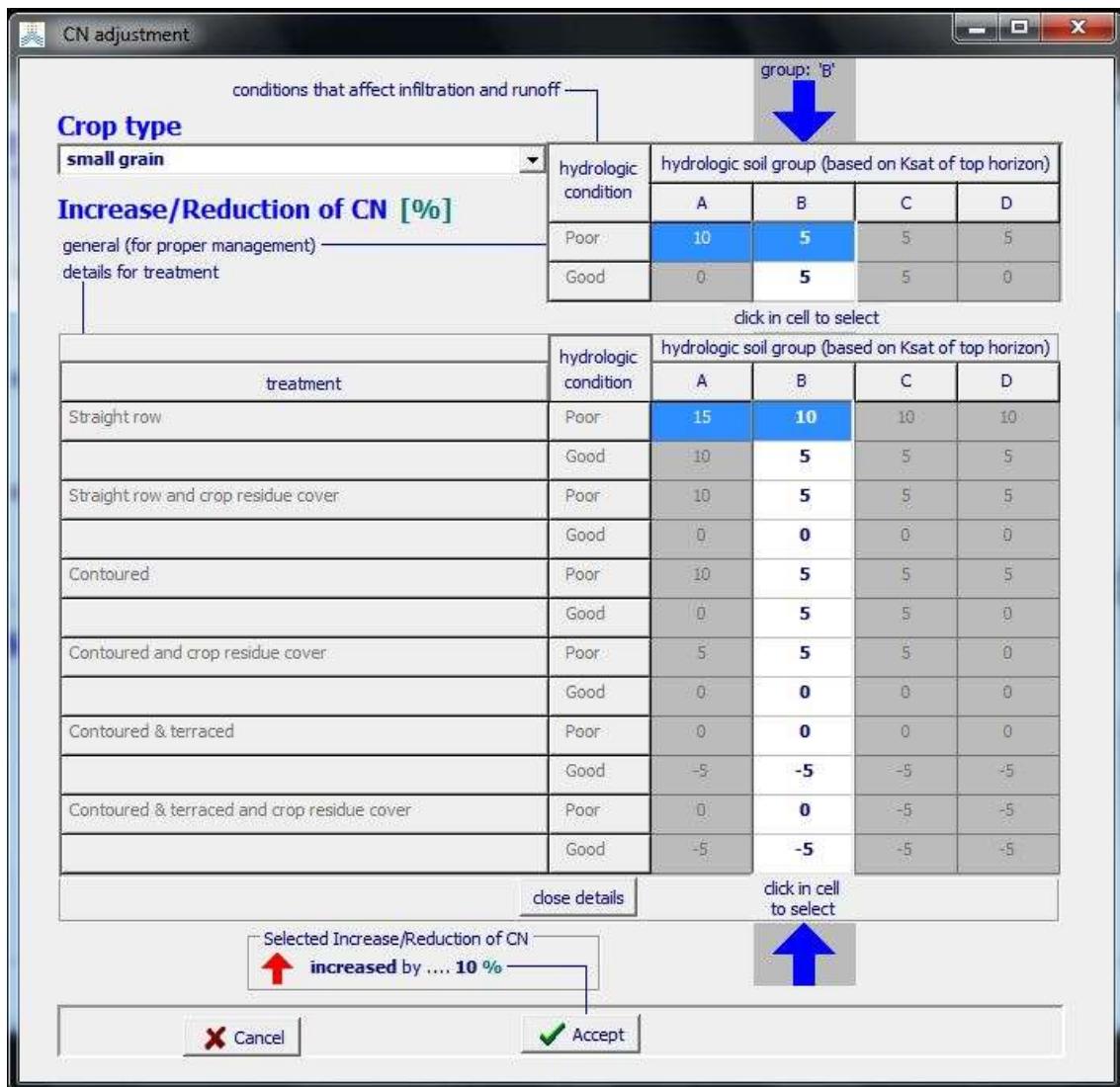


Figure 2.13f – Selection of the percent increase/decrease of the CN based on soil profile characteristics, by considering the crop type, treatment and hydrologic condition in the CN adjustment menu.

Table 2.13b – Runoff Curve Numbers (assuming an initial abstraction of 5 % of S), for agriculture lands (source National Engineering Handbook of the USDA, USDA 2004).

A. Row crops

| Cover/treatment | Hydrologic Condition | Increase/Decrease of CN in percentage Hydrologic soil group | | | |
|---|----------------------|---|----|----|----|
| | | A | B | C | D |
| Straight row | Poor | 61 | 74 | 84 | 88 |
| | Good | 55 | 70 | 80 | 85 |
| Straight row and crop residue cover | Poor | 60 | 72 | 83 | 87 |
| | Good | 51 | 65 | 75 | 80 |
| Contoured | Poor | 59 | 71 | 78 | 84 |
| | Good | 52 | 65 | 75 | 81 |
| Contoured and crop residue cover | Poor | 57 | 70 | 77 | 83 |
| | Good | 51 | 64 | 74 | 80 |
| Contoured & terraced | Poor | 53 | 64 | 72 | 75 |
| | Good | 48 | 60 | 70 | 74 |
| Contoured & terraced and crop residue cover | Poor | 52 | 63 | 71 | 74 |
| | Good | 47 | 59 | 68 | 72 |

B. Small grain

| Cover/treatment | Hydrologic Condition | Increase/Decrease of CN in percentage Hydrologic soil group | | | |
|---|----------------------|---|----|----|----|
| | | A | B | C | D |
| Straight row | Poor | 52 | 67 | 78 | 84 |
| | Good | 50 | 65 | 77 | 83 |
| Straight row and crop residue cover | Poor | 51 | 65 | 77 | 81 |
| | Good | 46 | 61 | 72 | 78 |
| Contoured | Poor | 50 | 64 | 75 | 80 |
| | Good | 47 | 63 | 74 | 78 |
| Contoured and crop residue cover | Poor | 48 | 63 | 74 | 78 |
| | Good | 46 | 61 | 72 | 77 |
| Contoured & terraced | Poor | 47 | 61 | 71 | 75 |
| | Good | 45 | 59 | 70 | 74 |
| Contoured & terraced and crop residue cover | Poor | 46 | 60 | 70 | 74 |
| | Good | 44 | 57 | 68 | 72 |

C. Close-seeded or broadcast legumes

| Cover/treatment | Hydrologic Condition | Increase/Decrease of CN in percentage Hydrologic soil group | | | |
|---|----------------------|---|----|----|----|
| | | A | B | C | D |
| Straight row | Poor | 53 | 68 | 80 | 85 |
| | Good | 44 | 61 | 74 | 80 |
| Straight row and crop residue cover | Poor | - | - | - | - |
| | Good | - | - | - | - |
| Contoured | Poor | 51 | 65 | 77 | 80 |
| | Good | 40 | 57 | 70 | 77 |
| Contoured and crop residue cover | Poor | - | - | - | - |
| | Good | - | - | - | - |
| Contoured & terraced | Poor | 50 | 63 | 72 | 77 |
| | Good | 36 | 55 | 67 | 72 |
| Contoured & terraced and crop residue cover | Poor | - | - | - | - |
| | Good | - | - | - | - |

D. Pasture, grassland, or range-continuous forage for grazing

| Cover/treatment | Hydrologic Condition | Increase/Decrease of CN in percentage Hydrologic soil group | | | |
|-----------------|----------------------|---|----|----|----|
| | | A | B | C | D |
| Poor | Poor | 56 | 71 | 81 | 85 |
| | Fair | 34 | 57 | 71 | 78 |
| | Good | 24 | 47 | 64 | 72 |

E. Meadow-continuous grass, protected from grazing and generally mowed for hay

| Cover/treatment | Hydrologic Condition | Increase/Decrease of CN in percentage Hydrologic soil group | | | |
|-----------------|----------------------|---|----|----|----|
| | | A | B | C | D |
| | Good | 17 | 44 | 60 | 70 |

2.13.4 Weed infestation

▪ Relative cover of weeds (RC)

In AquaCrop weed infestation is expressed by the relative cover of weeds (RC), which is the ratio between the ground area covered by leaves of weeds and the total canopy cover of weeds and crop:

$$RC = \frac{WC}{WC + CC_w} = \frac{WC}{CC_{TOT}} \quad (\text{Eq. 2.13})$$

where WC (m^2/m^2) is the area covered by weeds per unit ground area, CC_w (m^2/m^2) the area covered by the crop canopy per unit ground area in the weed infested field, and CC_{TOT} (m^2/m^2) the total green canopy cover of crop and weeds per unit ground area. RC is easily determined by estimating the fraction of the total canopy cover that is weed. It can be assessed by a visual estimate in the field or by analyzing photographs taken vertically from above the crop.

Sattin and Berti (2003) discuss that the higher the relative cover of weeds (RC), the greater the share of solar radiation intercepted by the weeds, and therefore the more intense the competition caused by the weeds. The simulation of crop development and production in weed infested fields based on RC assumes that:

- interference for light is a measure of interference by all mechanisms: the leaf canopy may serve as an ‘integrator’ of the combined effects of competition for light, water and nutrients, and possibly also allelopathic effects, since these all reduce height, shoot weight and therefore leaf area and radiation interception of the crop;
- the competitive effect of weeds that are shorter than the crop at canopy closure is negligible; in other words, only the plants that are able to overgrow or, at least, reach a height similar to the crop can successfully compete.

The major strength of using RC for modelling crop response to weed infestation is that RC covers not only the density aspect of weed-crop competition, but also the duration, distribution and species of weeds:

- RC considers the relative development of the crop and weeds, and thus also their relative time of emergence (Kropff and Spitters, 1991). As such, a few early-emerging weeds can have the same RC as many late-emerging weeds;
- RC also accounts for the distribution of the weeds (e.g. regular pattern, in the interrow), because the spatial arrangement will directly influence RC (Berti and Sattin, 1996);
- RC is a multi-species parameter, so that it can be used to predict crop production under mixed weed infestations, easily covering the species aspect of competition.

Another advantage of RC lies in its directness of determination, since it requires only an estimate of the fraction of weed cover. This can be easily obtained by observing the total canopy vertically from above.

Because of the advantages of RC and the use of canopy cover in AquaCrop as the integrator of the combined effects of competition for light, water and nutrients, RC proved to be well

applicable for the simulation of the effect of weed infestation on crop development and production (Van Gaelen et al., 2016).

References:

- Berti, A. and Sattin, M. 1996. Effect of weed position on yield loss in soybean and a comparison between relative weed cover and other regression models. *Weed Res.* 36: 249-258.
- Kropff, M.J. and Spitters, C.J.T. 1991. A simple model of crop loss by weed competition from early observations on relative leaf area of the weeds. *Weed Research* 31: 97-105.
- Sattin, M. and Berti, A. 2003. Parameters for weed-free competition [on line]. FAO Plant production and Protection Papers No. 120. Addendum 1: Weed management for developing countries. <http://www.fao.org/docrep/006/y5031e/y5031e04.htm>
- Van Gaelen, H., Delbecque, N., Abrha, B., Tsegay, A., Raes, D. 2016. Simulation of crop water productivity in weed-infested fields for data-scarce regions. *Journal of Agricultural Science*, 154 (6):1026–1039

▪ Specification of weed management in the *Field management* menu

To simulate the effect of weeds on crop development and production, the user specifies in the ***Field management*** menu (Fig. 2.13g):

1. the Relative Cover (RC) of weeds in season, which expresses the weed infestation level as observed in the field. By selecting a class for weed management, default values for RC are assigned (Tab. 2.13c);
2. the expansion of CC due to weed infestation, which expresses how the total canopy cover responds to weed infestation under non limiting soil fertility. Since weeds can occupy space that is not used by the crop in weed-free conditions, the total CC might be larger than the crop canopy cover in weed-free conditions.

Weeds can not only occupy space that is not used by the crop, but can also suppress the canopy development of the crop. For that reason, the canopy cover of the crop in weed infested fields (dark green area in Fig. 2.13g), will be smaller than the crop canopy cover in weed-free conditions (black reference line in Fig. 2.13g).

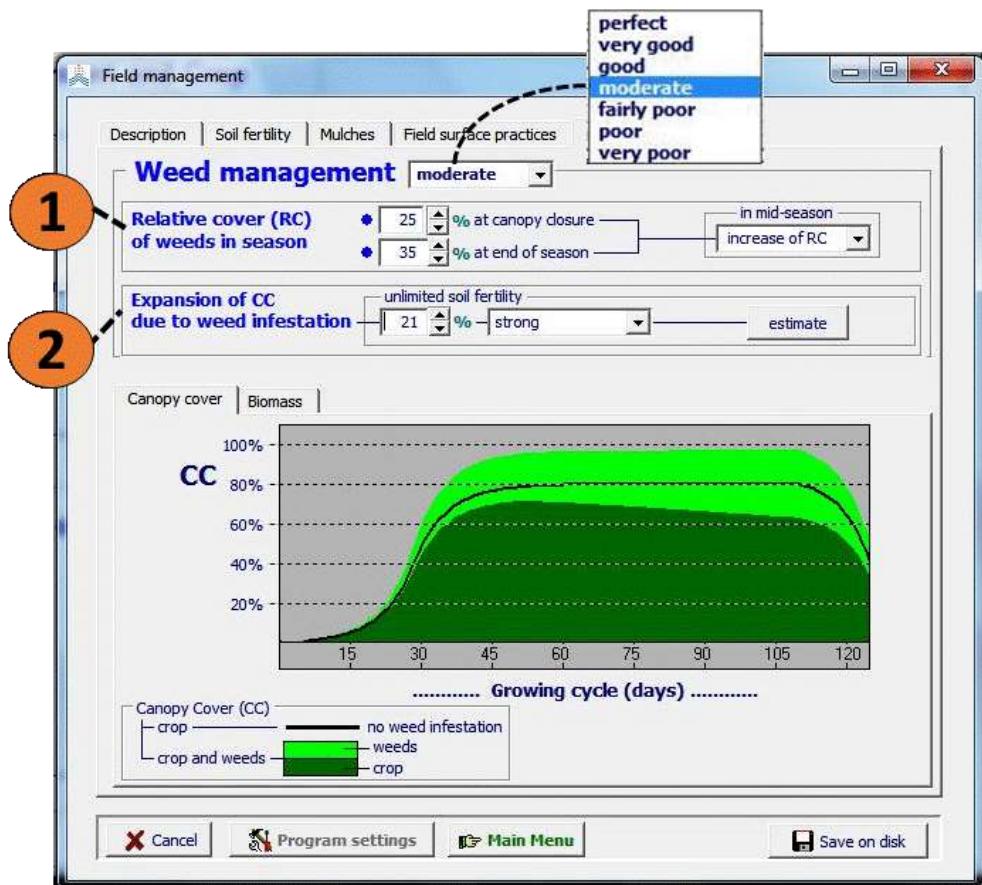


Figure 2.13g – Specification of (1) the Relative cover of weeds (RC) and (2) the expansion of canopy cover (CC) in the ‘Weed management’ tabular sheet of the *Field management* menu. In the graph the corresponding total canopy cover of crop (dark green) and weeds (light green) in the weed infested field is displayed. The canopy cover for weed-free conditions (black line) is given as a reference

Table 2.13c – Classes for weed management, and the corresponding default values and ranges for the relative weed cover (RC) at canopy closure.

| Class weed management | Relative weed cover (RC) at canopy closure | |
|-----------------------|--|--------------|
| | Default value | Range |
| Perfect | 0 % | - |
| Very good | 5 % | 1 – 9 % |
| Good | 15 % | 10 – 19 % |
| Moderate | 25 % | 20 – 29 % |
| Fairly poor | 35 % | 30 – 39 % |
| Poor | 45 % | 40 – 49 % |
| Very poor | 75 % | $\geq 50 \%$ |

- **Relative cover (RC) of weeds in season**

Distinction is made between (Fig. 2.13g):

- the Relative Cover of weeds (RC) at canopy closure. It is regarded as a crucial measurement of the competitive process of the weeds since it is far too late for any control treatment, and proved to be a good yield loss predictor. To avoid over parametrisation, the RC from crop emergence to canopy closure is assumed to be constant. This is acceptable since a variable RC during the crop development stage, when CC is relatively small, only has a small effect on the simulated crop production in weed infested fields;
- the Relative Cover of weeds (RC) at the end of the season (at the start of senescence). Due to the competitive ability of the crop and weeds to suppress each other (one overgrowing the other), the RC might not remain constant, but can significantly increase or decrease during the mid-season stage. The variation of RC in the mid-season, when CC is relatively large, needs to be considered since its impact on the simulated crop production in weed-infested fields, might be important.

- **Expansion of CC due to weed infestation**

Due to weed infestation and in the presence of unlimited soil fertility, the total canopy cover of crop and weeds (CC_{TOT}) can be larger than the crop canopy cover in weed-free conditions. The expansion of CC is quantified (Fig. 2.13h):

1. by specifying the expansion directly as a percentage increase of the crop canopy cover in weed-free conditions;
2. by specifying the total CC of crop and weeds in the mid-season stage;
3. by selecting a class for the canopy expansion (Table 2.13d).

By quantifying the expansion of CC and by considering the selected RC at canopy closure, a corresponding shape factor (f_{shape}) for the CC_{TOT} - RC relationship is assigned. By selecting f_{shape} directly (option 4 in Fig. 2.13h), the corresponding different ways of expressing the expansion of CC is calculated.

The shape factor (f_{shape}) for the CC_{TOT} - RC relationship (Fig. 2.13i), depends on the type of weed and hence might differ for various weed-crop combination:

- a negative f_{shape} value gives a concave relation between CC_{TOT} and RC, indicating that the crop is more competitive than the weed for light and that weeds will first occupy space that under weed-free conditions is not colonized by the crop;
- a positive value gives a convex relation, indicating that the weeds are more competitive than the crop for obtaining light, and will occupy first space that under weed-free conditions would be used by the crop. This results in a stronger suppression of the crop canopy cover than when f_{shape} is negative;
- a value for f_{shape} close to zero, gives an almost linear relationship between CC_{TOT} and RC.

It is expected that when the crop is sown at an optimal density, f_{shape} will mostly be positive, while crops sown with a suboptimal density will mostly lead to a situation where f_{shape} is negative.

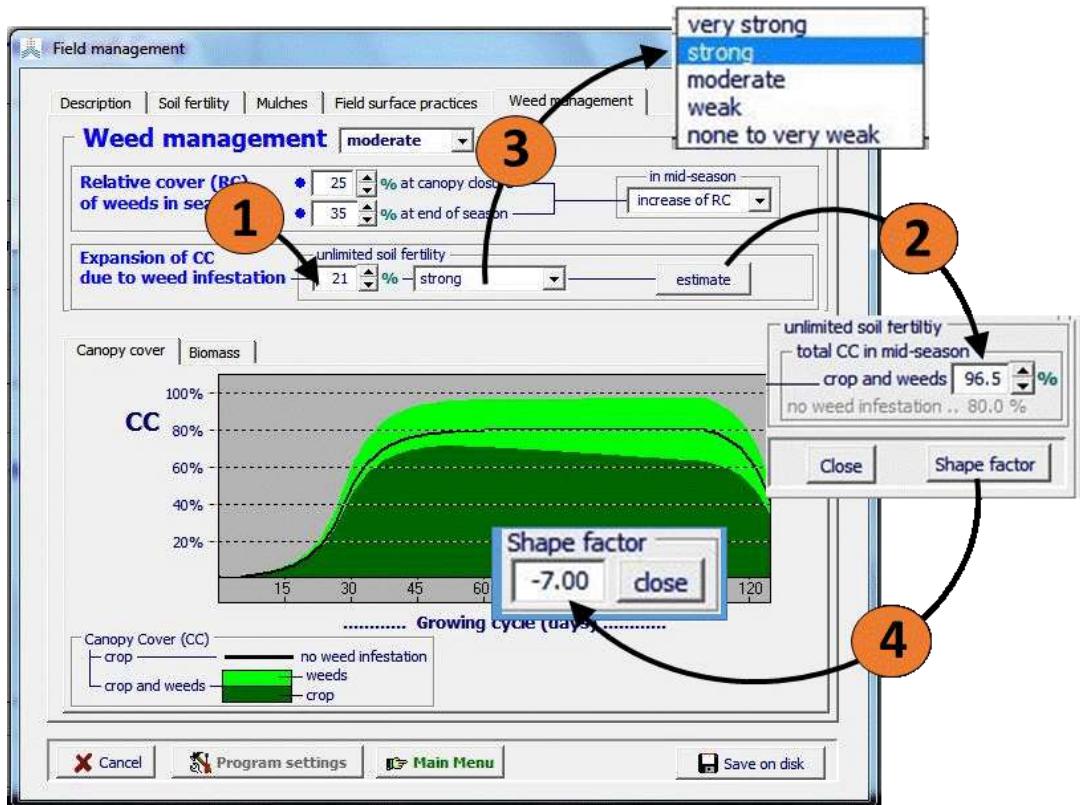


Figure 2.13h – Various ways of specifying the expansion of CC due to weed infestation, (1) by specifying a percent increase, (2) by specifying the total CC at mid-season in a weed infested field, (3) by selecting a class for the expansion of CC, or (4) by specifying a value for the shape factor

Table 2.13d – Classes for the expansion of CC due to weed infestation and the corresponding default values and ranges for the shape factor (f_{shape}).

| Class of expansion of CC due to weed infestation | f_{shape} | |
|--|-------------|-----------------|
| | Default | Range |
| Very strong | - 10 | ≤ -7.50 |
| Strong | - 4 | -7.49 ... -1.00 |
| Moderate | - 0.01 | -0.99 ... +0.99 |
| Weak | + 2 | 1.00 ... 2.99 |
| None to very weak | + 100 | ≥ 3.00 |

In case soil fertility limits the biomass production, the selection of the relative biomass production in the soil fertility tabular sheet determines the crop canopy cover that can be reached in weed-free conditions (Fig. 2.13j A). Since the expansion of CC is blocked by soil fertility, the total canopy cover of crop and weeds that can be obtained in the weed infested field is identical to the crop canopy cover that can be reached in weed-free conditions (Fig. 2.13j B).

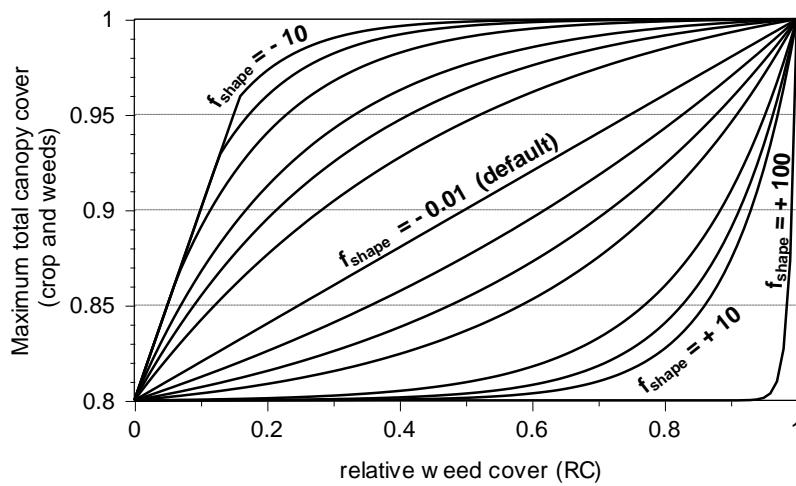


Figure 2.13i – Maximum total canopy cover of weeds and crop at mid-season ($CC_{x,TOT}$) for different relative weed covers (RC) and different shape factors (f_{shape}) for a field that in weed-free conditions would have a CC_x of 0.8

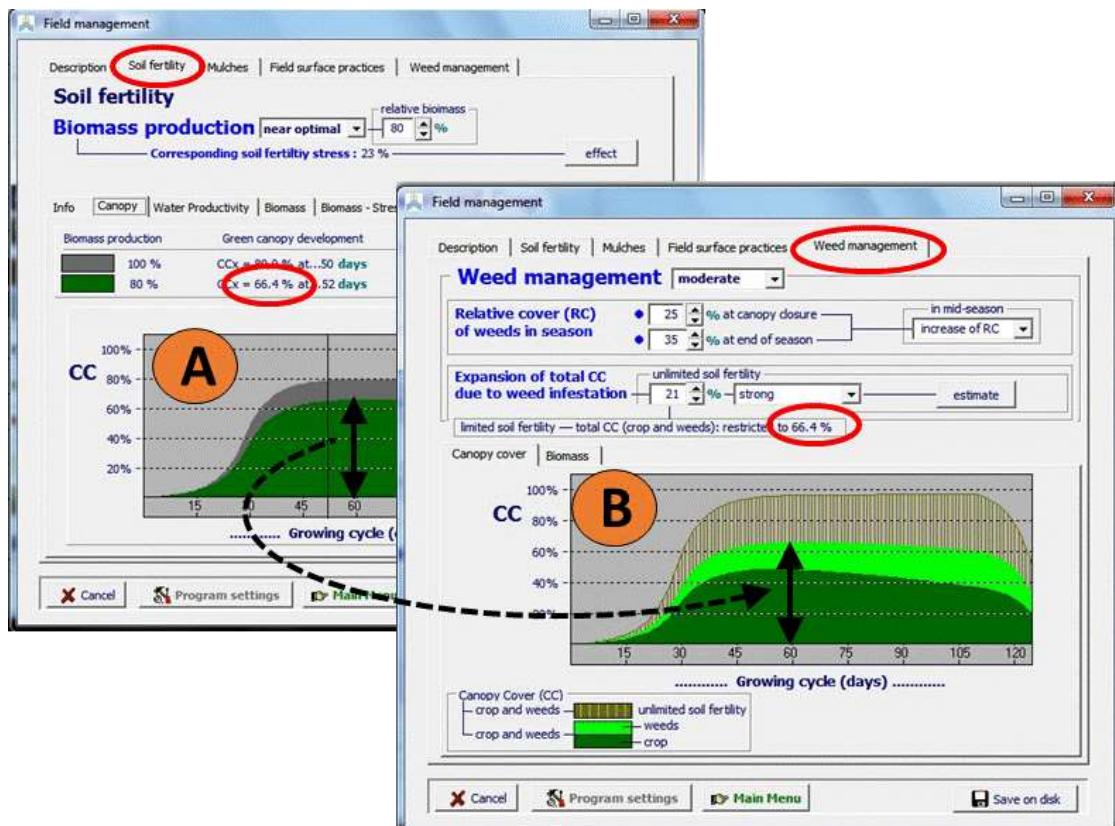


Figure 2.13j – (A) The crop canopy cover that can be reached with limited soil fertility in weed-free conditions and (B) the total canopy cover of crop and weeds that can be reached in a weed infested field with limited soil fertility, as displayed in the *Field management* menu

- Reduction in biomass production

In the ‘biomass’ tabular sheet of the weed-management sheet in the ***Field management*** menu, an estimate of the maximum crop biomass production that can be obtained in the weed infested field is displayed (Fig. 2.13k).

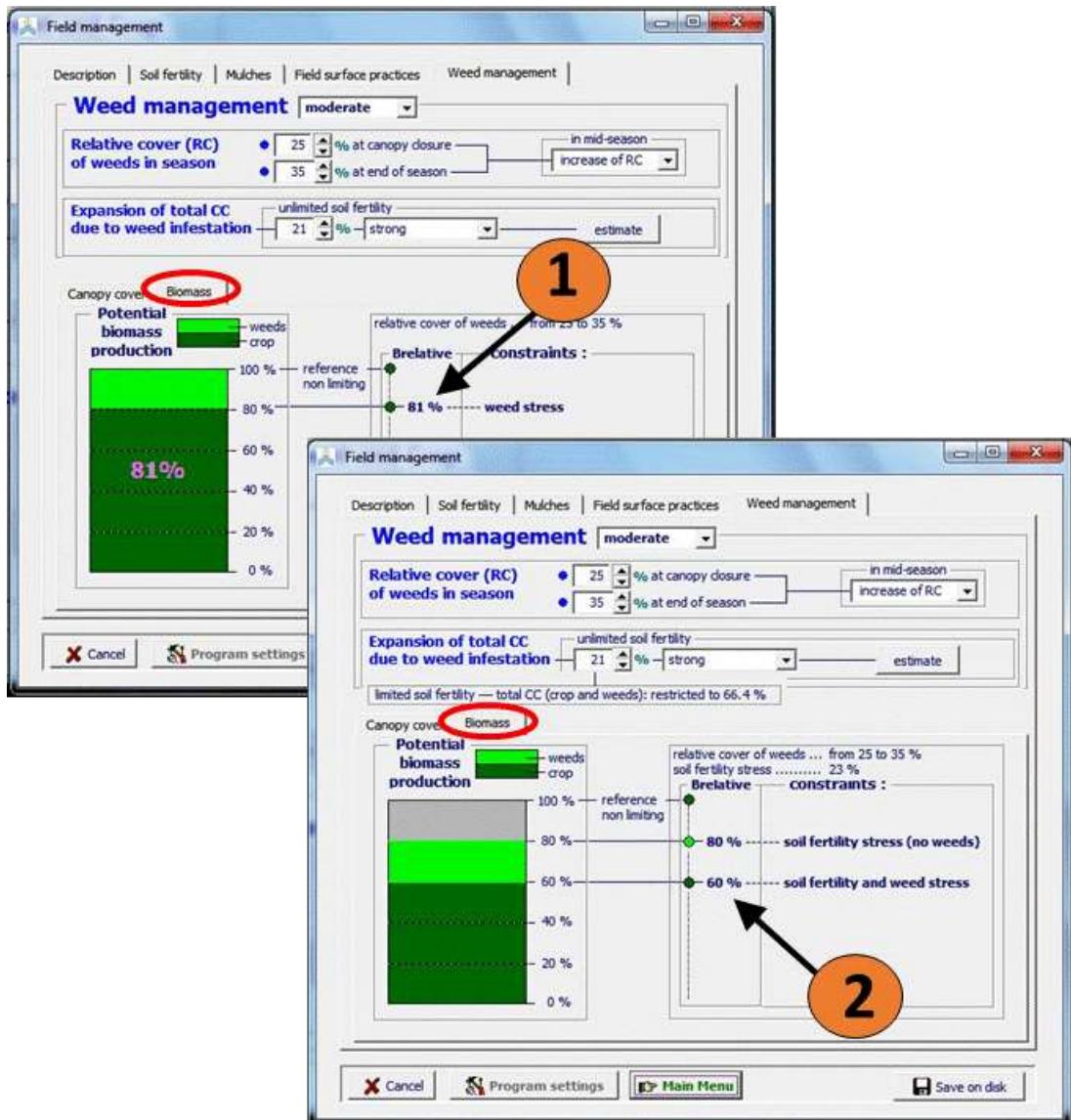


Figure 2.13k – The estimated relative maximum crop biomass production that can be obtained in a weed infested field, (1) without and (2) with soil fertility stress as displayed in the ***Field management*** menu

2.13.5 Program settings

From the **Field management** menu the user has access to the program setting of field parameters listed in Table 2.13e.

Table 2.13e – Program settings affecting soil evaporation

| Symbol | Program parameter | Default |
|--------|--|---------|
| | ▪ Soil depth from which evaporation can extract water out of the top of the soil profile | 30 cm |

2.13.6 Training videos about field management

A set of training modules (MP4 videos) are posted in an ‘AquaCrop Training’ channel of YouTube. The modules about field management are listed in Table 2.13f. For the playlist go to FAO AquaCrop website <http://www.fao.org/nr/water/aquacrop.html>

Table 2.13f – Set of training modules about field management

| Video | Learning objective | Length [min:sec] |
|--|--|------------------|
| 05.2 Field management | Know the required field management parameters | - |
| – Part 1. Estimate of surface runoff, Practices affecting surface runoff | | 18:59 |
| – Part 2. Mulches | | 05:19 |
| – Part 3. Soil fertility | | 12:05 |
| 05.3 Calibration for soil fertility | Understand the procedure to calibrate the crop response to soil fertility stress | 17:42 |

2.14 Soil profile characteristics

The soil profile characteristics refer to physical parameters required to simulate the retention and movement of water and salt in the soil profile and at its upper (soil surface), and lower (a shallow groundwater table) boundary. The selected characteristics of the various soil horizons and of the soil surface layer, and the maximum possible capillary rise are displayed in the various tabular sheets of the *Display of soil profile characteristics* menu and updated in the *Soil profile characteristics* menu (Fig. 2.14a).

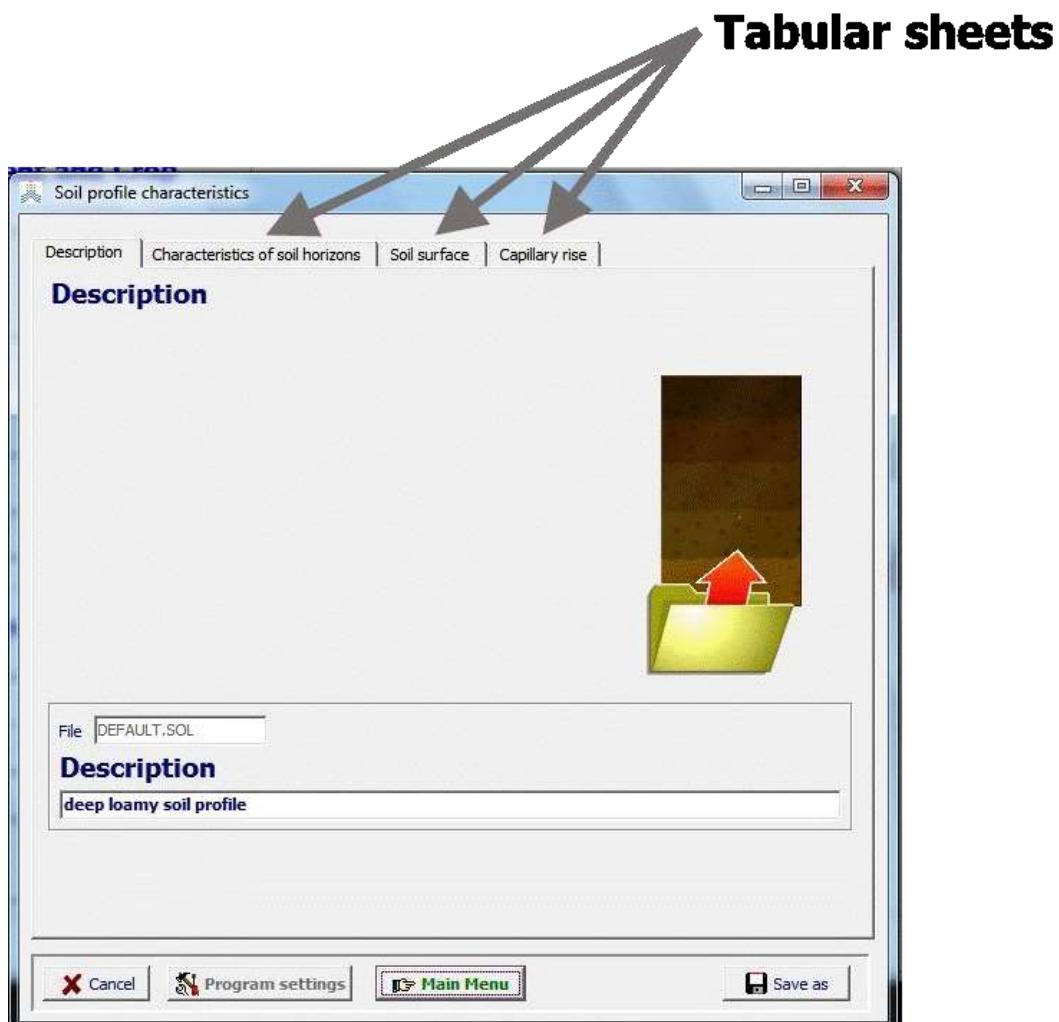


Figure 2.14a – The *Soil profile characteristics* menu with its tabular sheets: ‘Description’ (displayed), ‘Characteristics of soil horizons’, ‘Soil surface’, and ‘Capillary rise’

2.14.1 Soil horizons and their physical characteristics

The soil profile characteristics consist of soil physical parameters required to simulate the retention of water in the root zone and soil water movement. The soil profile can be composed of up to five different horizons, each with their own physical characteristics.

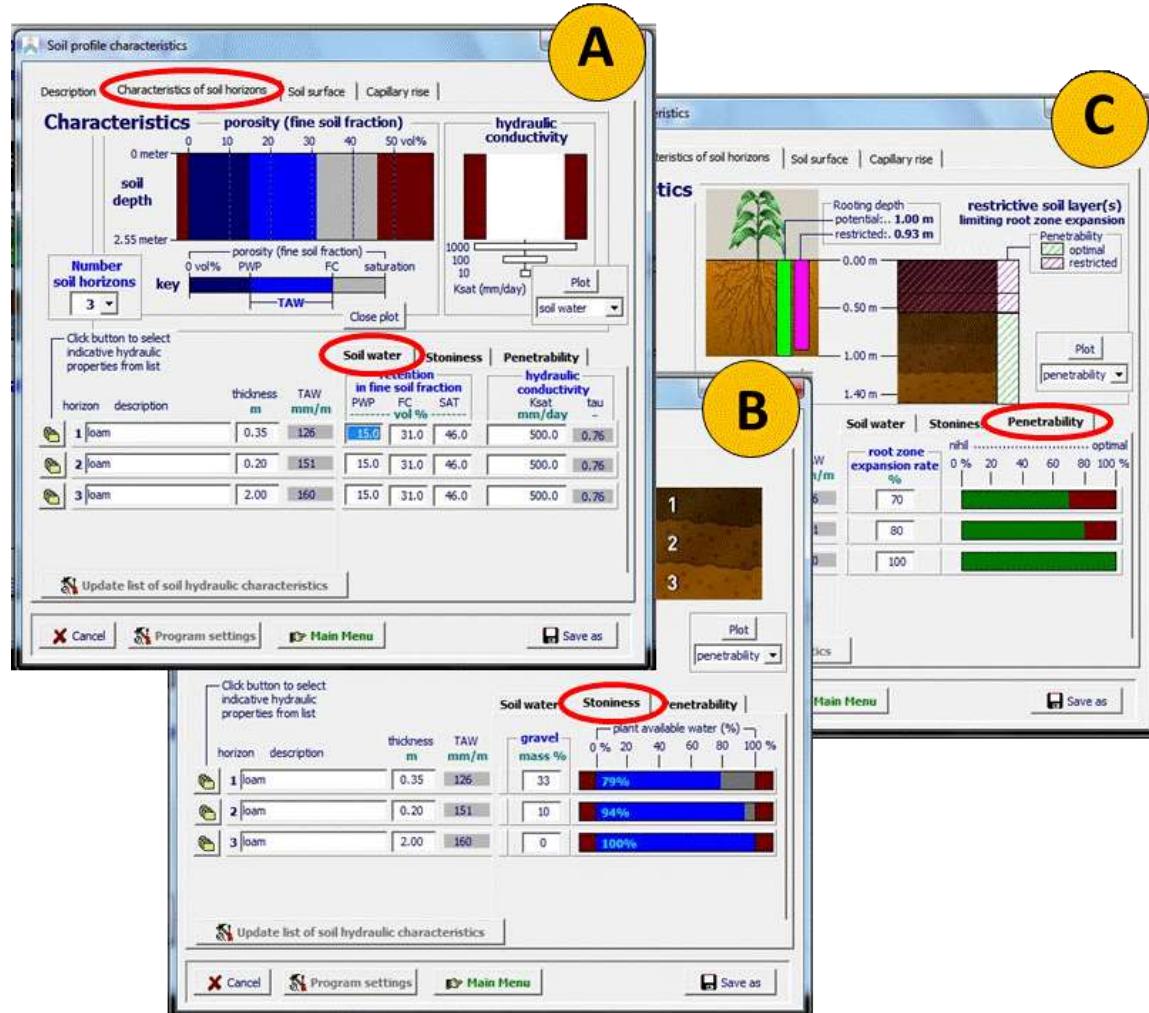


Figure 2.14b – Specification of physical characteristics of the various soil horizons in the (A) ‘Soil water’, (B) ‘Stoniness’ and (C) ‘Penetrability’ tab-sheet in the *Soil profile characteristics* menu.

In the ‘Characteristics of soil horizons’ tab-sheet of the *Soil profile characteristics* menu the number and thickness of the horizons are specified. The physical characteristics of the horizons and of their fine soil and mass fractions are specified in (Fig. 2.14b):

- the ‘Soil water’ tab-sheet (Fig. 2.14b A);
- the ‘Stoniness’ tab-sheet (Fig. 2.14b B);
- the ‘Penetrability’ tab-sheet (Fig. 2.14b C).

- ‘Soil water’ tab-sheet (Fig. 2.14b A)

The fine soil consists of soil mineral particles smaller than or equal to 2 mm, which are classified in a clay, silt and sand fraction according to their size. The relative proportion of the mass of the various fractions defines the textural class of the fine soil, and strongly specifies the physical characteristics of the soil horizon.

In this tab sheet (i) the water retention in the fine soil fraction at permanent wilting point (PWP), field capacity (FC) and saturation (SAT), and (ii) the hydraulic conductivity (Ksat) of the soil horizon, are specified. Default values for the 12 textural classes are available in AquaCrop’s data base and can be selected (see 2.14.2). AquaCrop displays the corresponding total available soil water (TAW) and drainage characteristic (tau) of the soil horizon.

Soil water content at saturation, field capacity and permanent wilting point:

- **Saturation.** When the total pore volume is filled with water, the soil water content is at saturation. Such conditions are rather uncommon in the root zone due to entrapped air and vertical drainage. Saturated conditions generally only exist when the groundwater table is in or near the root zone;
- **Field Capacity** is the quantity of water that a well-drained soil would hold against the gravitational forces. It is the upper limit for the plant extractable water. Although the soil matric potential at field capacity varies somewhat with the soil type and environmental conditions, the water content at a matric potential of -10 kPa (pF 2.0) up to -33 kPa (pF 2.5 or 1/3 bar) is often considered as field capacity;
- **Permanent Wilting Point** is the soil water content at which plants stop extracting water and will permanently wilt. It is as such the lower limit of the plant extractable water. Although permanent wilting point may somewhat vary for different crops, plant age and root distribution it is generally accepted that the soil water content at a matric potential of -1.5 MPa (pF 4.2) is a representative value for the permanent wilting point.

Saturated hydraulic conductivity (Ksat):

The hydraulic conductivity expresses the property of the soil to conduct water through a soil. When the soil is saturated all pores are filled with water and the value for the hydraulic conductivity is at its maximum. The saturated hydraulic conductivity or permeability defines the rate for the soil layer to transmit water through the saturated soil under the influence of gravity.

- ‘Stoniness’ tab-sheet (Fig. 2.14b B)

In this tab sheet the mass percentage of the gravel for the distinctive soil horizons is specified. Gravel refers to soil particles larger than 2 mm. It is thereby assumed that gravel cannot hold water and do not conduct water movement. The presence of gravel is described by specifying the mass percentage of the gravel fraction (Mass%_{gravel}):

$$\text{Mass\%}_{\text{gravel}} = 100 \frac{m_{\text{gravel}}}{m_{\text{gravel}} + m_{\text{fine soil}}} \quad [\text{Eq. 2.14}]$$

where m_{gravel} is the mass (kg) of the gravel fraction and $m_{\text{fine soil}}$ the mass (kg) of the fine soil fraction.

By considering the corresponding volume percentage of the gravel fraction, AquaCrop calculates the reduction of the volume of the fine soil fraction in which water can be stored, and plots the corresponding relative amount of available water for the plant in the horizon. The presence of gravel will reduce the total available soil water (TAW) of the soil horizon. Aquacrop displays the adjusted TAW for the soil horizon.

Aquacrop adjusts only the TAW value of the soil horizons containing gravel. In the absence of wide-ranging and well described responses to the presence of gravel, other characteristics of the soil profile, soil horizons, and of the crop are not adjusted. If effects of gravel on those characteristics are known, the user can adjust:

- the CN and REW of the soil surface, and the Ksat, penetrability and capillary rise of the soil horizon, in the corresponding tab-sheets of the *Soil profile characteristics* menu;
- the water extraction pattern and maximum root extraction in the ‘ET’ tab sheet of the *Crop characteristics* menu.

- **‘Penetrability’ tab-sheet (Fig. 2.14b C)**

In this tab sheet the root zone expansion rate in the various soil horizons are specified. This might affect the maximum rooting depth that can be reached. The limiting effect on root zone expansion can be plotted in the menu.

The distinct layer can be a hardpan, formed by deposits in the soil that fuse and bind the soil particles. Hardpans limits or inhibited the expansion of the root zone and are also largely impervious to water. A restrictive soil layer may also be the result of soil compaction which increases its bulk density. Practices that can lead to poor bulk density are listed in Table 2.14a. Whenever the bulk density exceeds a certain level, root growth is restricted (Tab. 2.14b). Compacted soil layers with high bulk densities, do not only restrict root growth, but may also inhibit the movement of air and water through the soil.

Table 2.14a – Practices that can lead to poor bulk density

- | |
|---|
| <ul style="list-style-type: none">- Consistently ploughing or disking to the same depth;- Allowing equipment traffic, especially on wet soil;- Using a limited crop rotation without variability in root structure or rooting depth;- Incorporating, burning, or removing crop residues;- Overgrazing forage plants, and allowing development of livestock loafing areas and trails;- Using heavy equipment for building site preparation, or land smoothing and levelling |
|---|

Reference: Arshad M.A., Lowery, B., and Grossman, B. 1996. Physical test for monitoring soil quality. In: Doran, J.W. and A.J. Jones (Eds). 1996. Methods for assessing soil quality. SSSA Spec. Pub. 49. Soil Science Society if America, Madison, WI.

Table 2.14b – Ideal and root restricting bulk densities

| Soil texture | Ideal bulk densities kg.m⁻³ | Bulk densities that may affect root growth kg.m⁻³ | Bulk densities that restrict root growth kg.m⁻³ |
|------------------------|---|---|---|
| Sand | 1.60 | 1.69 | > 1.80 |
| Loamy sand | 1.60 | 1.69 | > 1.80 |
| Sandy loam | 1.40 | 1.63 | > 1.80 |
| Loam | 1.40 | 1.63 | > 1.80 |
| Sandy clay loam | 1.40 | 1.60 | > 1.75 |
| Clay loam | 1.40 | 1.60 | > 1.75 |
| Silt | 1.30 | 1.60 | > 1.75 |
| Silt loam | 1.30 | 1.60 | > 1.75 |
| Silty clay loam | 1.40 | 1.55 | > 1.65 |
| Sandy clay | 1.10 | 1.49 | > 1.58 |
| Silty clay | 1.10 | 1.49 | > 1.58 |
| Clay | 1.10 | 1.39 | > 1.47 |

Reference: USDA, 1999. Soil quality test kit guide. USDA Soil quality institute, Washington, D.C.

The presence of a hardpan or a compacted soil layer, most likely will not only restrict root growth, but might also reduce water infiltration. As such the user might have to adjust the saturated hydraulic conductivity (K_{sat}) of the restricted layer, as well as the soil water retention at saturation (θ_{SAT}) and field capacity (θ_{FC}). Since compaction of top layers can lead to increased runoff from sloping land, the Curve Number (CN) might need to be adjusted as well. The values for K_{sat} , θ_{SAT} , θ_{FC} and CN can be adjusted in the corresponding tab-sheets of the *Soil profile characteristics* menu.

- **Derived soil physical characteristics.**

From the specified data, AquaCrop determines (Fig. 2.14c):
for each horizon:

- TAW: the total available soil water for the soil water balance calculations. TAW is derived from the soil water characteristics of the fine soil fraction and the percentage of gravel);
- The drainage characteristic (tau) by considering K_{sat} . The dimensionless drainage coefficient is used for the simulation of the downward water movement in the soil profile (Chapter 3);
- Soil textural class of the fine soil fraction: for the determination of the capillary rise. From the water retention characteristics of the fine soil fraction and K_{sat} , default values for the coefficients for capillary rise of the soil horizon are derived. In the ‘Capillary rise’ tab-sheet of the *Soil profile characteristics* menu, the values for the coefficients can be adjusted if required (see 2.14.4);

for the surface layer:

- REW: the Readily Evaporable Water for the simulation of soil evaporation. A default value for REW is derived from the soil water retention characteristics of the fine soil fraction of the top horizon. REW expresses the maximum amount of water that can be extracted from the top soil in stage I of the evaporation process. In the ‘Soil surface’ tab-sheet of the *Soil profile characteristics* menu the value for REW can be adjusted if required (2.14.3);
- The default value for the curve number (CN) by considering the Ksat of the top soil horizon. CN is required for the simulation of the amount of rainfall lost by surface runoff. In the ‘Soil surface’ tab-sheet of the *Soil profile characteristics* menu the value for CN can be adjusted if required (2.14.3);

Different horizons need only be considered if there is a substantial difference in TAW (differences larger than 10 mm/m), Ksat, gravel content or permeability between the horizons.

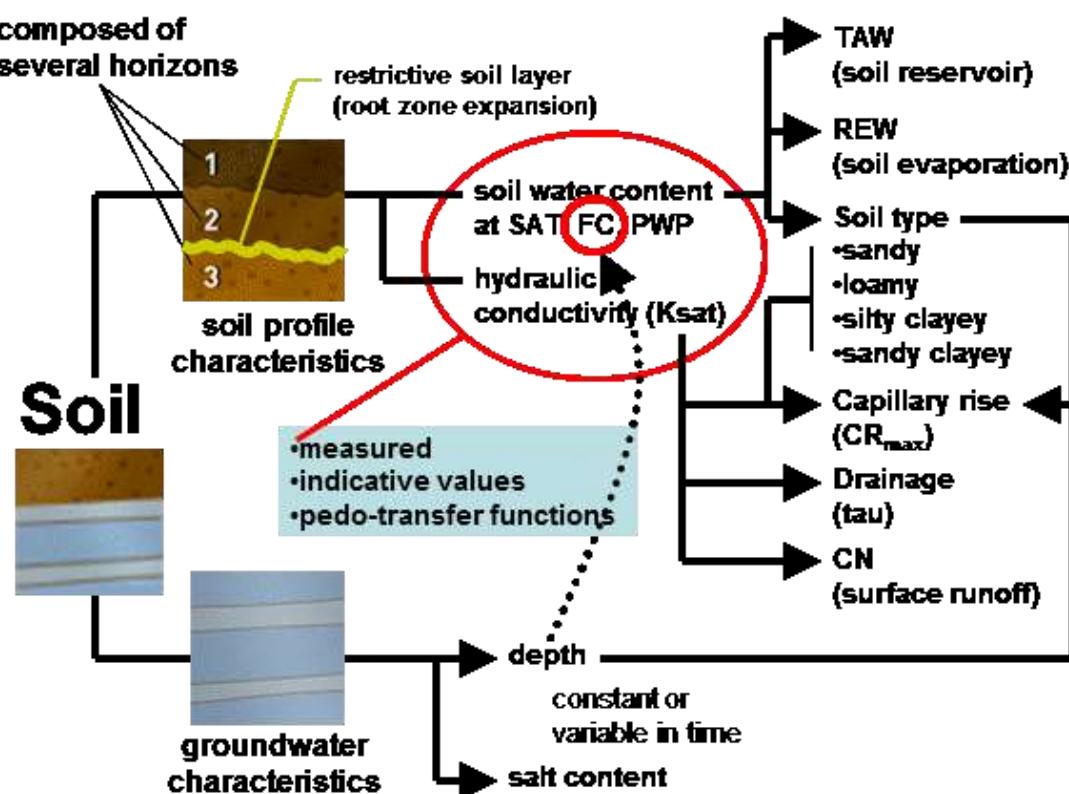


Figure 2.14c – Soil physical and groundwater table characteristics

2.14.2 Indicative values for soil physical characteristics

The amount of water remaining in the soil at saturation and field capacity varies with the soil texture, organic matter content and structure. The clay and organic matter content of a soil horizon predominantly define its soil water content at permanent wilting point. The saturated hydraulic conductivity (K_{sat}) does not only vary between soil types, but even for one specific soil type, a typical K_{sat} value does not exist. Even in a single field, it is not uncommon to measure rather important variations for K_{sat} in space and time as a result of variations in soil structure, bulk density, biological activity and soil management.

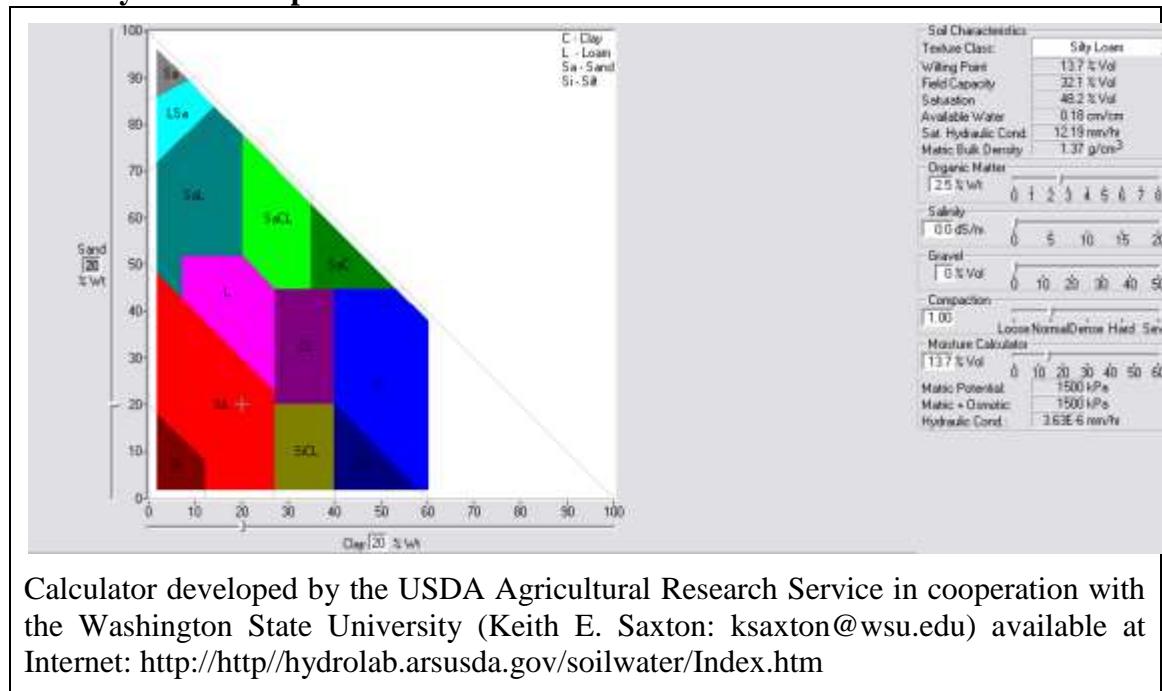
The user can make use of indicative values provided by AquaCrop for various soil textural classes (Tab. 2.14c), or import locally determined or derived data from soil texture with the help of pedo-transfer functions (Box 2.14). The values presented in Table 2.14c are derived with the help of pedo-transfer functions are only indicative values. The default values for the hydraulic conductivity at saturation (K_{sat}) were obtained by sampling 260 times the textural triangle of the Hydraulic Properties Calculator, and by averaging the values for each textural class. The indicative values in Table 2.14c are not intended to replace measurements.

By selecting the <Update list of soil hydraulic characteristics> command in the *Soil Profile characteristics* menu (Fig.2.14b), the indicative values for the soil hydraulic characteristics can be updated and soil types can be added or removed from the list. The characteristics are stored in the file ‘SOILS.DIR’ of the SIMUL subdirectory of the AquaCrop directory.

Table 2.14c – Indicative values for the soil water content at saturation (SAT), field capacity (FC) and permanent wilting point (PWP), and for the updated saturated hydraulic conductivity (K_{sat}) for the 12 ‘soil profile’ files (corresponding with the twelve soil textural classes) in the DATA subdirectory of AquaCrop.

| Soil textural class | soil water content | | | Saturated hydraulic conductivity |
|---------------------|--------------------|----------------|-------------------------|----------------------------------|
| | Saturation | Field Capacity | Permanent Wilting Point | |
| | vol % | vol % | vol % | mm/day |
| Sand | 36 | 13 | 6 | 3,000 |
| Loamy sand | 38 | 16 | 8 | 2,200 |
| Sandy loam | 41 | 22 | 10 | 1,200 |
| Loam | 46 | 31 | 15 | 500 |
| Silt loam | 46 | 33 | 13 | 575 |
| Silt | 43 | 33 | 9 | 500 |
| Sandy clay loam | 47 | 32 | 20 | 225 |
| Clay loam | 50 | 39 | 23 | 125 |
| Silty clay loam | 52 | 44 | 23 | 150 |
| Sandy clay | 50 | 39 | 27 | 35 |
| Silty clay | 54 | 50 | 32 | 100 |
| Clay | 55 | 54 | 39 | 35 |

Box 2.14 – Soil water characteristics derived from pedo-transfer functions available in the Hydraulic Properties Calculator



2.14.3 Characteristics of the soil surface layer

When specifying soil data for the top horizon, default values for the Curve Number (Tab. 2.14d) and the Readily Evaporable Water are derived and displayed (Fig. 2.14d).

- The Curve Number (CN) is required for the simulation of the surface runoff (see Chapter 3) and its value refers to the value for antecedent moisture class II (AMC II).
- The Readily Evaporable Water (REW) expresses the amount of water that can be evaporated from the soil surface layer in the energy limiting stage (see Chapter 3).

The user can specify other than the displayed default values for CN and REW if specific information about the soil surface is available.

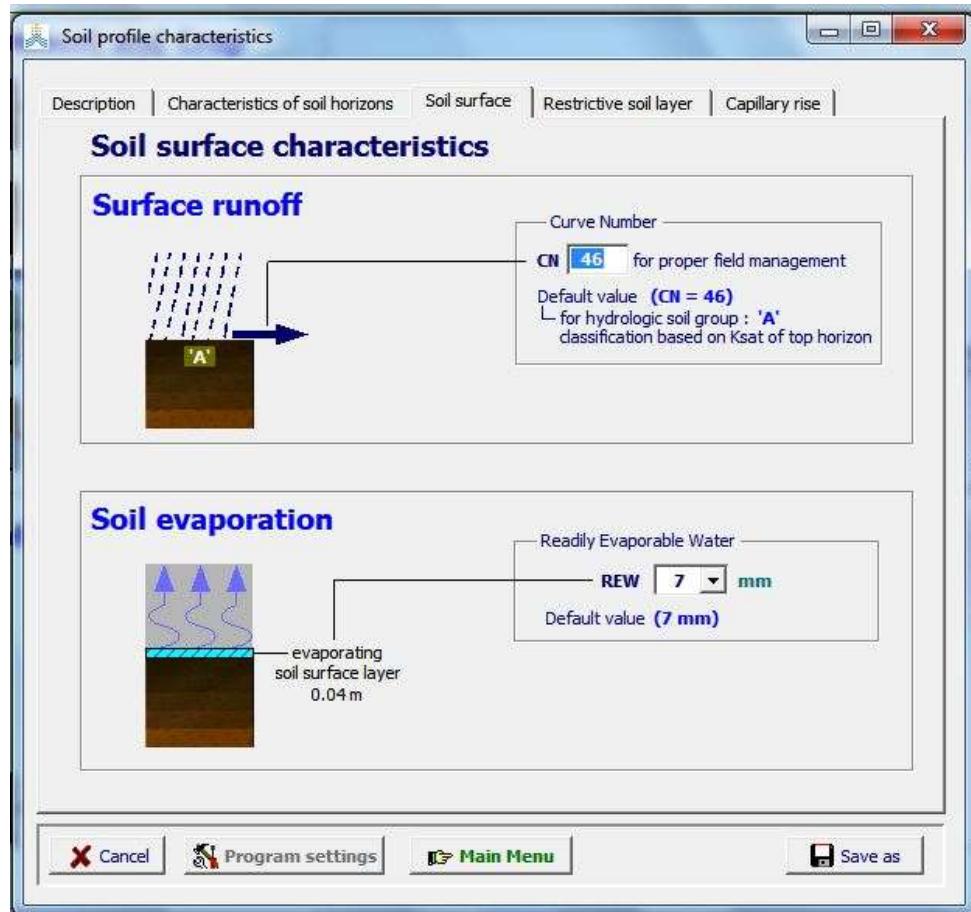


Figure 2.14d – Characteristics of the soil surface layer

Table 2.14d – Hydrologic soil groups, the corresponding range for the saturated hydraulic conductivity (K_{sat}) of the top horizon, and default CN values (assuming an initial abstraction of 5 % of S) for antecedent moisture class II (AMCII).

| Hydrologic soil group | Saturated hydraulic conductivity (K_{sat}) mm/day | CN default value for AMC II |
|-----------------------|---|-----------------------------|
| A | > 864 | 46 |
| B | 864 – 347 | 61 |
| C | 346 – 36 | 72 |
| D | ≤ 35 | 77 |

The user can still specify a CN value different from the default (Fig. 2.14d), but should thereby not consider the effect of land use and cover, since these effects are considered when specifying the field management. Hence a clear distinction is made between the CN value based on soil profile characteristics (CN_{soil} : which is a soil parameter), and the adjustment of CN_{soil} as a result of field management practices (which is a field management parameter).

The user should be aware that CN values differ if they are calculated with an initial abstraction of 20% S or 5% S. To convert $CN_{0.20}$ to the corresponding $CN_{0.05}$ value (used in AquaCrop version 5.0 and later), the user can find the corresponding values in Table 2.14e.

Table 2.14e – $CN_{0.20}$ values (assuming an initial abstraction of 20% S) with the corresponding $CN_{0.05}$ values (assuming an initial abstraction of 5% S).

| $CN_{0.20}$ | $CN_{0.05}$ | $CN_{0.20}$ | $CN_{0.05}$ | $CN_{0.20}$ | $CN_{0.05}$ |
|-------------|-------------|-------------|-------------|-------------|-------------|
| 100 | 100 | 80 | 72 | 60 | 46 |
| 98 | 98 | 78 | 70 | 58 | 44 |
| 96 | 95 | 76 | 67 | 56 | 41 |
| 94 | 93 | 74 | 64 | 54 | 39 |
| 92 | 90 | 72 | 61 | 52 | 37 |
| 90 | 87 | 70 | 59 | 50 | 35 |
| 88 | 84 | 68 | 56 | 48 | 33 |
| 86 | 81 | 66 | 53 | 46 | 31 |
| 84 | 78 | 64 | 51 | 44 | 29 |
| 82 | 75 | 62 | 48 | 42 | 27 |

2.14.4 Capillary rise

In the ‘Capillary rise’ tab sheet the user can study the maximum possible upward flow to the top soil for various depths of the groundwater table (Fig. 2.14e).

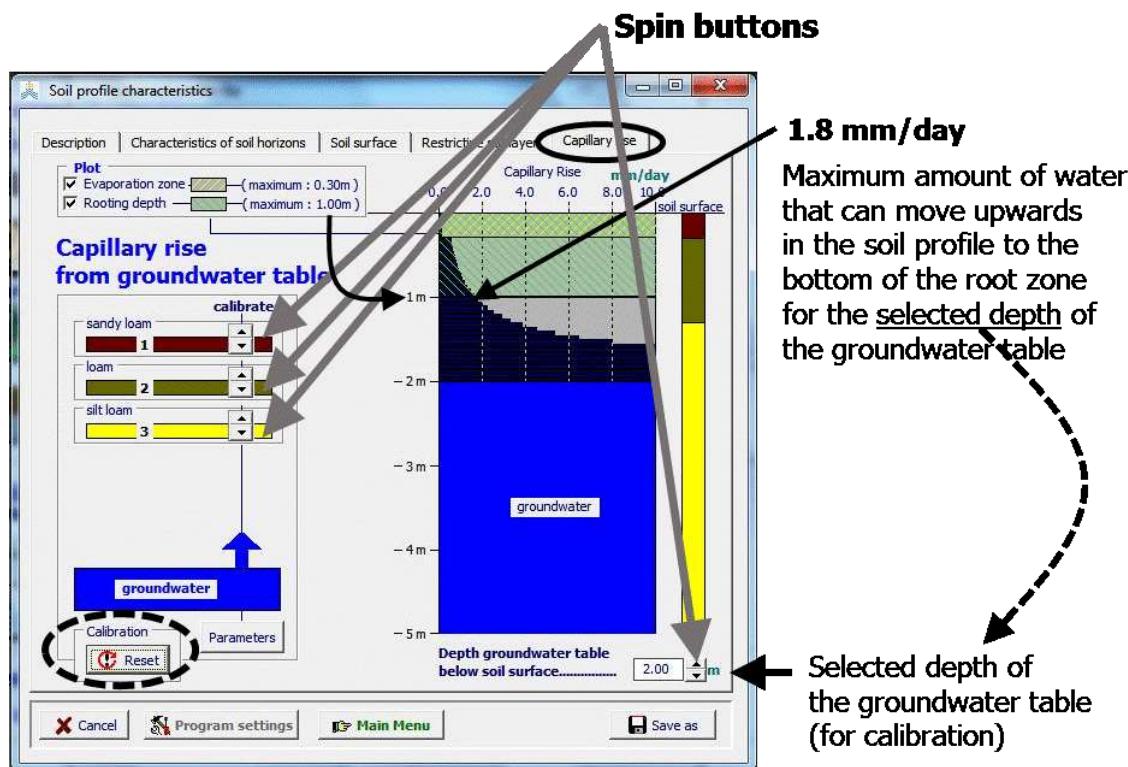


Figure 2.14e – The ‘Capillary rise’ tabular sheet of the *Soil profile characteristics* menu in which the maximum amount of water that can be transported upwards to the bottom of the root zone (for the specified crop), can be calibrated with the help of spin buttons, for a selected groundwater table depth.

The maximum possible capillary rise is calculated with an exponential equation (Chapter 3). The default a and b parameters, describing the capillary rise for each soil horizon, are obtained by considering the class of the soil type and the saturated hydraulic conductivity.

With the help of ‘spin’ buttons the user can calibrate the maximum amount of water that can move upwards to the root zone from a groundwater table at a selected depth. For the example in Fig. 2.14e: if for the soil characteristics of the soil horizons, the maximal capillary rise to the root zone (thickness of 1 m, which is a crop characteristic) is known to be only 1 mm/day (instead of the displayed 1.8 mm/day) for a groundwater table depth at 2 meter, (i) set the depth of the water table at 2 m, and (ii) use the spin button of the horizons (mainly horizon 3 in this case), to reduce the capillary rise to the bottom of the root zone to 1.0 mm/day;

By selecting the <Parameters> button, the calibrated and defaults values for the a and b parameters are displayed. By hitting on the <Reset> button, the user undoes the calibration and the a and b parameters are reset at their default values.

When running a simulation, the magnitude of the capillary rise can differ from the calibrated maximum value (see Chapter 3):

- Capillary rise will be smaller if the soil water content in the root zone is at or above field capacity (no driving force) or close to wilting point (hydraulic conductivity too small to move water upwards);
- If the depth of the groundwater is different from the one selected in the ***Soil profile characteristics*** menu for calibration, capillary rise will be different. The depth (and water quality) of the groundwater table for the simulation are specified in the ***Groundwater characteristics*** menu (see 2.15 (Groundwater table characteristics)).

2.14.5 Program settings

From the ***Soil profile characteristics*** menu the user has access to the program settings affecting the simulation of surface runoff, soil salinity and capillary rise (Tab. 2.14f).

Table 2.14f – Program settings affecting surface runoff and soil salinity

| Symbol | Program parameter | Default |
|--------|--|---------------------|
| | Surface runoff | |
| | <ul style="list-style-type: none"> ▪ Adjustment of the CN value to the relative wetness of the topsoil (The CN values for the three different antecedent moisture classes (AMC) are displayed) ▪ Default thickness of the topsoil that will be considered for the determination of its wetness (required for the determination of AMC) | Yes 30 cm |
| | Soil salinity | |
| | <ul style="list-style-type: none"> ▪ Salt diffusion factor (expressing the capacity of salt diffusion in the soil matrix) ▪ Salt solubility | 20 % 100 g/litre |
| | Capillary rise | |
| | <ul style="list-style-type: none"> ▪ Shape factor for effect of soil water content gradient on capillary rise | 16 |

2.14.6 Training videos about the soil profile

A set of training modules (MP4 videos) are posted in an ‘AquaCrop Training’ channel of YouTube. The modules about the soil profile are listed in Table 2.14g. For the playlist go to FAO AquaCrop website <http://www.fao.org/nr/water/aquacrop.html>

Table 2.14g – Set of training modules about the soil profile

| Video | Learning objective | Length [min:sec] |
|--|--|-------------------------|
| 03.1 Water retention and movement | Understand how AquaCrop describes water retention and water movement in the soil profile | - |
| – Part 1. Soil physical characteristics | | 06:18 |
| – Part 2. Soil water content | | 09:28 |
| – Part 3. Soil water retention, soil water balance and required physical characteristics | | 15:36 |
| – Part 4. Soil water movement and required physical characteristics | | 10:01 |
| 03.2 Soil profile characteristics | Know the required soil profile characteristics | 10:23 |

2.15 Groundwater table characteristics

The selected characteristics of the groundwater table can be displayed in the *Display of groundwater characteristics* menu and updated in the *Groundwater characteristics* menu. The user can choose between the presence or the absence of water table. The considered characteristics of the groundwater table are its depth below the soil surface and its salinity.

2.15.1 Constant depth and salinity

If the characteristics remain constant during the season the user specifies the depth and salinity of the groundwater table (Fig. 2.15a). The characteristics are graphically displayed in the Plot tab sheet.

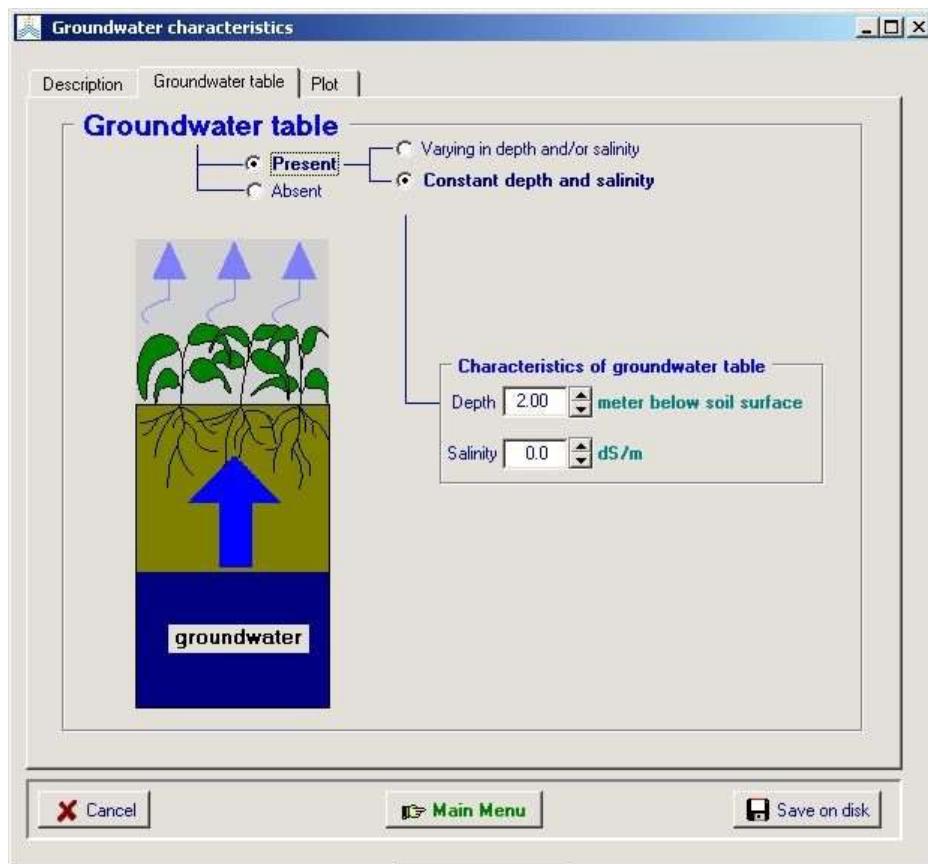


Figure 2.15a – Specifying the constant characteristics of a groundwater table in the Groundwater table tab sheet of the *Groundwater characteristics* menu.

2.15.2 Characteristics vary throughout the year(s)

The characteristics can vary throughout the year. The characteristics are specified in the Groundwater table tab sheet (Fig. 2.15b and 2.15d) and graphically displayed in the Plot tab sheet (Fig. 2.15c and 2.15e).

The characteristics of the groundwater table (depth and water quality) are specified for various instants in the (successive) season(s) with reference to the ‘First day of observations’ (Fig. 2.15b and 2.15d). If the characteristics of the groundwater table are valid for each year, do not specify the year of the ‘First day of observation’.

At run time, AquaCrop will derive the depth and water quality of the groundwater table for each day, by linear interpolation between the specified values (Fig. 2.15c and 2.15d). For moments out of the listed period, the depth and soil water quality is assumed to be equal to the 1st value in the list (for earlier dates) or the last value in the list (for later dates).

- Characteristics are not linked to a specific year

If the characteristics are not linked to a specific year, linear interpolation also applies between the characteristics specified on the last and first day number (Fig. 2.15b and 2.15c).

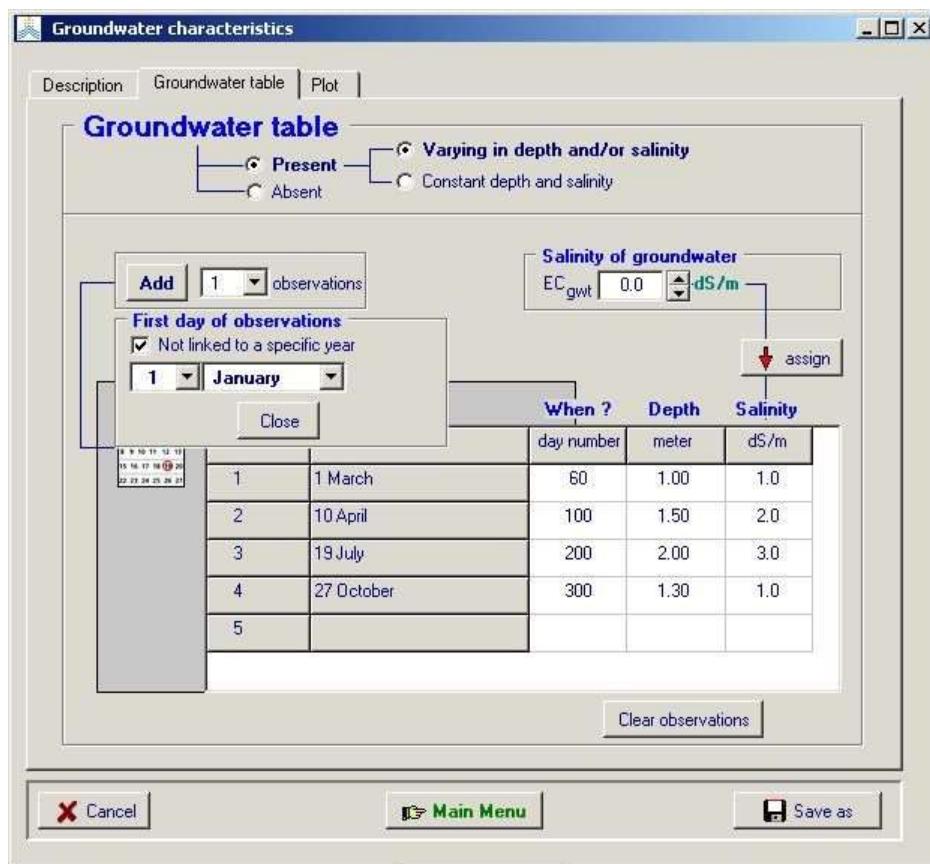


Figure 2.15b – Specifying the variable characteristics of a groundwater table not linked to a specific year in the **Groundwater characteristics** menu

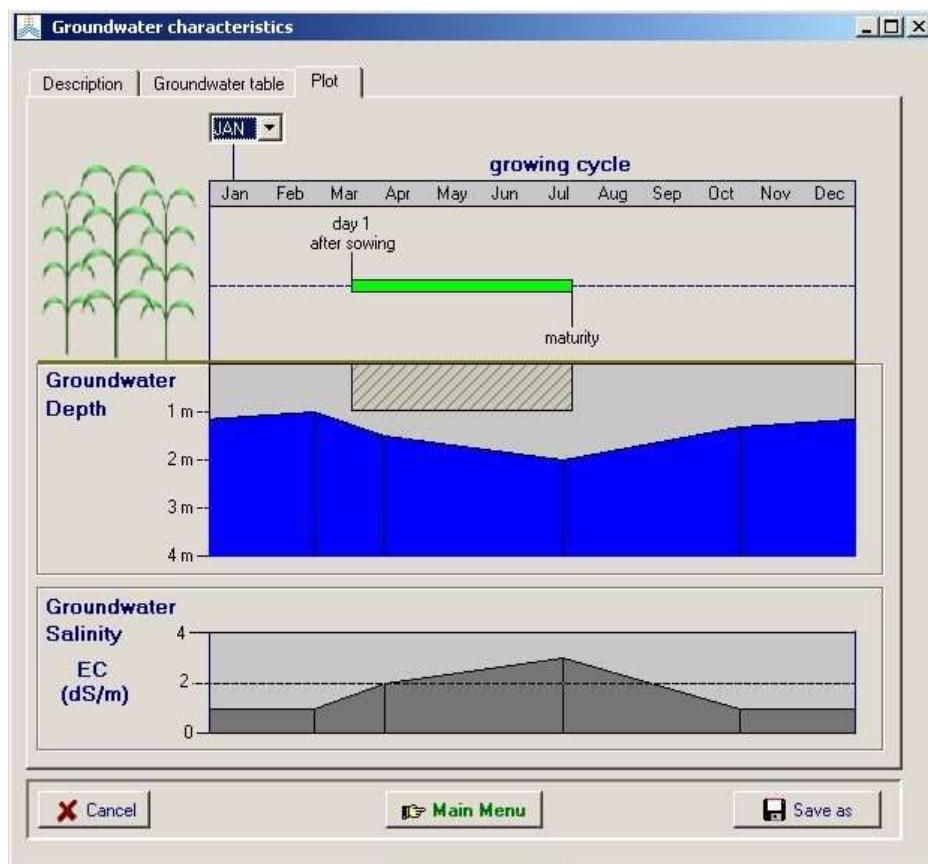


Figure 2.15c – Graphical display of the variable characteristics of a groundwater table not linked to a specific year in the *Groundwater characteristics* menu.

- Characteristics are linked to specific year(s)

If the characteristics are linked to specific year(s), linear interpolation is only applied between the characteristics specified on the day numbers (Fig. 2.15d and 2.15e). The characteristics for days before the first specified day number are identical to the characteristics specified on the first day number. The characteristics specified on the last day number remain valid for all successive days.

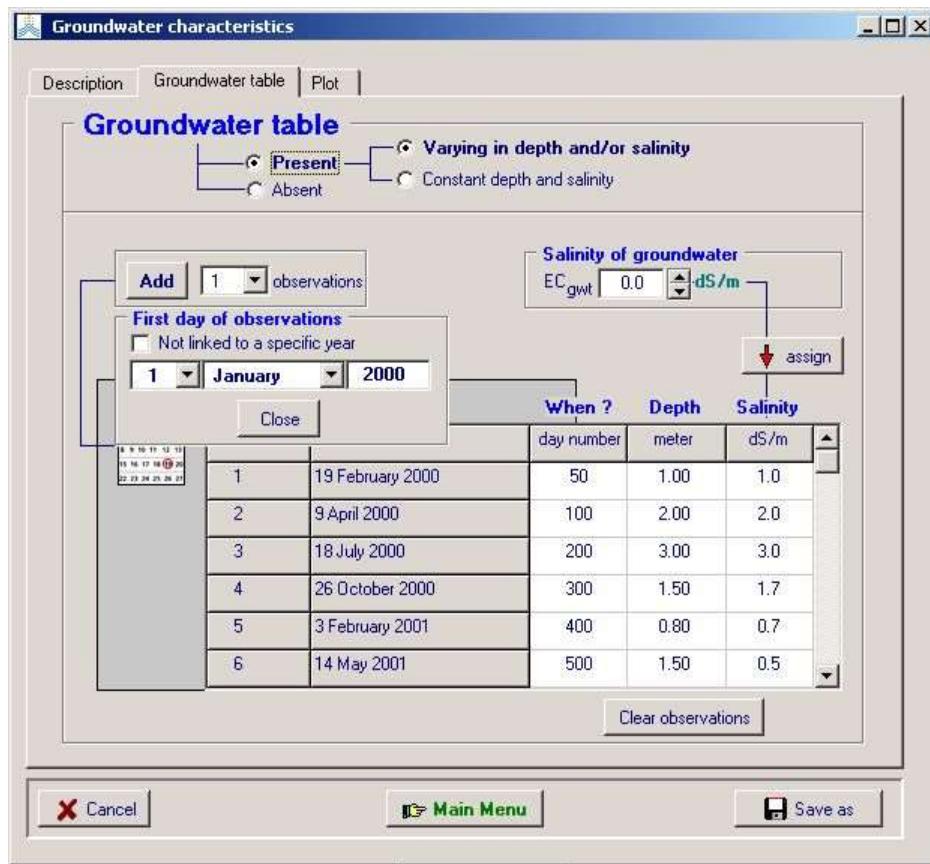


Figure 2.15d – Specifying the variable characteristics of a groundwater table linked to a specific year in the ***Groundwater characteristics*** menu.

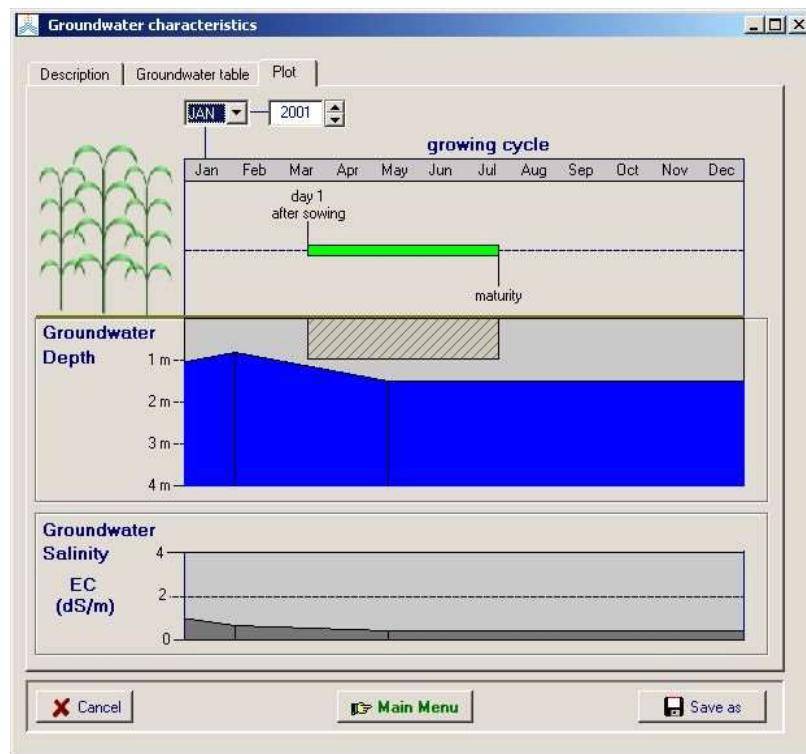
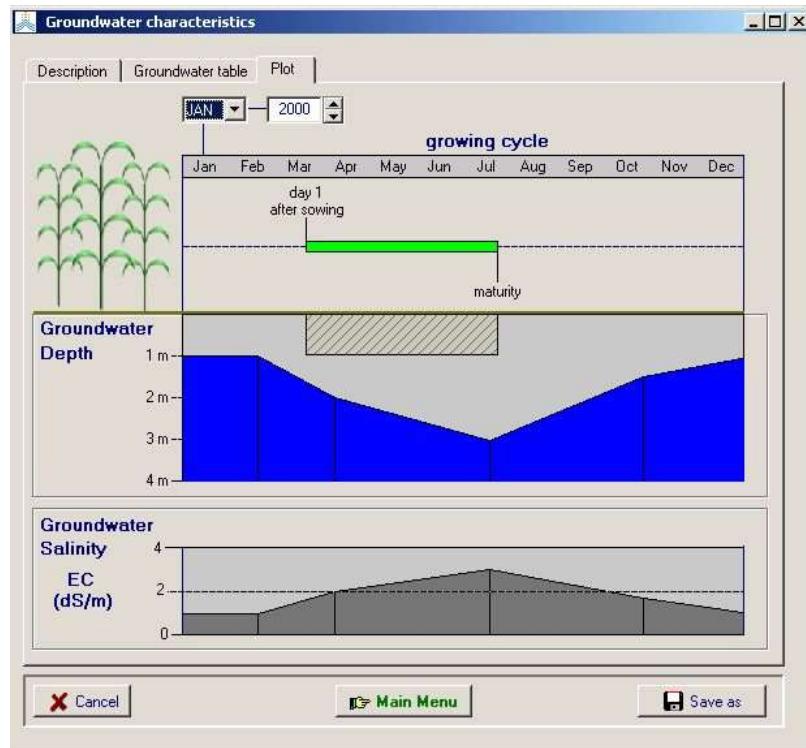


Figure 2.15e – Graphical display of the variable characteristics of a groundwater table linked to specific years (2000 and 2001) in the **Groundwater characteristics** menu

2.15.3 Training video about the groundwater table

A set of training modules (MP4 videos) are posted in an ‘AquaCrop Training’ channel of YouTube. The module about the groundwater table is listed in Table 2.15a. For the playlist go to FAO AquaCrop website <http://www.fao.org/nr/water/aquacrop.html>

Table 2.15a – The training module about the groundwater table

| Video | Learning objective | Length [min:sec] |
|--|--|-----------------------------|
| 03.3 Depth and quality of the groundwater table | Know the required conditions at the lower boundary | 04:56 |

2.16 Simulation period

The selected simulation period for a simulation run can be displayed in the *Display of simulation period* menu and adjusted in the *Simulation period* menu. The length of the growing cycle and range of available climatic data is given as a reference in the menu (Fig. 2.16a and 2.16b).

2.16.1 Specifying the range of the simulation period

The user adjusts the range of the simulation period by specifying the first and last day, month and eventually year. The simulation period can be shorter, longer or linked with the growing cycle (Fig. 2.16a), as long as the period does not exceed the range of climatic data. If no climate file is selected, the user can select any simulation period but will have to specify the climatic data at run time.

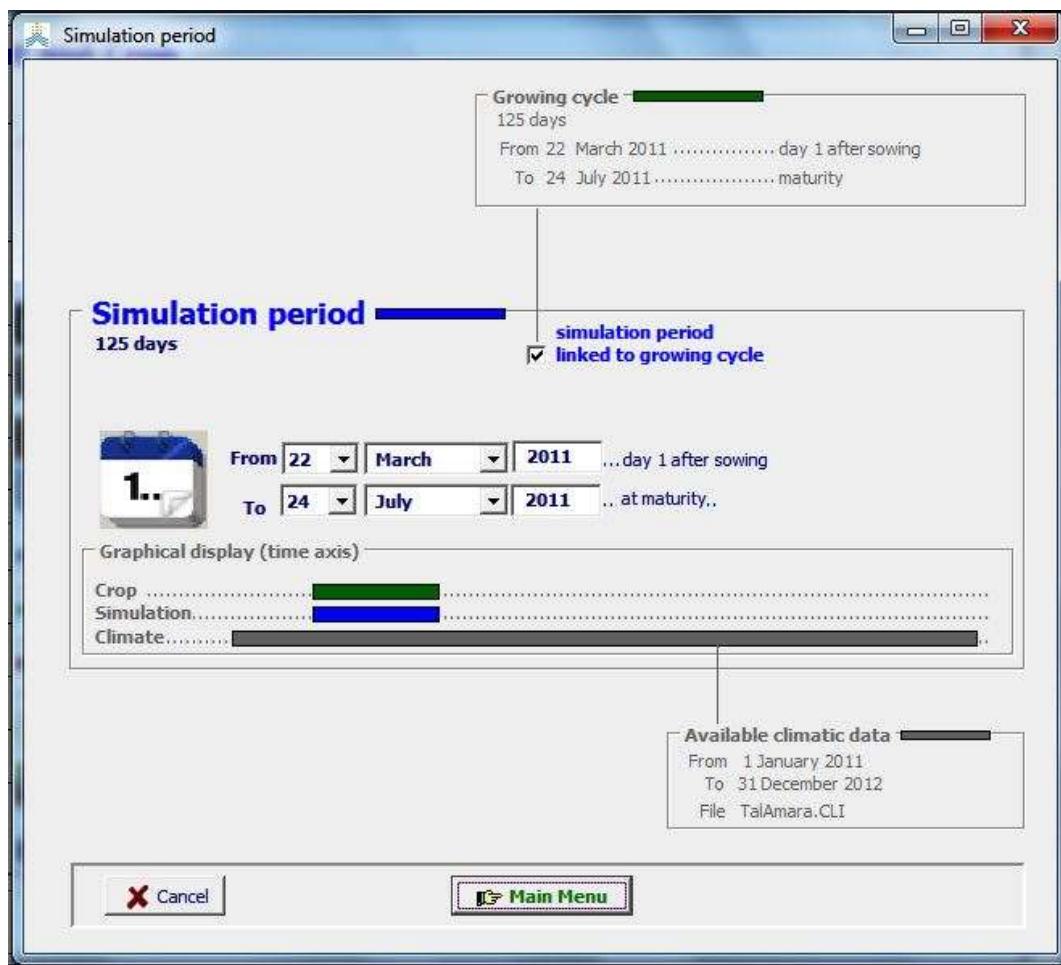


Figure 2.16a – Specification of the simulation period in the *Simulation period* menu (linked to the growing cycle)

The graph in the menu displays on a time axis (i) the length of the cropping period (Crop – in green), (ii) the selected simulation period (Simulation – in blue), and (iii) the length of the period for which climatic data is available (Data – in gray).

2.16.2 Starting day of the simulation period

If the soil water content was obtained from representing soil samples collected in the field at the start of the growing cycle, or if the soil water content can be well estimated at that day, the simulation period can be linked with the growing cycle (Fig. 2.16a). This is the default setting.

If field data is not available at the start of the growing cycle, the simulation can start at a day at which soil water conditions can be well estimated, such as early spring when the soil water content is likely to be at field capacity after long winter rains. Another appropriate starting time of the simulation might be at the end of a long dry period when the soil water content is likely to be close to permanent wilting point. Since the simulation period has not to coincide with the growing cycle, putting the start of the simulation period at an appropriate date well before planting, is a good method to become well estimated initial conditions at the moment of crop germination.

2.16.3 Hot start within the growing cycle

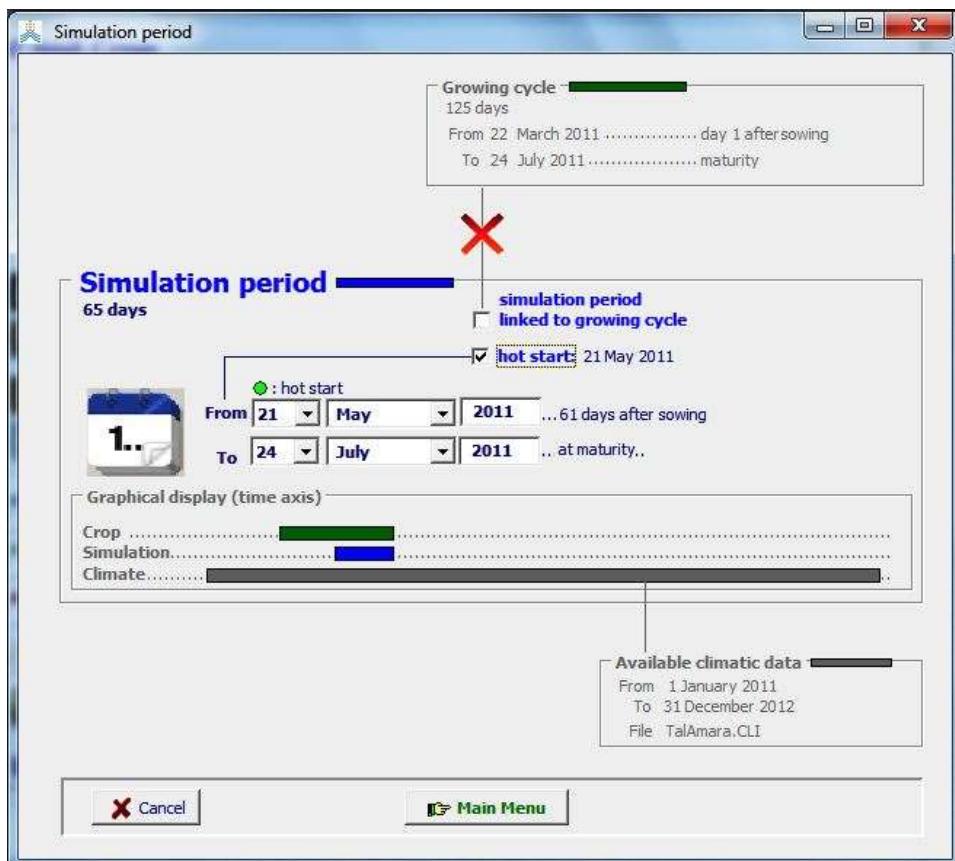


Figure 2.16b – Specification of a hot start in the *Simulation period* menu

When a simulation finishes within the growing cycle, the final simulation results are saved for the next simulation run (see ‘Hot start’ in 2.17 Initial conditions). If the first day of the next run, neatly succeeds the last day of the previous run, AquaCrop recognises a ‘hot start’ and loads the saved final simulation results of the previous run. As such the conditions at the end of the previous run become the initial conditions for the simulation run.

If the simulation was halted within the growing cycle (after the sowing/plant day and before the end of the growing cycle), a hot start will be possible when returning to the **Main menu** (the message ‘hot start pending’ will be displayed below the Simulation period). Adjust if required the environmental conditions in the **Main menu** (e.g. select another climate, irrigation management and/or field management file). Specify the simulation period (hot start) for the successive run in the **Simulation period** menu:

- From (first day): To fulfil the requirements for a ‘hot start’, the first day of a next simulation period should be equal to the last day of the previous run. To facilitate the selection, AquaCrop displays this ‘hot start’ day in the **Simulation period** menu. By checking the ‘hot start’ check-box, the last day of previous run becomes the first day of the next run (Fig. 2.16b);
- To (last day): The last day needs not to be redefined if it was already set at the end of the growing cycle (or a later day) in the initial selection (Fig. 2.16a).

2.17 Initial conditions

The information used by AquaCrop at the start of each simulation run can be displayed in the *Display of initial conditions* menu and adjusted in the *Initial conditions* menu (Fig. 2.17a). It determines the status of the soil water and salt content, canopy and root development, and biomass production at the start of the first day of the simulation period

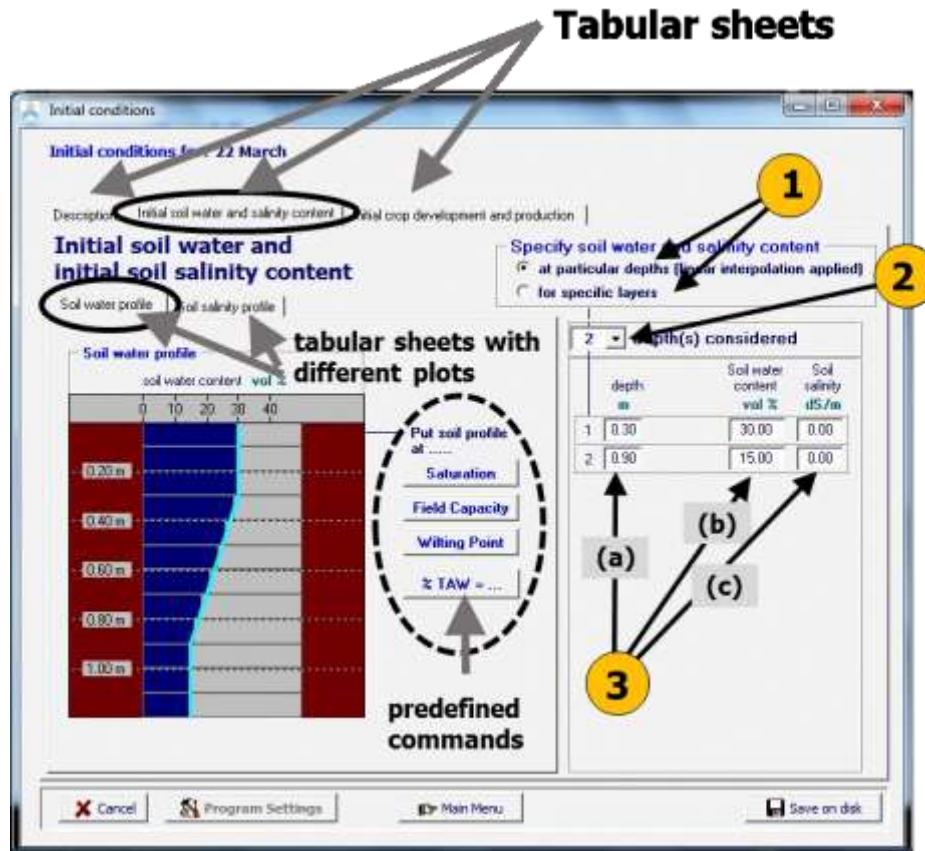


Figure 2.17a – The *Initial conditions* menu with its tabular sheets: ‘Description’, ‘Initial soil water and salinity content’ (displayed), and ‘Initial crop development and production’.

2.17.1 Initial soil water and salinity content

In the ‘Initial soil water and salinity content’ tabular sheet of the *Initial conditions* menu, the soil water content and salinity content at various points in the soil profile at the start of the simulation period can be specified (Fig. 2.17a):

1. Indicate if the contents are specified at particular depths or for specific soil layers. This is not the same as the number of horizons, specified in the soil profile file;
2. Select the number of different depths (layers) that were sampled or for which the water and salinity contents can be estimated (from 1 representative up to 12 distinctive depths/layers);

3. Specify (a) the depth (or thickness of the layer), and (b) the soil water and (c) salinity content at each depth (or for each layer). Soil water contents are specified in volume percentage and soil salinity in the Electrical Conductivity of the saturation soil-paste extract (ECe).

With the help of predefined commands, the whole soil profile can be put at a specific soil water content (at saturation, field capacity, permanent wilting point, or at a specific percentage of TAW) and salinity content (specific ECe). To use the predefined commands, the correct soil profile file should have been selected.

- **Initial conditions when simulation period is linked with the growing cycle**

The initial soil water and salinity content can be obtained by measuring the soil water content in the soil profile. Ideally sampling is done at the day of sowing/planting. In that case, the start of the simulation period should coincide with the sowing/planting date (i.e. linked with the growing cycle).

In the absence of sampling, the initial soil water and salinity content can also be estimated since the conditions in the soil profile are strongly determined by the climatic conditions (ETo and Rain) and irrigation applications in the period before the cropping period. If the cropping period starts at the end of a very rainy season, the soil water content of the soil profile might be close to field capacity. If the crop is planted in the hot dry season, the topsoil might be wet by pre-irrigation but the subsoil will be dry and the water content close to wilting point.

- **Initial conditions when simulation period starts before the growing cycle**

In the absence of observations at the time of sowing/planting, measurements or samples collected earlier can be used to determine the initial soil water content. In this case the simulation should start at the day the sampling was done (before the sowing/planting) and the simulation period is no longer linked with the growing cycle (Fig. 2.17b). The initial soil water content at sowing/planting is estimated while running AquaCrop. The software updates θ_{initial} for every day before the start of the growing cycle, with the infiltrated rainfall, (pre)-irrigation, soil evaporation, deep percolation and capillary rise.

In the absence of any measurement or sampling, the initial soil water content needs to be estimated at the start of the simulation period:

- for a climate where the winter period is characterized by ample rainfall and a small to negligible evaporative demand of the atmosphere (i.e. with ETo close to zero) as is the case in Northwest Europe, it is safe to assume that in winter (January) the initial soil water content is close to Field Capacity. Although the crop is only sown/planted in spring (March/April), the simulation can start at 1 January since at that day the initial soil water can be assumed to be at Field Capacity;
- for a climate where the summer period is characterized by the absence of rainfall and a high evaporative demand of the atmosphere (with a reference evapotranspiration (ETo) of 5 mm/day or above) as is the case in the Mediterranean region, it is safe to assume

that at the end of the summer period (mid-August), the initial soil water content will be close to Permanent Wilting Point (PWP). Although in rainfed agriculture the crop is only sown/planted when the winter rains have started (November/December), the simulation can start already at mid-summer (15 August) because at that moment a good estimate of the initial soil water content (PWP) can be made.

In both examples, the simulation starts well before the sowing/planting of the crop (Fig. 2.17b).

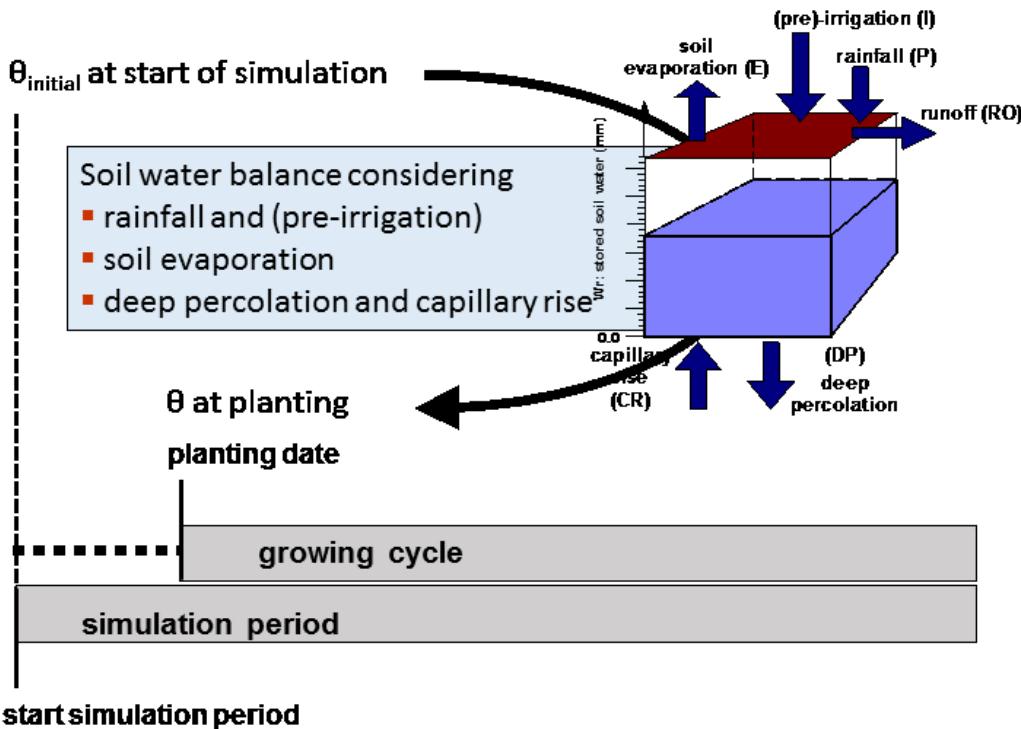


Figure 2.17b – Determination of the soil water content at planting by considering the weather conditions between the start of the simulation and the sowing/planting date

2.17.2 Water between soil bunds

If the field is surrounded by soil bunds (see 2.13 Field management) the depth of the water layer on top of the soil surface and its water quality at the start of the simulation run can be specified (Fig. 2.17c).

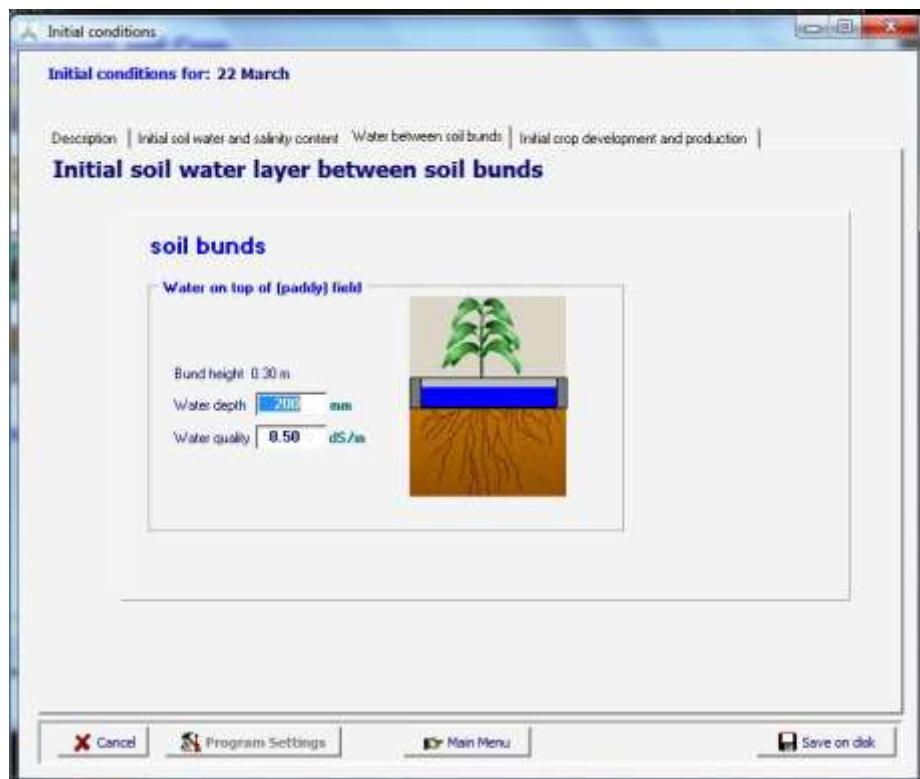


Figure 2.17c – Specification of the depth and quality of the water between soil bunds at the start of the simulation period in the *Initial conditions* menu when soil bunds are present

2.17.3 Initial crop development and production

Next to the initial soil water and salinity content, the user can also specify the initial Canopy Cover (CC) and effective rooting depth (Z), as well as the above-ground biomass (B) already produced before the start of the simulation period in the tabular sheet ‘Initial crop development and production’.

This is required if the simulation period starts after the germination of the crop (for example due to the absence of climatic data). In the absence of any stress, canopy cover and rooting depth will have their maximum values that could have been reached at the end of the day before the start of the simulation period. Since this is not necessarily true, there is the option to specify the initial status of CC and Z in the **Initial conditions** Menu, when stresses have affected crop development before the simulation period. In the same menu, the above-ground biomass already produced before the start of the simulation period (if any), can be specified (Fig. 2.17d and 2.17e). The initial conditions of CC, B and Z can be measured at the field or estimated with the help of remote sensing.

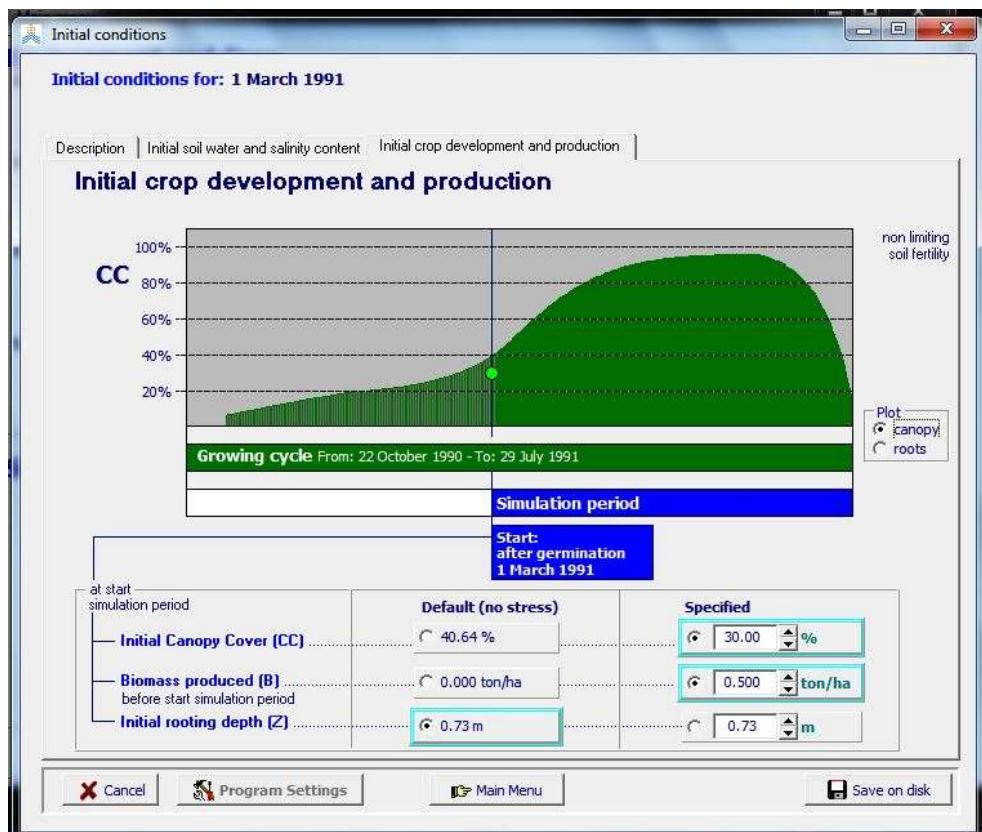


Figure 2.17d – Specification of the green Canopy Cover (CC) and produced Biomass (B) at the start of the simulation period in the *Initial conditions* Menu for a simulation period which starts after germination

The user specifies as initial conditions at the start of the first day of the simulation period:

- the initial canopy cover (CC), if different from the maximum canopy cover that could have been reached without water stress (which is the default), at the start of the simulation period (Fig. 2.17d);
- the biomass already produced at the start of the simulation period (Fig. 2.17d), if different from zero (which is the default);
- the initial rooting depth (Z), if different from the maximum rooting depth that could have been reached without water stress (which is the default), at the start of the simulation period (Fig. 2.17e).

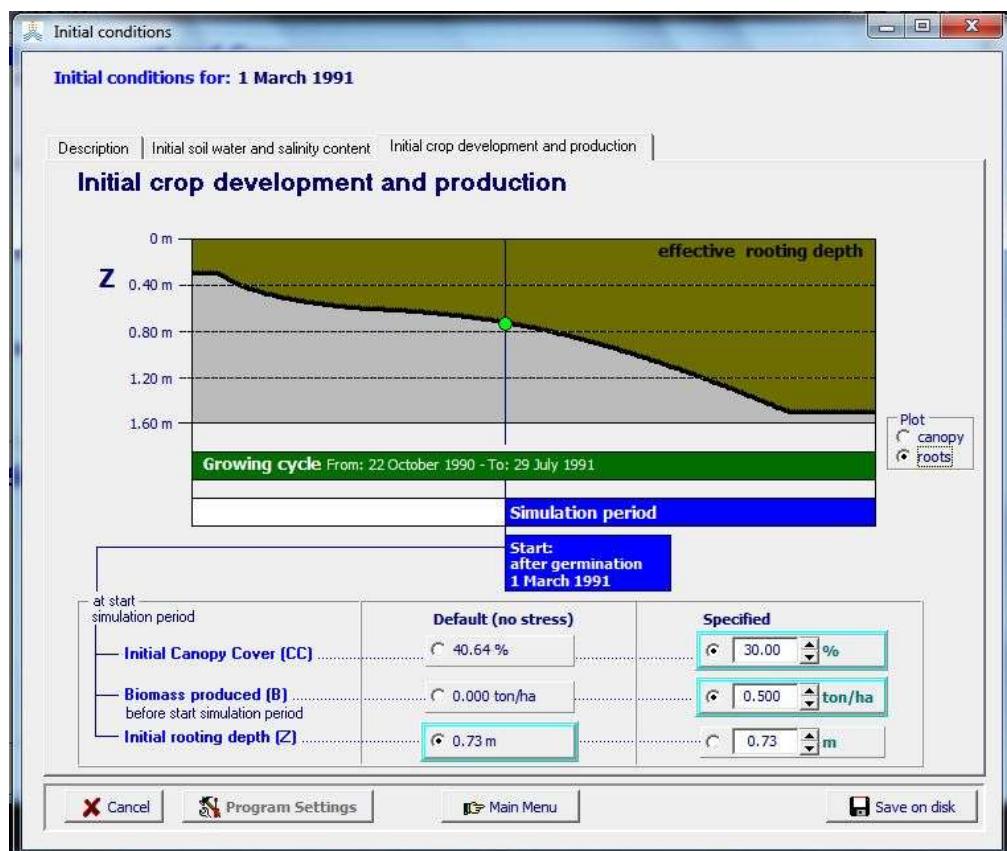


Figure 2.17e – Specification of the rooting depth (Z) at the start of the simulation period in the *Initial conditions* Menu for a simulation period which starts after germination

2.17.4 Keep/Reset initial conditions

By default the specified conditions in the **Initial conditions** menu are reconsidered at the start of each simulation run (RESET to specified Initial conditions). AquaCrop offers also the option to consider the simulated soil water and salinity content at the end of the simulation run, as the initial conditions for the next run (KEEP values from previous simulation run). Since this is not the default option, it requires a change in the settings of one of the program parameters, which has to be done in the **Program settings: Simulation run parameters** menu (see 2.17.6 Program settings). The <KEEP values from previous simulation run> setting applies as long as the soil file remains the same, and the option is not reset to its default (<RESET to specified initial conditions>).

Running with the “KEEP” option is for example useful for simulating the building up of salts over successive years. By repeating the simulations and by taking whole years as the simulation periods, the effect of winter rains leaching salts out of the root zone can be studied. In the example presented in Figure 2.17f, successive simulations were run for tomato's planted on 1 May in the region of Tunis (Tunisia) on a uniform sandy clay loam soil. The crop was irrigated by furrows and a pre-irrigation at planting was provided. The irrigation water was of poor quality (4 dS/m). Simulations were run from 1 January to 31 December, and repeated for a number of years, until the salt content in the root zone and the corresponding salinity stress and drop in crop production reached a more or less constant level.

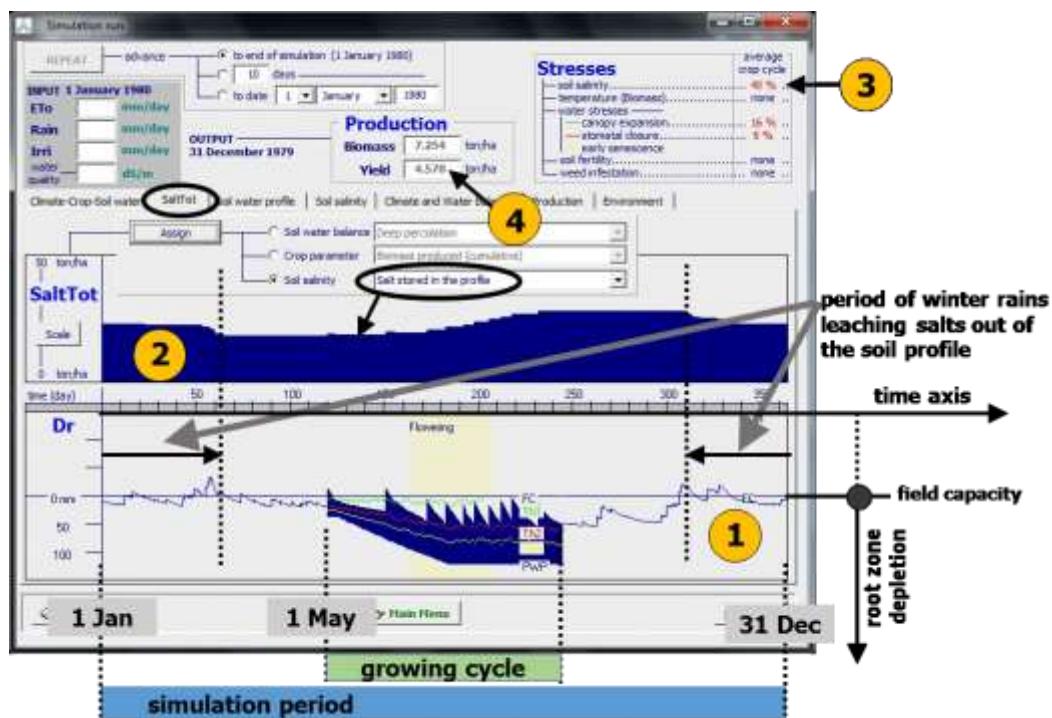


Figure 2.17f – Display, in the **Simulation run** menu, of (1) root zone depletion, (2) salt stored in the soil profile, (3) soil salinity stress and (4) crop yield, as a result of irrigating with water of poor quality and the leaching effect of winter rains in the off-season. Runs were repeated for a number of years, with the KEEP option for the initial conditions

2.17.5 Hot starts within the growing cycle

When a simulation finishes within the growing cycle, the final simulation results are saved for the next simulation run. It consists of the water and salinity content in the soil profile, and the status of crop development and production simulated at the last day of the simulation run. If the first day of the next run, neatly succeeds the last day of the previous run, AquaCrop recognises a ‘hot start’ and loads the saved final simulation results of the previous run. As such the conditions at the end of the previous run become the initial conditions for the simulation run. A hot start is the default option when running successive simulations within the growing cycle (see 2.17.6 Program settings).

Hot starts are useful when running AquaCrop to obtain a first yield estimate before the end of the ongoing season, or to assess the irrigation requirement for the next part of the season. The procedure consists in running a series of successive simulations with different climate files, and eventually different irrigation management files (Tab. 2.17a).

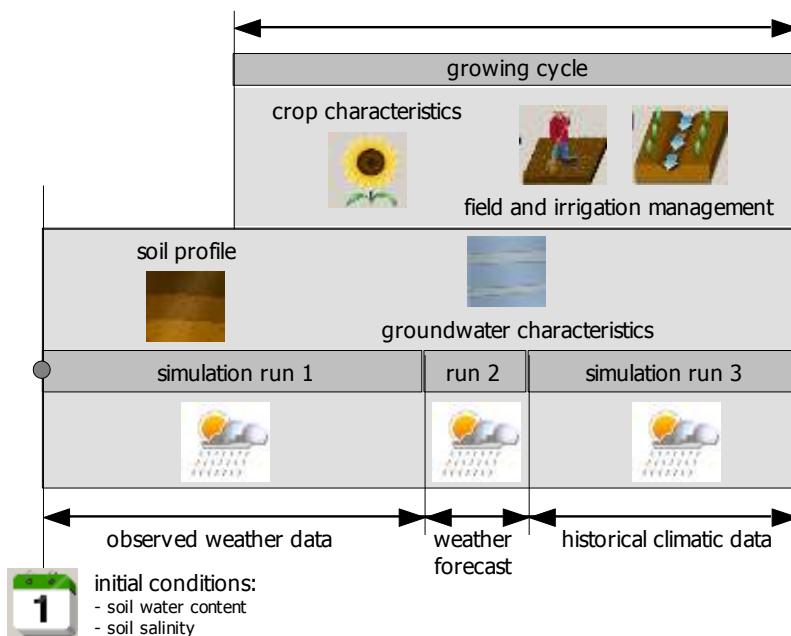


Figure 2.17g – Three successive simulations within one growing cycle, each with its own climate file

In the example of Fig. 2.17g, the first simulation runs till day i of the season with observed weather data for that period, the second simulation runs for the next n days with a weather forecast, and the third simulation runs from day $(i+n+1)$ till the end of the growing cycle with historical climatic data. By repeating the exercise with different historical climatic data for simulation run 3, the range within which the yield or the irrigation requirement can vary is obtained. As the season advances, the series of observed weather data become longer, and the estimates become more accurate. When assessing the irrigation requirement for the remaining part of the season, each of the three simulation runs can have its own irrigation management file. For example, it can consist of a file with the observed ‘irrigation schedule’ in run 1, (ii) a file with criteria to ‘generate an irrigation schedule’ in run 2, and a file with the option to ‘determine net irrigation requirement’ in run 3.

Table 2.17a. – Steps for running successive simulations within the growing cycle

Step 1. – Select a crop;

Step 2. – Specify the planting/sowing date;

Step 3. – Specify the environment. The description of the environment consists in accepting the default settings or in selecting an appropriate Climate file, Irrigation management file, Field management file, Soil profile file, Groundwater file, and/or Initial conditions file;

Step 4. – Specify the simulation period for the first run (Fig. 2.16a):

- From (first day): The simulation period may start before, at, or after the planting/sowing date. It is the day for which the specified conditions in the **Initial conditions** menu are valid;
- To (last day): When running a series of successive runs within the growing cycle, it is recommended to select the end of the growing cycle (or a later day) as the last day of the simulation period. This facilitates the settings for the successive simulation run(s) in Step 10;

Repeat till end of growing cycle (Step 5 till 10):

Step 5. – Start the simulation by selecting the <Run> command in the **Main menu**;

Step 6. – Specify in the advance panel, at the top left corner of the **Simulation run** menu (Fig. 2.17h - a), either a date (selected option: ‘to date:’) or the number of days with which the simulation has to advance (selected option: ‘n days’). A hot start will be possible for the next run, when the advance date is smaller than the last day of the growing cycle.

When in simulation run the conditions for a hot start at the start of the run are fulfilled, the ‘●: hot start’ message is displayed in the advance panel (Fig. 2.17h - b);

| | |
|--|--|
| (a) | |
| (b) | |
| Figure 2.17h –Specification of the date, at the start of a simulation, to which the simulation run has to advance, in the advance panel of the <i>Simulation run</i> menu | |

Step 7. – Start the simulation, which will stop at the date specified in the advance panel (Fig. 2.17i);

Step 8. – Exit the **Simulation run** menu, and return to the **Main Menu**. If the simulation was halted within the growing cycle (after the sowing/plant day and before the end of the growing cycle), a hot start will be possible in the next run and the simulated final conditions are kept. In the **Main menu** the message ‘hot start pending’ will be displayed below the Simulation period.

Step 9. – Adjust if required the environmental conditions in the **Main menu** (e.g. select another climate, irrigation management and/or field management file);

Step 10. – Specify the simulation period for the successive run (Fig. 2.16b):

- From (first day): To fulfil the requirements for a ‘hot start’, the first day of a next simulation period should be equal to the last day of the previous run. To facilitate the selection, AquaCrop displays this ‘hot start’ day in the **Simulation period** menu. By checking the ‘hot start’ check-box, the last day of previous run becomes the first day of the next run (Fig. 2.16b);
- To (last day): The last day needs not to be redefined if it was already set at the end of the growing cycle (or a later day) in the initial selection (Step 4).

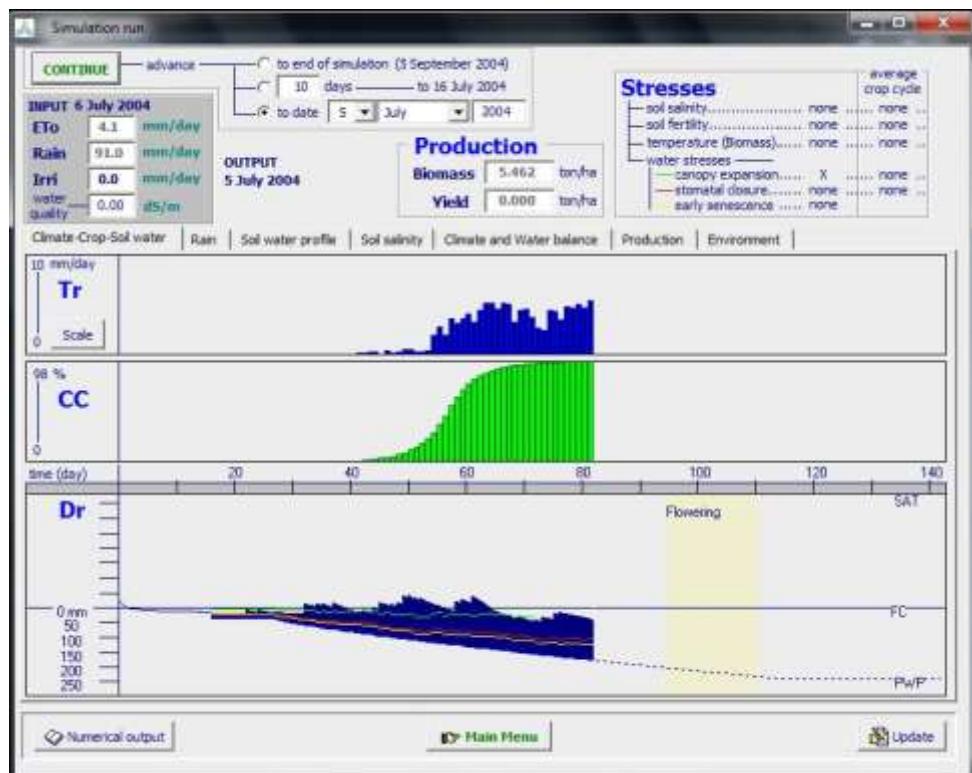


Figure 2.17i – End of the simulation within the growing cycle

2.17.6 Program settings

In program settings the user can adjust the number and size of the soil compartments and alter the setting assumed at the start of the simulation run.

▪ Soil compartments

To describe accurately the retention and movement of water and salts in the soil profile throughout the growing season, AquaCrop divides the soil profile into small fractions (see Soil water balance in Chapter 3). The soil profile is divided into soil compartments (12 by default) with thickness Δz (0.10 m by default). However, after the crop selection AquaCrop will adjust the size of the compartments to cover the entire root zone if the maximum rooting depth exceeds 1.20 meter. For deep root zones, Δz is not constant but increases exponentially with depth, so that infiltration, soil evaporation and crop transpiration from the top soil layers can be described with sufficient detail. The hydraulic characteristics of each compartment are that of the soil horizon to which it belongs. In program settings the user has the option to overwrite the AquaCrop settings by adjusting the number and thickness of the soil compartments (Fig. 2.17j).

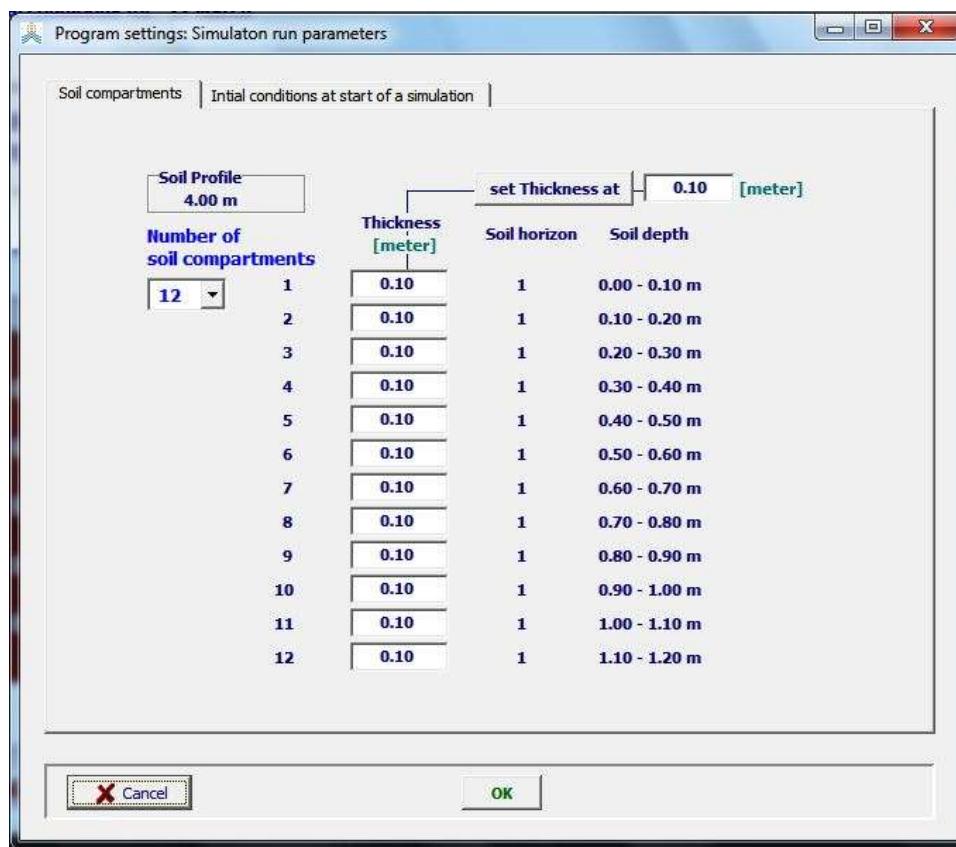


Figure 2.17j – Specification of the number and thickness of the soil compartments in the *Program settings: Simulation run parameters* menu

- Initial conditions at start of a simulation

New simulation (not within the growing cycle)

When starting a new simulation, the soil water content and soil salinity conditions in the soil profile are by default reset to the specified initial conditions (see 2.17.1 ‘Initial soil water and salinity content’). This is correct when successive simulation runs are not linked in time or apply to different fields.

With the ‘Keep’ option the soil water content and soil salinity at the end of a simulation run becomes the soil water content and/or soil salinity at the start of the next run (Fig. 2.17k). This assumes that the various runs refer all to one particular field and are successive in time (one crop after another is cultivated in the same field). It is obvious that in such cases the user can no longer alter the soil type.

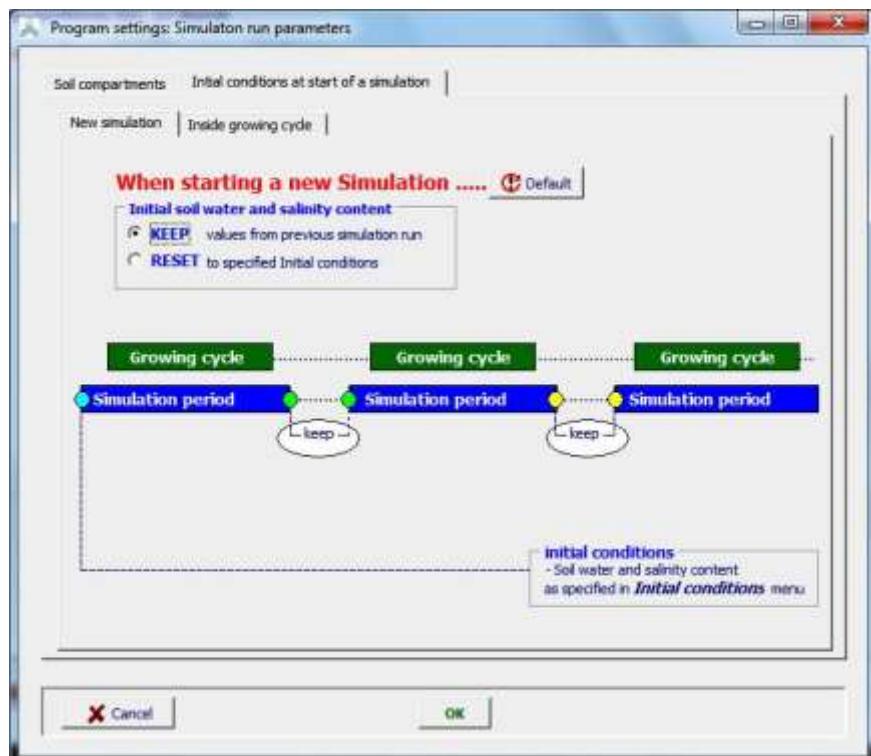


Figure 2.17k – Specification of the program parameter for the initial soil water and soil salinity content in the *Program settings: Simulation run parameters* menu

The <KEEP values from previous simulation run> setting applies as long as the soil file remains the same, and the option is not reset to its default (<RESET to specified initial conditions>).

Inside growing cycle

When running successive simulations within the same growing cycle, a ‘hot start’ is possible in AquaCrop. In a hot start, which is the default option in the *Program settings: Simulation run parameters* menu (Fig. 2.17m), the soil water and salinity content, and the status of crop development and production, simulated at the end of a simulation run, become the initial conditions for the next run.

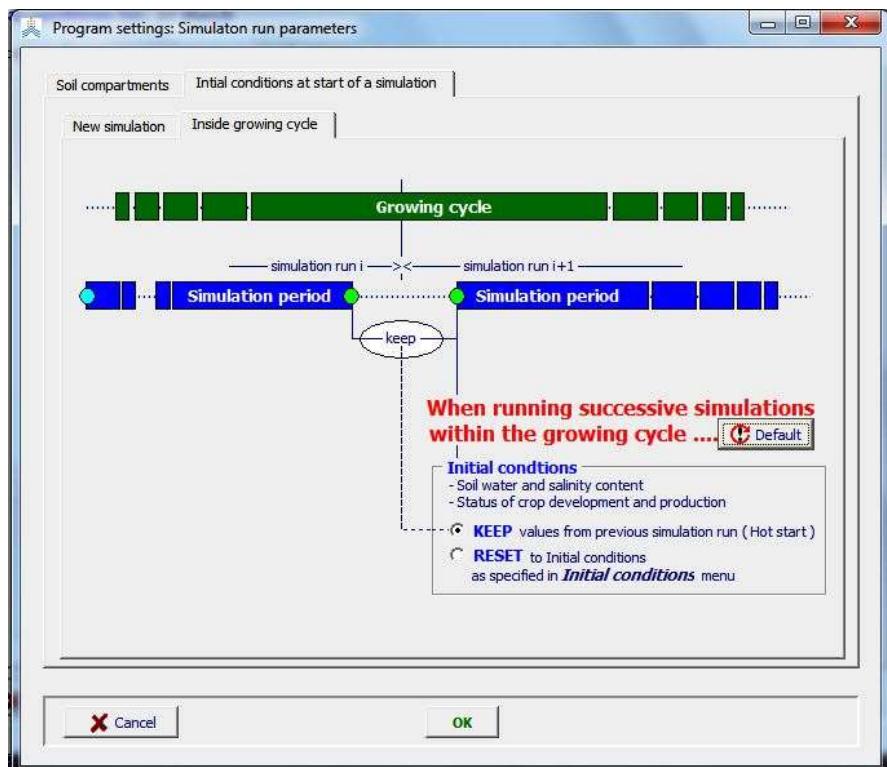


Figure 2.17m – Default option for the program parameter for the initial conditions, when running successive simulation runs within the growing cycle, in the *Program settings: Simulation run parameters* menu

Hot starts apply as long as:

- the user does not alter, between the successive simulation runs, the selected soil and crop file and the initial conditions specified in the ***Initial conditions*** Menu;
- the end of the previous run is still within the growing cycle; and
- the first day of the simulation period, follows neatly the last day of the previous run.

2.17.7 Training video about initial conditions

A set of training modules (MP4 videos) are posted in an ‘AquaCrop Training’ channel of YouTube. The module about the initial conditions is listed in Table 2.17b. For the playlist go to FAO AquaCrop website <http://www.fao.org/nr/water/aquacrop.html>

Table 2.17b – The training module about the initial conditions

| Video | Learning objective | Length [min:sec] |
|--|--|------------------|
| 06.1 Initial conditions at start of the simulation period | Know the required initial conditions at the start of the simulation period | 17:30 |

2.18 Off season conditions

If the simulation period (see 2.16 Simulation period) is not fully linked with the growing cycle but starts before the planting or sowing of the crop or finishes after the moment of maturity, the management conditions outside the growing cycle needs to be considered. The information used by AquaCrop in the off-season (such as the presence of mulches, the occurrence of irrigation events and the quality of the irrigation water outside the growing cycle) can be displayed in the ***Display of off-season conditions*** menu and adjusted in the ***Off-season conditions*** menu (Fig. 2.18a and 2.18b).

2.18.1 Mulches in the off-season

The soil cover (mulches) of the fallow land before and/or after the growing cycle and the type of surface mulches can be specified (Fig. 2.18a). The soil cover will reduce the evaporation losses from the non-cropped land.

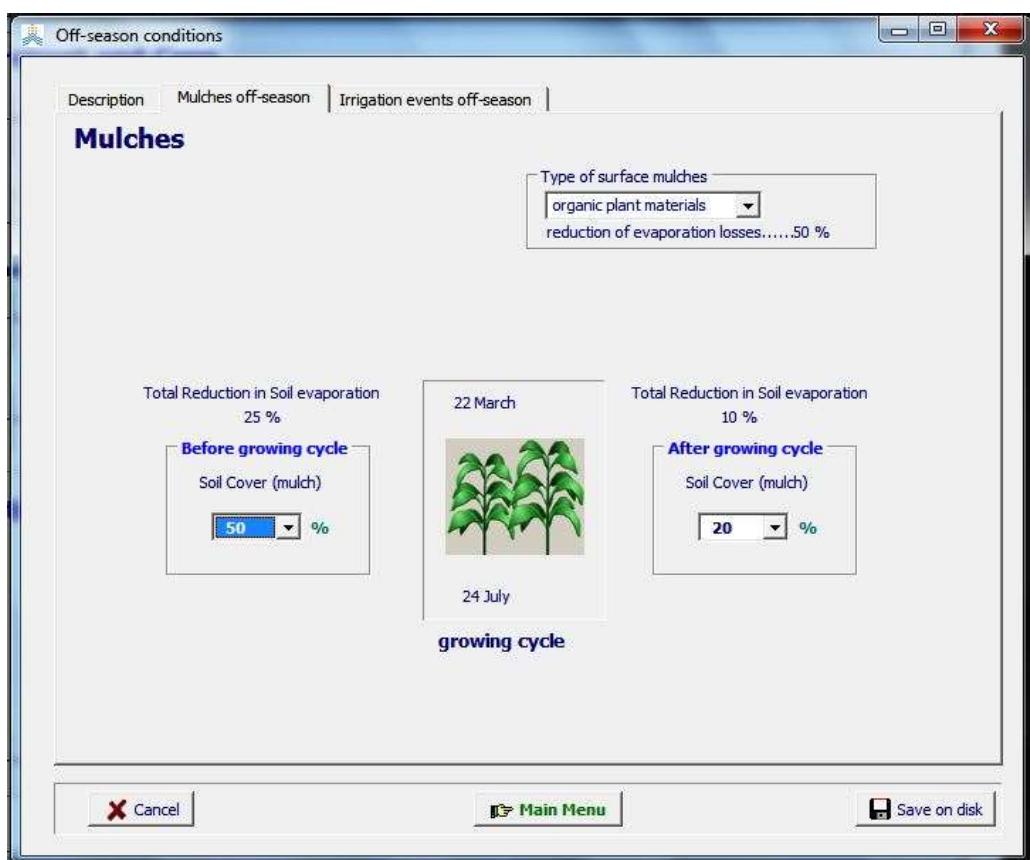


Figure 2.18a – Specification of mulches in the *Off-season conditions* menu

2.18.2 Irrigation events in the off-season

Irrigation events can be scheduled before and after the growing cycle (Fig. 2.18b). This allows the users to simulate a pre-irrigation before the sowing or planting of the crop or to schedule irrigations out of the crop season to leach accumulated salts out of the root zone. The quality of the irrigation water, which may differ from the quality in the season, is specified by selecting an irrigation water quality class (Tab. 2.18) or by specifying a value for the electrical conductivity of the irrigation water.

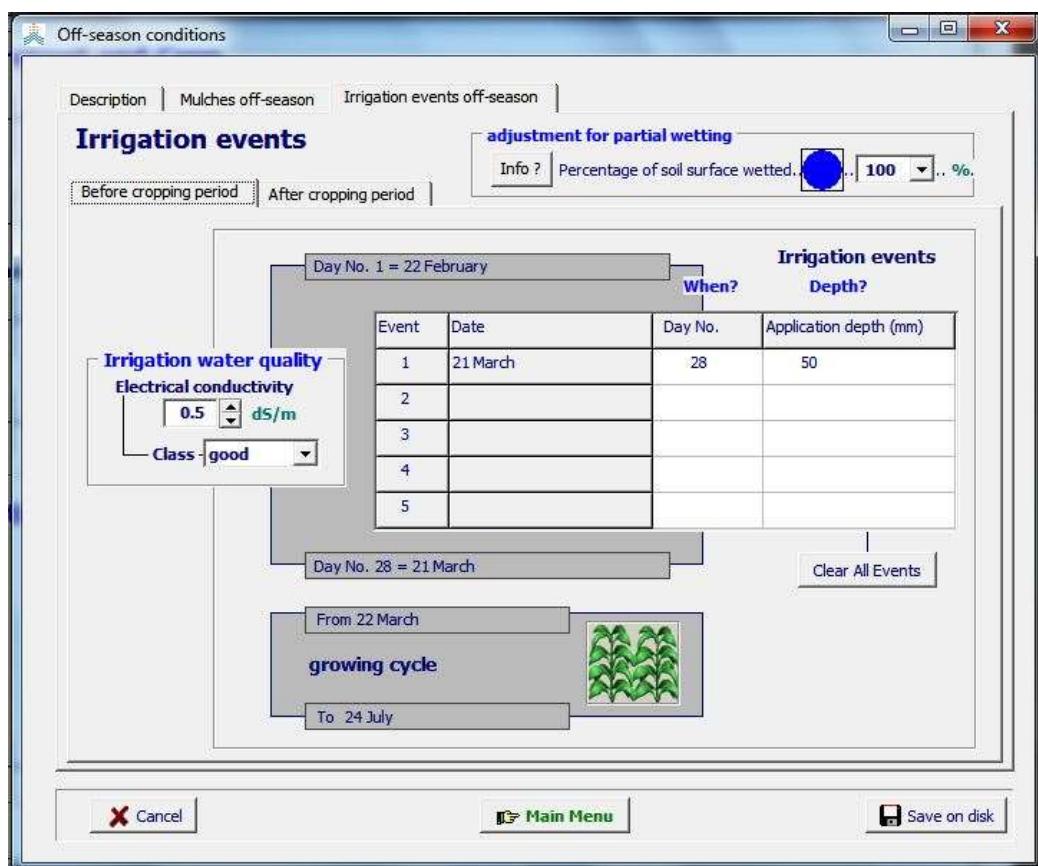


Figure 2.18b – Specification of a pre-irrigation in the *Off-season conditions* menu

Table 2.18 – Classes and corresponding default values for the quality of the irrigation water

| Class Quality of irrigation water | Electrical Conductivity (dS/m) | |
|--------------------------------------|--------------------------------|-------------|
| | Default value | Range |
| excellent | 0 | 0.0 ... 0.2 |
| good | 0.4 | 0.3 ... 1.0 |
| moderate | 1.0 | 1.1 ... 2.0 |
| poor | 1.7 | 2.1 ... 3.0 |
| very poor | 2.5 | > 3.0 |

2.19 Project characteristics

When running a simulation, initial conditions applicable at the start of the simulation period and environmental conditions relevant during the simulation period are considered. If the simulation period does not fully coincide with the growing cycle of the crop, off-season conditions valid outside the growing period will be considered as well. Before running a simulation, the user can specify in the Main menu the sowing date, the simulation period and the appropriate environmental, initial and off-season conditions (Project file is ‘None’).

The user can also load a project file containing all the required information for that run. Once a project file is loaded, its characteristics can be displayed in the ***Display of project characteristics*** menu and adjusted in the ***Project characteristic*** menu.

2.19.1 Single run and multiple run projects

Distinction is made between projects containing the required information for a single simulation run (with ‘PRO’ as the filename extension) or projects consisting of a set of successive runs, the so called multiple run projects (with ‘PRM’ as the filename extension).

With a multiple run project the user can assess the effect of weather conditions (rainfall, evaporative demand and air temperature) on crop development and production by running a particular simulation for a number of successive years. A multiple run project can also be used to simulate a crop rotation (successive crops).

2.19.2 Structure of project files

A project file is a text file which contains (a) information about the project, (b) the simulation and cropping period, (c) settings for program parameters, and (d) the names of files (crop, environment, initial conditions) which are required for the simulation run (Tab. 2.19a).

Table 2.19a – Structure of a project file

| Line Number | Description |
|---|---|
| a. – Information | |
| 1 | Description of the project |
| 2 | AquaCrop version number |
| b. – Simulation and cropping period (the growing cycle) for the first run | |
| 3 | Day number ⁽¹⁾ for the first day of the simulation period |
| 4 | Day number ⁽¹⁾ for the last day of the simulation period |
| 5 | Day number ⁽¹⁾ for the first day of the growing cycle |
| 6 | Day number ⁽¹⁾ for the last day of the growing cycle |
| c. – Program parameters | |
| 7 up to 27 | Values for 21 program parameters |
| d. – The names⁽²⁾ and directories⁽³⁾ for the 12 files containing the characteristics of the fine-tuned crop, environment (climate, management and soil), and initial conditions | |
| 28 up to 37 | <ul style="list-style-type: none"> - Climate file and the enveloped: <ul style="list-style-type: none"> - air temperature file, - ETo file, - rainfall file, and - CO2 file; - Crop file; - Irrigation management file; - Field management file; - Soil profile file; - Groundwater table file; - Initial conditions file; - Off-season conditions file. |
| In case of multiple projects , section ‘b’ and section ‘c’ are specified for each of the successive runs (in the next 40 lines). Program parameters cannot be re-specified, since the settings specified for the 1 st run (section c) are valid for all runs. | |
| <p>⁽¹⁾ Day number: The day number refers to the days elapsed since 0th January 1901 at 0 am (see Table 2.19b and 2.19c for the calculation procedure);</p> <p>⁽²⁾ File name: in the absence of a file (None), the default conditions (see 2.3 Default settings at start) are considered;</p> <p>⁽³⁾ Directory (path): in the absence of a file, (None) is specified as directory.</p> | |

Table 2.19b – Number of days elapsed since 0th January 1901, 0 am

| |
|--|
| Validity: The method is valid from 1901 to 2099 only (time range in AquaCrop) |
|--|

Rules

1. Subtract 1901 from the year
2. Multiply by 365.25
3. According to the month add:
 - January : 0
 - February : 31
 - March : 59.25
 - April : 90.25
 - May : 120.25
 - June : 151.25
 - July : 181.25
 - August : 212.25
 - September : 243.25
 - October : 273.25
 - November : 304.25
 - December : 334.25
4. Add the number of the day within the month
5. Take the integer

Example

| |
|--------------------|
| For 24 August 1982 |
|--------------------|

| | |
|--------------------------------|-------------------------------|
| 1. Subtract 1901 from the year | $1982 - 1901 = 81$ |
| 2. Multiply by 365.25 | $81 \times 365.25 = 29585.25$ |
| 3. Add 212.25 for August | $29585.25 + 212.25 = 29797.5$ |
| 4. Add the number of the day | $29797.5 + 24 = 29821.5$ |
| 5. Take the integer | 29821 |

**Table 2.19c – Calculation code to derive a day-number from a given date
(day/month/year)**

| |
|---|
| <pre> CONST ElapsedDays : ARRAY[1..12] of double = (0,31,59.25,90.25,120.25,151.25,181.25, 212.25,243.25,273.25,304.25,334.25); INPUT: Dayi : DD (Integer); Monthi : MM (Integer); Yeari : YYYY (Integer); OUTPUT: DayNr (LongInt); PROCEDURE DetermineDayNr (Dayi,Monthi,Yeari : INTEGER; VAR DayNr : Longint); BEGIN DayNr := TRUNC((Yeari - 1901)*365.25 + ElapsedDays[Monthi] + Dayi + 0.05); END; (* DetermineDayNr *) </pre> |
|---|

2.19.3 Selecting and creating a project

▪ Selecting a project

Since the single and multiple run projects have different file extensions, the list of project files displayed in the *Select project file* menu depends on the selected type of projects (Fig. 2.19a).

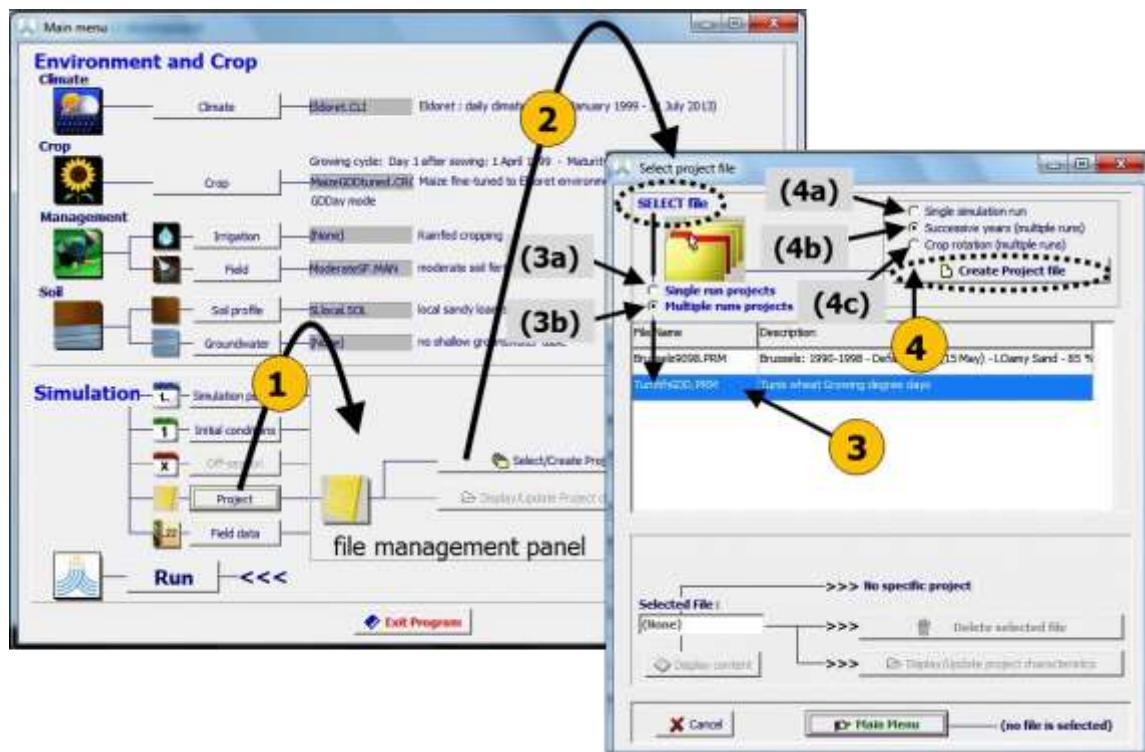


Figure 2.19a – By selecting (1) the <Project> command and subsequently (2) the <Select/Create Project file> command in the file management panel of the *Main menu*, the user gets access to the *Select project file* menu, in which (3) one of the available project files (by specifying its type: ‘3a’, or ‘3b’) or (4) the option to <Create project file> by specifying its type: ‘4a’ (Single simulation run), ‘4b’ (Successive years (multiple runs)), or ‘4c’ (Crop rotation (Multiple runs)) is selected

▪ Creating a project

Creating a project becomes straight forward, when before launching the creation, the files containing the characteristics of the fine-tuned crop, environment (climate, management, and soils), and initial conditions for the specific run are selected in the *Main menu*.

The project is created by selecting the <Create project file> command in the *Select project file* menu, after specifying its type (Fig. 2.19a):

- Single simulation run;
- Successive years (multiple runs);
- Crop rotations (multiple runs).

After selecting the <Create project file> command, the *Create project file* menu is displayed (Fig. 2.19b and 2.19c). In the case of a multiple run project, which consists in repeating a simulation over a number of successive years, the number of years (according to the data available in the selected Climate file) are displayed at the top of the menu. By means of a spin button, the number of years (series of simulation runs) can be altered.

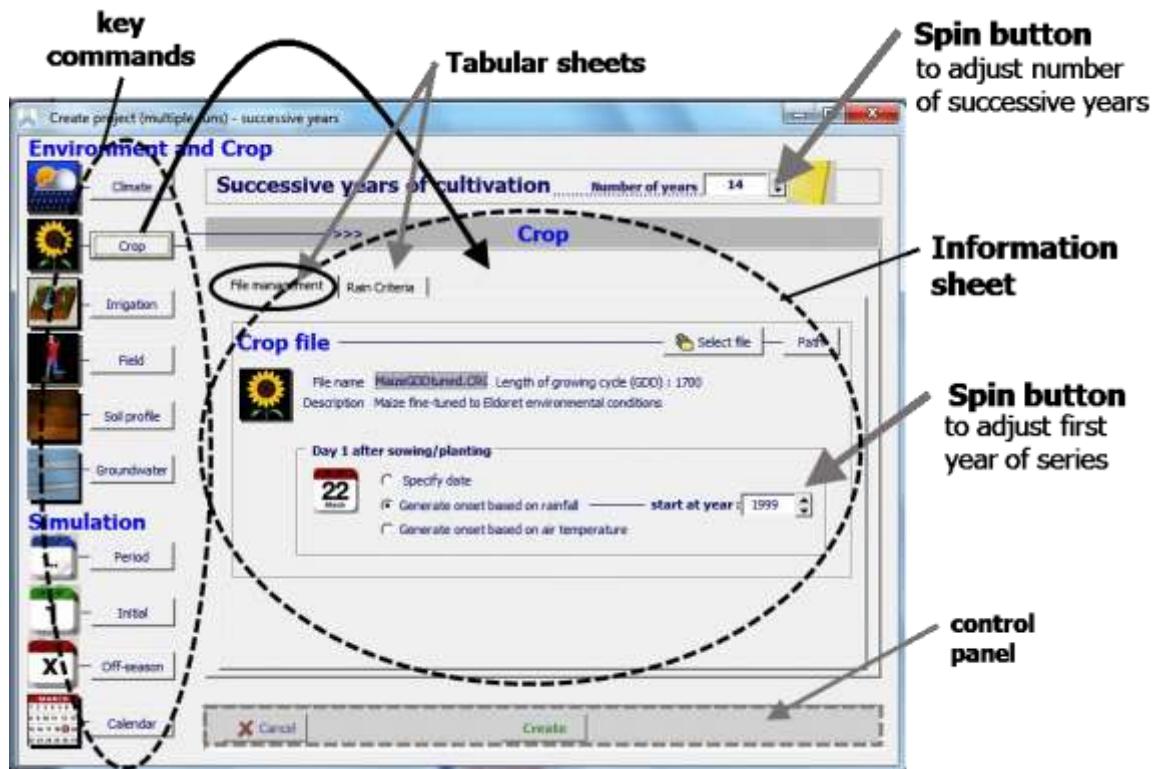


Figure 2.19b – The key commands in the *Create project* menu, with which information sheets can be displayed for file management and other data

By selecting one of the key commands at the left side of the *Create project file* menu, a corresponding information sheet is displayed with indication of the selected file (and the option to select another file) and other required information. If no file is selected, default conditions are considered (see 2.3 Default settings at start). The data specified in the information sheets consist of:

- **Climate:** Selected files containing the rainfall, ETo, air temperature and CO₂ data and the name of the enveloping climate file;
- **Crop:** Selected crop file, and the way the sowing/planting date is specified (Fig. 2.19b):
 - specific date;
 - generated date, based on rainfall data: The search window, selected criterion and the number of occurrence the criterion has to be met before the onset is generated, are specified in the ‘Rain criteria’ tabular sheet (see section 2.11.2 ‘Generated onset’);
 - generated date, based on air temperature data: The search window, selected criterion and number of occurrence the criterion has to be met before the onset

is generated, are specified in the ‘Temperature criteria’ tabular sheet (section 2.11.2 ‘Generated onset’);

In the case of a multiple run project with successive years, the year is only specified for the 1st of the series of simulation runs;

- **Irrigation:** Selected irrigation management file;
- **Field:** Selected field management file;
- **Soil profile:** Selected soil profile file;
- **Groundwater:** Selected groundwater table file;
- **Period:** The simulation period, which can be:
 - linked to the growing cycle;
 - start at a specific date.

In the case of a multiple run project with successive years, also the start of the simulation period for the next runs (successive years) is specified:

- linked to the growing cycle;
- start at a specific date for each year;
- linked to the simulation run of the previous year (the ‘KEEP’ option for the initial conditions applies for this case. See 2.17.4 ‘Keep/Reset Initial conditions’);
- **Initial:** Selected file with the initial conditions;
- **Off-season:** Selected file with the off-season conditions;
- **Calendar:** Graphical and numerical display with the start and end day of the growing cycle and simulation period in the various tabular sheets (Fig. 2.19c).

By selecting the <Create> command in the control panel at the bottom of the *Create project file* menu (Fig. 2.19c), the project is created (which consists in saving a text file with the structure and information presented in Table 2.19a).

General remarks:

1. If no file is selected default conditions are considered (see 2.3 Default settings at start).
2. If the selected irrigation management, field management, groundwater and/or file with off-season conditions are not common in the successive runs or crop rotation of multiple runs projects, the selection can be adjusted in the *Project characteristics* menu (see 2.19.5).

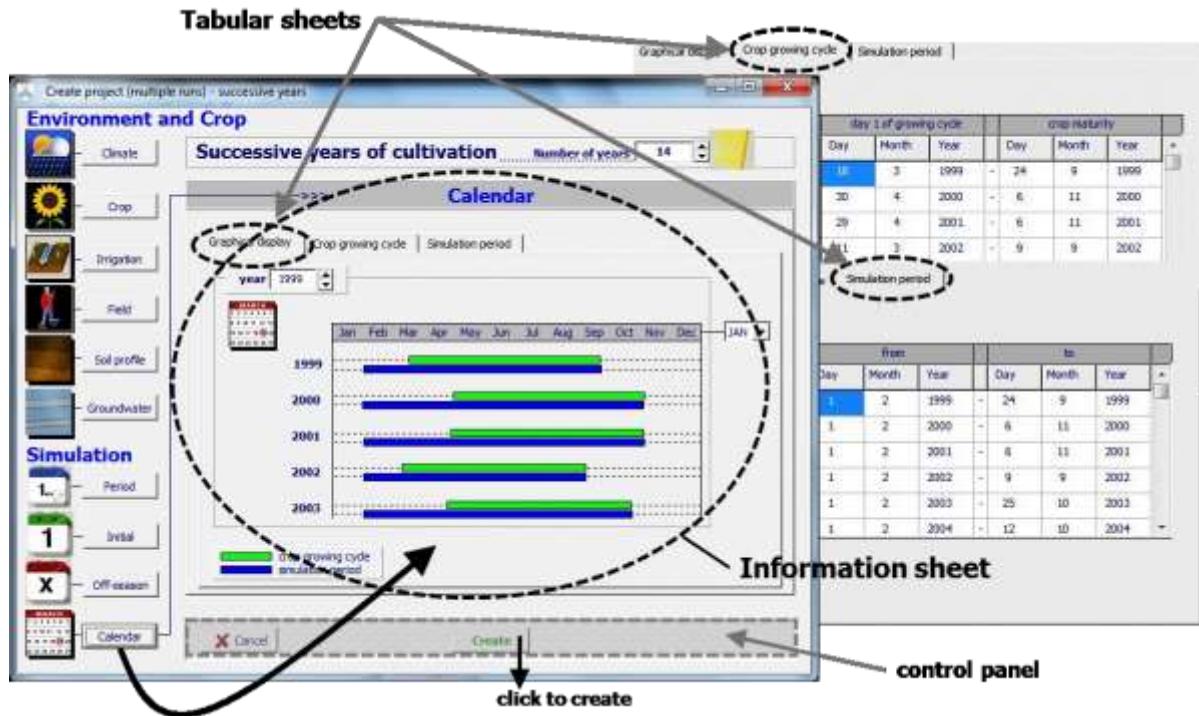


Figure 2.19c – The selected ‘Calendar information sheet’ in the *Create project* menu, with the graphical and numerical display of the start of the growing cycle and simulation period in the various tabular sheets. In the example, planting is based on meeting a rainfall criterion (2nd occurrence) in the time window 1 March – 30 April, while simulation starts each year on 1 February at which a dry soil profile can be assumed

2.19.4 Running AquaCrop in project mode

Once a project is loaded (Fig. 2.19a – 3) or created (Fig. 2.19c) the layout of the **Main menu** is adjusted (Fig. 2.19d). This is required to prevent the selection of files different from the one enclosed by the project. As such, the key commands for selecting other files are no longer available in the **Main menu** (Fig. 2.19d). However, by clicking on the icons, the corresponding characteristics of the input can still be displayed (see also 2.5.1 ‘Displaying input characteristics’). In case of multiple runs project, the content of other runs (which can contain different set of files) can be displayed with the spin button at the top of the menu.

By selecting the <UNDO project selection> command in the **Main menu**, one return to the default settings considered at the start of AquaCrop (see 2.3 Default settings at start).

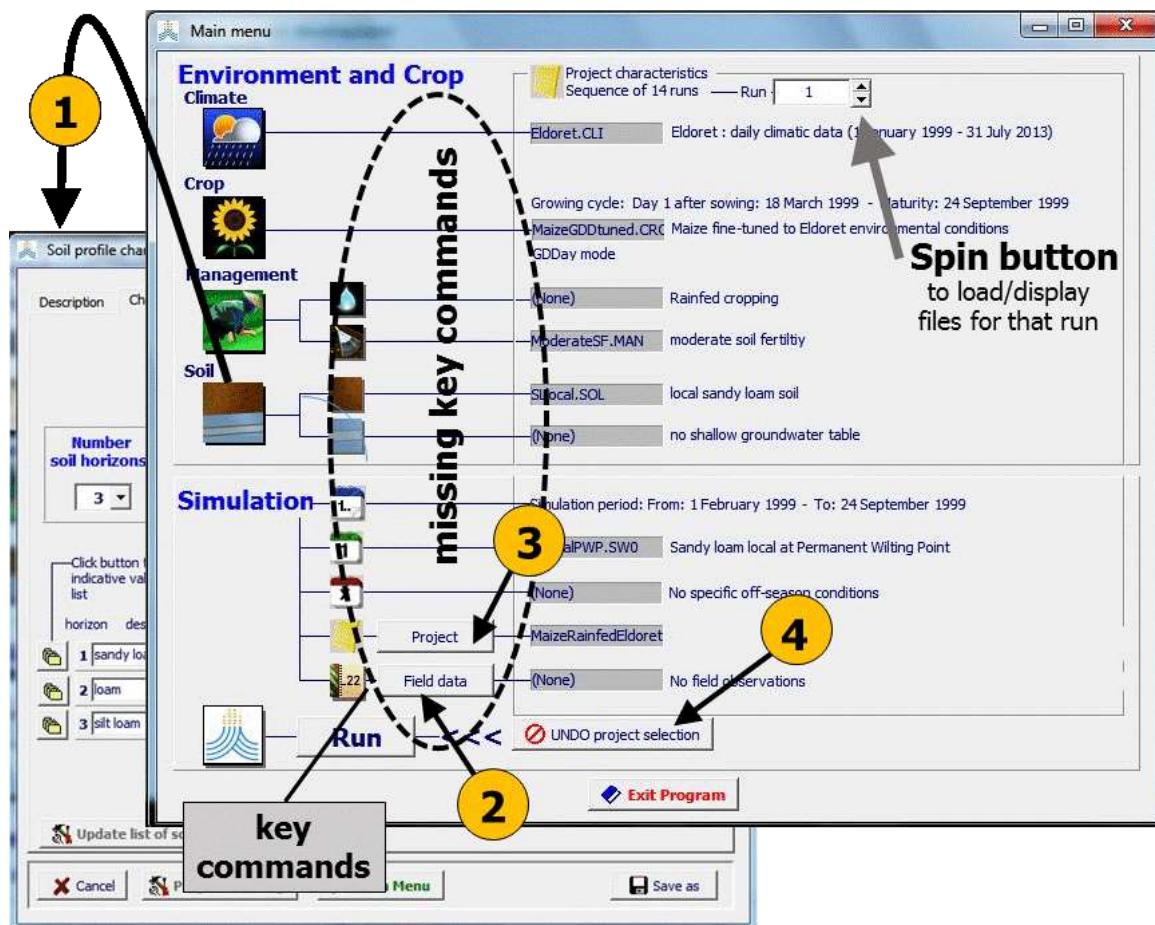


Figure 2.19d – The Main menu in project mode (with missing key commands), in which (1) characteristics of the input can be displayed, (2) field data can be added, (3) characteristics of projects can be updated and/or other projects can be created or selected, and (4) the project selection can be undone (return to the default mode).

2.19.5 Updating project characteristics

The selected files, planting date, simulation period and program parameters for running a project, are displayed and can be updated in the various tabular sheets of the ***Project characteristics*** menu, (Fig. 2.19e).

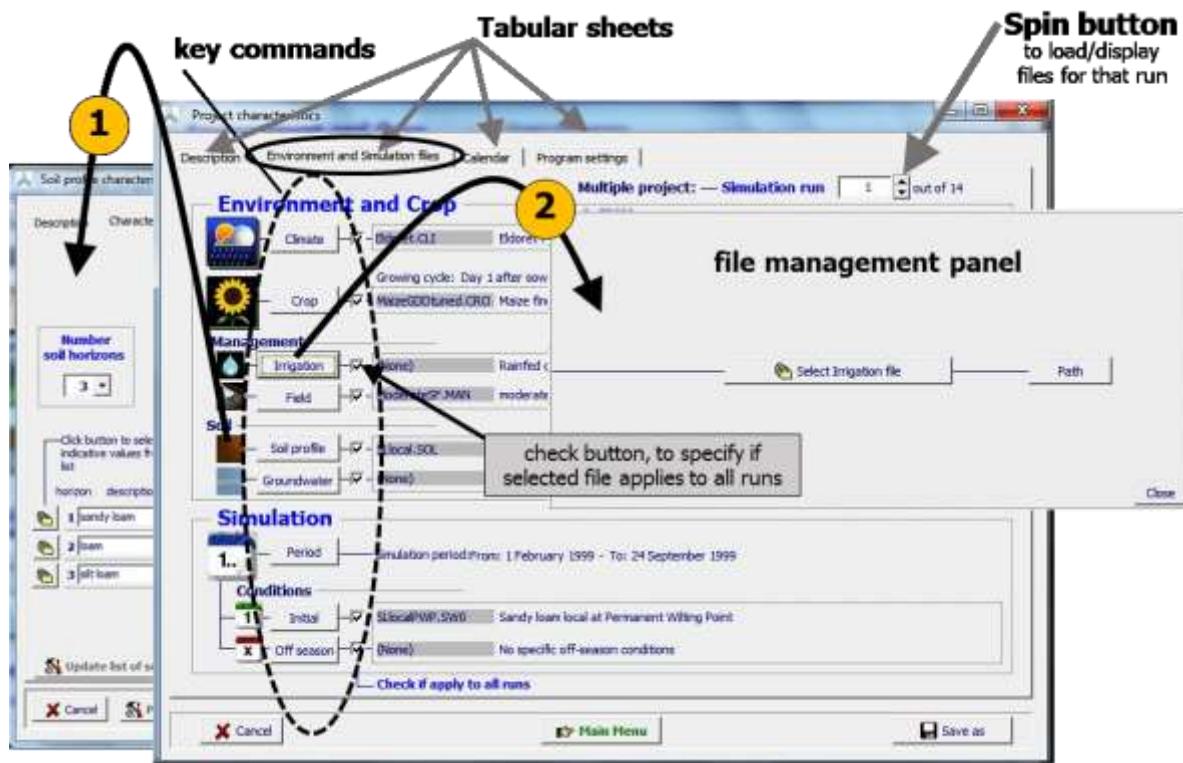


Figure 2.19e – The *Project characteristics* menu with its tabular sheets: ‘Description’, ‘Environment and Simulation files’ (displayed), ‘Calendar’, and ‘Program settings’. In the ‘Environment and Simulation files’ tabular sheets (1) characteristics of the selected input can be displayed, and (2) other input files can be selected in the appropriate file management panels

Tabular sheets:

- **Description:** to adjust the description of the project file;
 - **Environment and simulation files:** In case of multiple run projects, select the run number, since the planting date, simulation period and set of files might differ between the runs:
 - to display the characteristics of the input;
 - to select other crop file(s), irrigation file(s), field management file(s), another soil profile file, groundwater file(s), file(s) with initial conditions, and file(s) with off-season conditions in the corresponding file management panels.
- With the exception of the climate file, the soil profile file and the crop file (if successive years are considered), the files need not to be common between the

- simulation runs of a multiple runs project. Use the corresponding check buttons if the selected files apply to all runs of a multiple runs project;
- to alter the start of the growing cycle;
 - to alter the start and the end of the simulation period;
 - **Calendar**: to display the period of the growing cycle and simulation period;
 - **Program settings**: to alter the settings of program parameters.

Projects can also be updated by making the changes directly in the project file (Box 2.19). This is an advanced way, that gives the user more flexibility than via the software interface.

Box 2.19 – Advanced way of updating project files with more flexibilities

By respecting the structure of the project file (Table 2.19a), the user can alter its content by making the required changes directly in the text file. This is useful for making a quick adjustment in multiple runs projects, or to build other types of multiple runs projects than the two available through the interface (successive years and crop rotation). By doing so, one is no longer restricted by current limitations of the interface. For example, by copying/pasting one can design very fast multiple runs projects, with runs that only differ in soil type or field management, while all other input (included climate) remains identically.

2.19.6 Running successive simulations within the growing cycle with the help of projects

Actual shortcoming: - When creating single projects in AquaCrop, (i) the first day of the simulation period cannot be taken later than the sowing/planting plant, and (ii) the end of the simulation period is automatically taken as the last day of the growing cycle (crop maturity). This still needs to be adjusted, but as long as this is not yet done the procedure is somewhat cumbersome and not straightforward.

Step 1. – Create as much single projects as planned simulations within the growing cycle.

It consists in selecting a crop file with a planting date and in specifying the environment. The description of the environment consists in selecting an appropriate Climate file, Irrigation management file, Field management file, Soil profile file, Groundwater file, and/or Initial conditions file. To fulfil the conditions for a hot start between the successive simulation runs, the crop file, the planting date, the soil profile and groundwater file in all projects should be identical.

In the project which will be used for the first of a series of successive simulation runs, the simulation starts at the day for which the conditions specified in the ***Initial conditions*** menu are valid. The last day of the simulation period is automatically crop maturity.

For the second, third, ... project, keep at this stage the same settings for the simulation period as for the first run, but select the appropriate climate files, irrigation management files, and/or field management files (which may be different from the files specified in the first project). These files describe the specific environment (valid from their starting day, which still need to be adjusted in Step 2) during their part of the simulation.

Step 2. – Update in each of the created projects, the (i) first and (ii) last day of the simulation period (Fig. 2.19f and 2.19g). The first day follows the last day of the previous run, and the last day is the day before the first day of the next run of the series of successive runs within the growing cycle.

An alternative for step 2 consists in adjusting the first and last day of the simulation period directly in the project files (Tab. 2.19a). Note that AquaCrop uses day numbers to specify the start and end of the simulation period and of the growing cycle. The day number refers to the days elapsed since 0th January 1901 at 0 am. The calculation procedure is given in Table 2.19b and the code in Table 2.19c.

Step 3. – Run the projects one after the other. Since the first day of the next run neatly follows the last day of the previous runs, a ‘hot start’ is recognized and applied as long as the successive runs of the series remain within the same growing cycle.

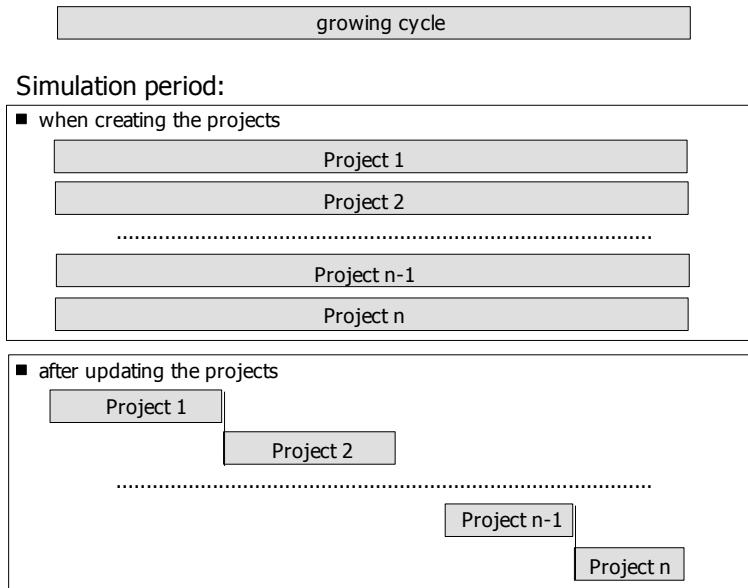


Figure 2.19f – Specification of the first and last day of the simulation period in a series of successive simulation runs within the growing cycle

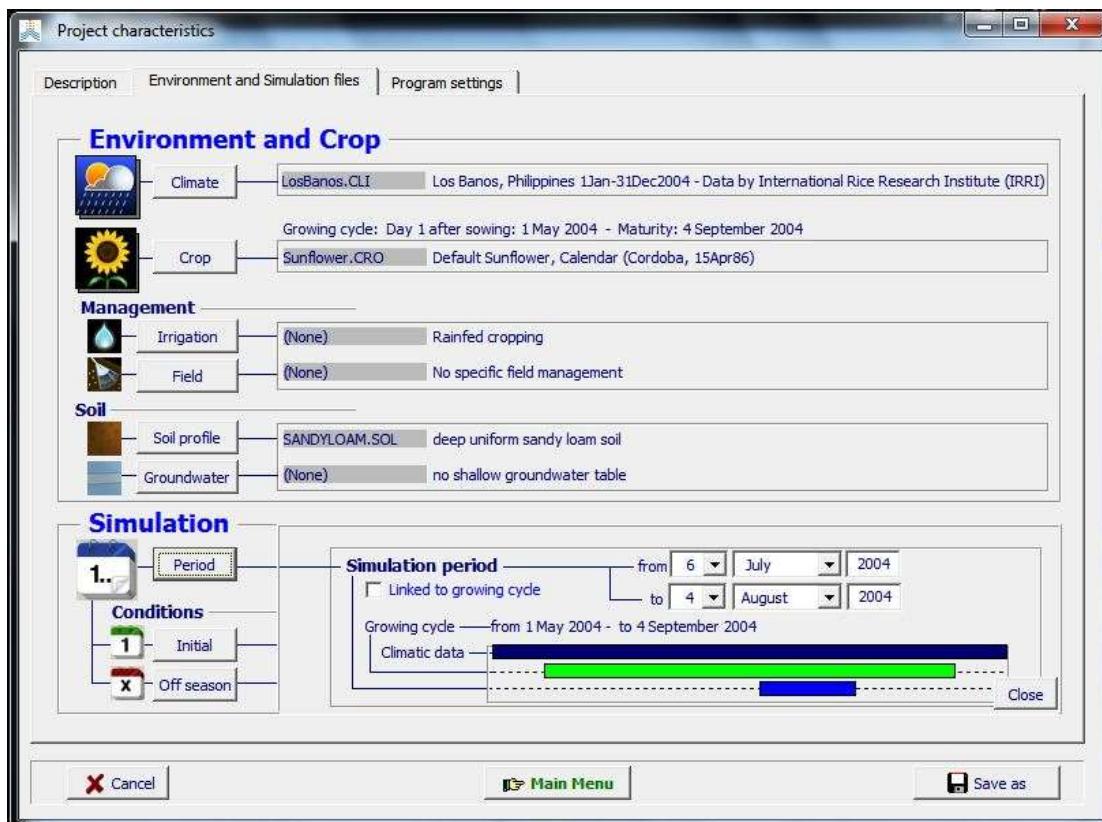


Figure 2.19g – Update of the first and last day of the simulation period of a project, in the *Project characteristics* menu

2.20 Field data

2.20.1 Creating field data files

A file containing observed field data can be created by selecting the <Create Field data file> command in the *Select field data file* menu (Fig. 2.20a).

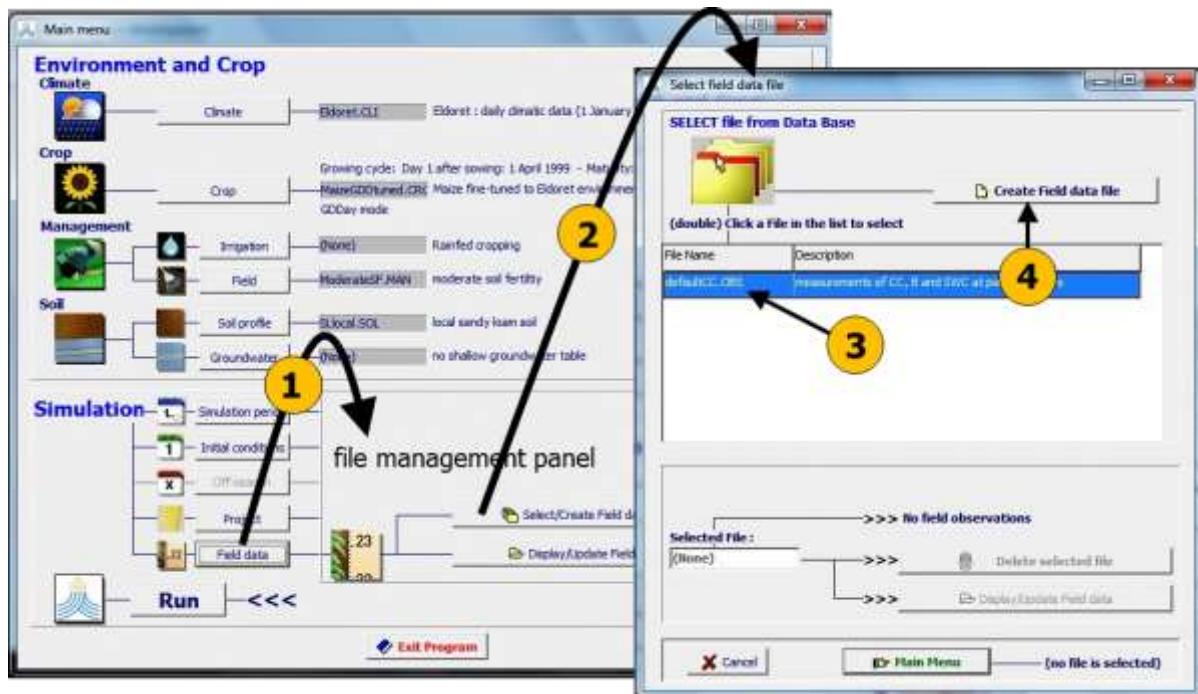


Figure 2.20a – By selecting (1) the <Field data> command and subsequently (2) the <Select/Create Field data file> command in the file management panel of the *Main menu*, the user gets access to the *Select field data file* menu, in which (3) one of the available field data files or (4) the command to <Create Field data file> can be selected

2.20.2 Field data characteristics

The field data are displayed and can be updated in the various tabular sheets of the **Field data menu** (Fig. 2.20b):

- **Description:** to adjust the description of the file containing the field data;
- **Field data:** to adjust the observed green Canopy cover (CC), dry above-ground Biomass (B) and soil water content (SWC) at particular days:
 - the time of the observations are expressed as day numbers with reference to a specified first day whether or not linked to a specific year;
 - field data can cover several years;
 - a mean value together with its standard deviation can be specified, if several observations were made during the sampling at a specific day;
 - green Canopy cover (CC) is expressed as a percentage;
 - dry above-ground Biomass (B) is expressed in ton/ha;
 - soil water contents (SWC) are expressed as totals (mm of water) for a well specified depth (e.g. maximum root zone): see inset within Fig. 2.20b.

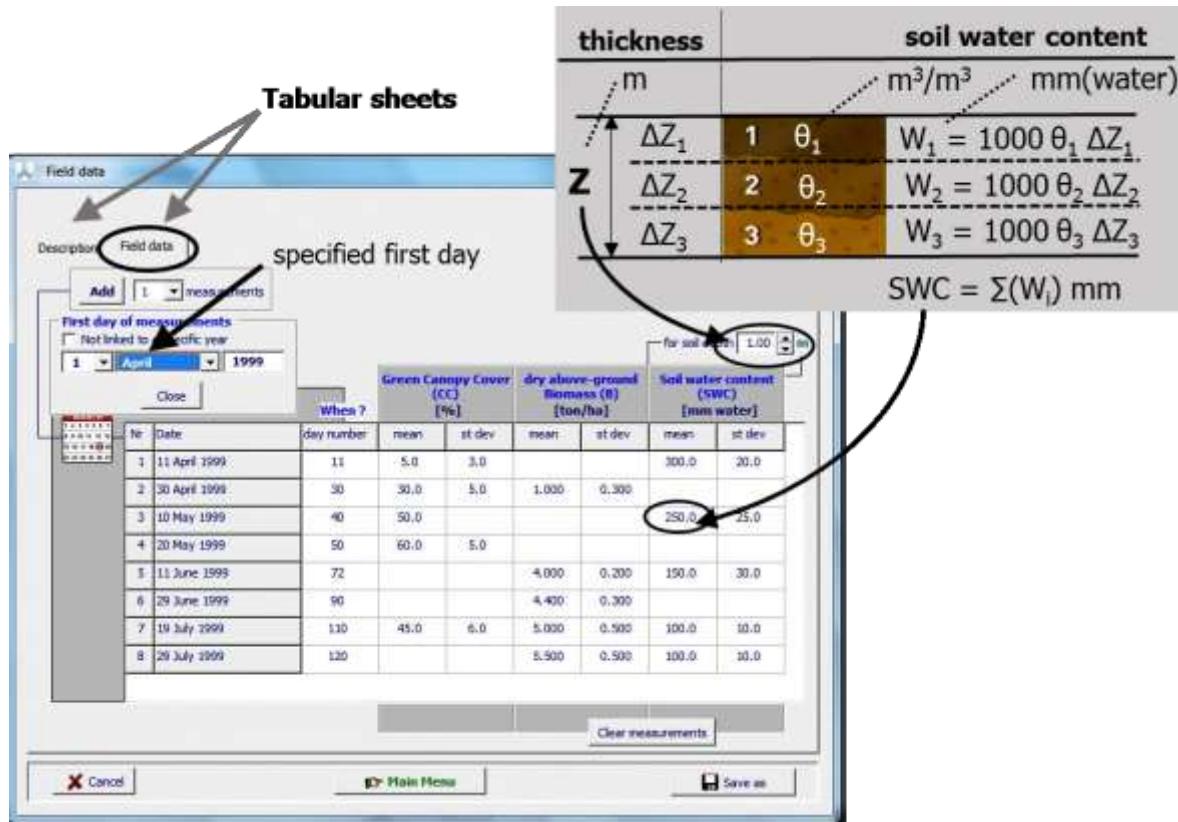


Figure 2.20b – The *Field data* menu with its tabular sheets ‘Description’ and ‘Field data’ (displayed) in which the first day of observations and field data (green canopy cover, dry above-ground biomass and/or soil water contents) at particular days are specified

2.21 Simulation run

2.21.1 Launching the simulation

By selecting the <Run> command in the *Main menu*, the user gets access to the *Simulation run* menu, in which the simulation can be launched (Fig. 2.21a). By selecting one of the options, the simulation will advance:

- to the end of the simulation period. In case of multiple runs projects, the simulation advances to the end of the simulation period of the specified run number;
- by the specified number of days; or
- to a specified date.

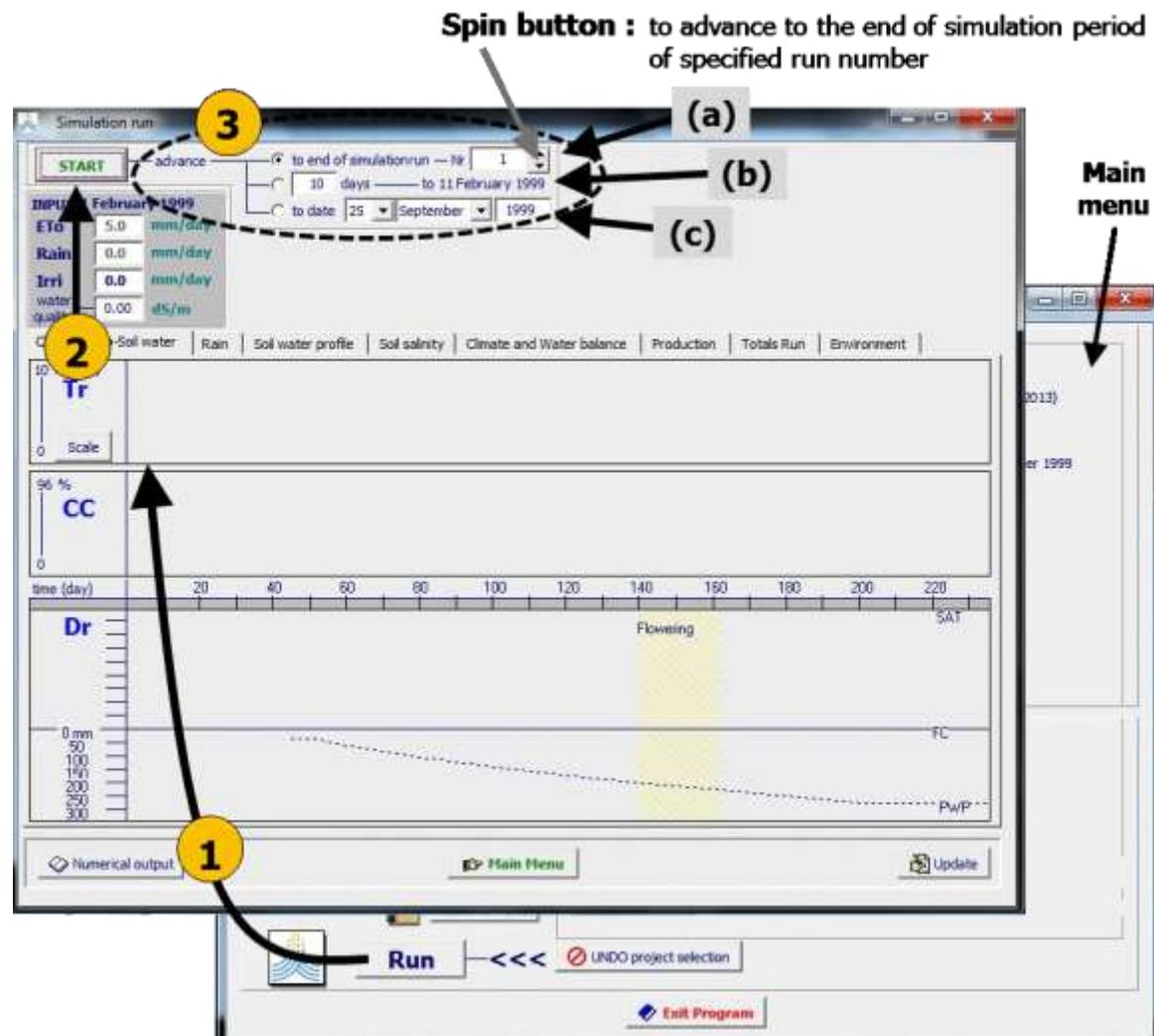


Figure 2.21a – By selecting (1) the <Run> command in the *Main menu*, the user gets access to the *Simulation run* menu, in which (2) the simulation can be started. Depending on (3) the selected advance option the simulation will (a) run to the end of the simulation period, (b) advance by a specified number of days, or (c) run to a specified date

2.21.2 Display of simulation results

Simulation results, which are updated at the end of each daily time step, are available in the **Simulation run** menu (Fig. 2.21b). The results are valid for the displayed output date (day to which the simulation is advanced). It consists of the total biomass and crop yield produced at that day, stress levels occurring on that day, and averages of stresses over the growing cycle till that day. Additionally a lot of data and graphs are available in a series of tabular sheets, through which the user can follow the effects of water, temperature, fertility, salinity and weed stress on crop development and production during the simulation run. The capacity of simulating in short time steps and switching between several folders is particularly useful if one wants to study the effect of a particular event on a specific parameter.

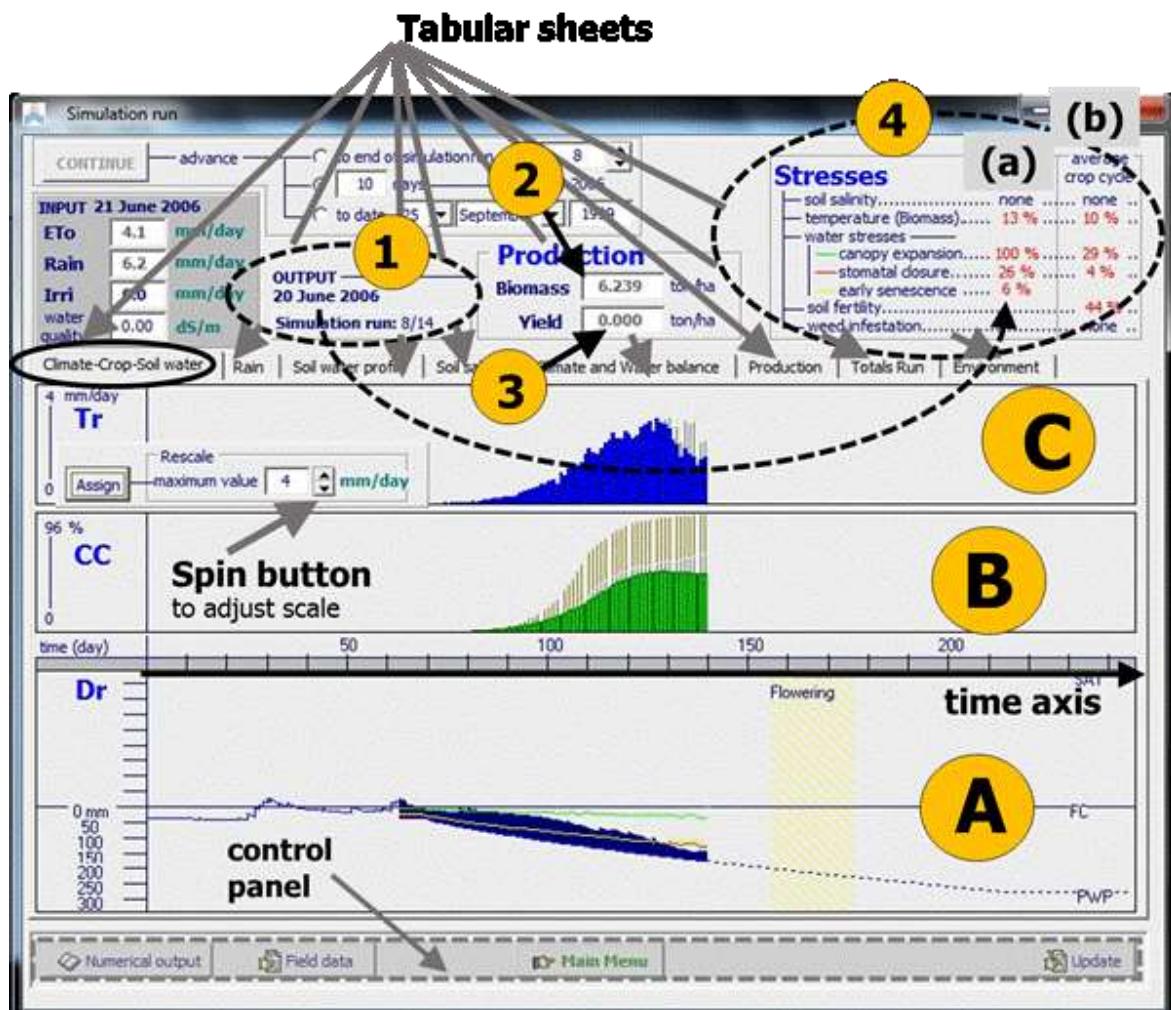


Figure 2.21b – Display of simulation results in the **Simulation run** menu (1) for the day to which the simulation has advanced. Total (2) biomass and (3) crop yield produced so far at the end of that day, (4) stress levels occurring (a) on that day and (b) averages of stresses over the growing cycle till that day, are displayed. In the tabular sheet of 'Climate-Crop-Soil water' the (A) root zone depletion, (B) green canopy development, and (C) crop transpiration is plotted in different panels

- **Tabular sheet: ‘Climate-Crop-Soil water’**

The ‘Climate-Crop-Soil water’ tabular sheet contains graphs with plots of (A) the soil water depletion of the root zone (Dr), (B) the corresponding development of the green canopy cover (CC), and (C) the transpiration (Tr), plotted as functions of time (Fig. 2.21b).

If the water content in the root zone drops below the threshold (green line) canopy expansion is affected. This will result in a slower canopy development than expected. In the canopy cover graph (CC) the canopy cover without water stress is plotted in light gray in the back portion of the figure as a reference.

More severe water stress will result in stomata closure (red line), resulting in reduced crop transpiration. In the transpiration graph (Tr), the maximum crop transpiration that can be reached when the crop is well watered is plotted in light gray in the back as a reference.

Severe water stress might even trigger early canopy senescence when the root zone depletion exceeds the threshold for senescence (yellow line).

- **Tabular sheet: with a selected parameter**

In the second sheet of the *Simulation run* menu, the user can select a particular parameter (default is ‘Rain’) for further analysis (Tab. 2.21a). Several crop parameters and parameters of the soil water and soil salinity balance, as well as simulated stresses can be selected and the scale for the plot can be adjusted (Fig. 2.21c)

Table 2.21a – Parameters and variables of the soil water balance, crop, soil salinity and stresses that can be selected for display in the Simulation run menu

| Symbol | Description | Units |
|---------------------------|---------------------------------|-------|
| Soil water balance | | |
| CR | Capillary rise | mm |
| Sum(Cr) | Capillary rise (cumulative) | mm |
| Drain | Deep percolation | mm |
| Sum(Drain) | Deep percolation (cumulative) | mm |
| Zgwt | Depth groundwater table | m |
| ET | Evapotranspiration | mm |
| Sum(ET) | Evapotranspiration (cumulative) | mm |
| ETx | Evapotranspiration (maximum) | mm |
| ET/ETx | Evapotranspiration (relative) | % |
| Inf | Infiltrated water | mm |
| Sum(Inf) | Infiltrated water (cumulative) | mm |
| Irri | Irrigation | mm |
| Sum(Irri) | Irrigation (cumulative) | mm |
| Rain | Rainfall | mm |
| Sum(Rain) | Rainfall (cumulative) | mm |
| Evap | Soil evaporation | mm |
| Sum(E) | Soil evaporation (cumulative) | mm |
| Ex | Soil evaporation (maximum) | mm |

| | | |
|-----------------------|--|------------------|
| E/Ex | Soil evaporation (relative) | % |
| Runoff | Surface runoff | mm |
| Sum(RO) | Surface runoff (cumulative) | mm |
| Crop variables | | |
| Biomass | Biomass produced (cumulative) | ton/ha |
| B(rel) | Biomass produced (relative) | % |
| Sum(Tr) | Transpiration (cumulative) | mm |
| Tr/Trx | Transpiration (relative) | % |
| GDD | Growing degrees | °C-day |
| HI | Harvest Index (HI) | % |
| Z | Rooting depth (effective) | m |
| WP | Water Productivity (WP) | g/m ² |
| Yield | Yield | ton/ha |
| Soil salinity | | |
| SaltIn | Salt infiltrated in the profile | ton/ha |
| Sum(Sin) | Salt infiltrated in the profile (cumulative) | ton/ha |
| SaltOut | Salt drained out of the profile | ton/ha |
| Sum(Sout) | Salt drained out of the profile (cumulative) | ton/ha |
| SaltUp | Salt moved upward from groundwater table | ton/ha |
| Sum(Sup) | Salt moved upward (cumulative) | ton/ha |
| SaltTot | Salt stored in the profile | ton/ha |
| SaltZ | Salt stored in the root zone | ton/ha |
| ECe | EC of saturated soil-paste extract from root zone | dS/m |
| ECsw | EC of soil water in root zone | dS/m |
| ECgw | EC of groundwater table | dS/m |
| Stresses | | |
| StExp | Water stress reducing canopy expansion | % |
| StSto | Water stress inducing stomatal closure | % |
| StSen | Water stress triggering early canopy senescence | % |
| StTr | Cold stress affecting crop transpiration | % |
| StSalt | Salinity stress affecting development and production | % |
| StWeed | Weed infestation (relative cover of weeds) | % |

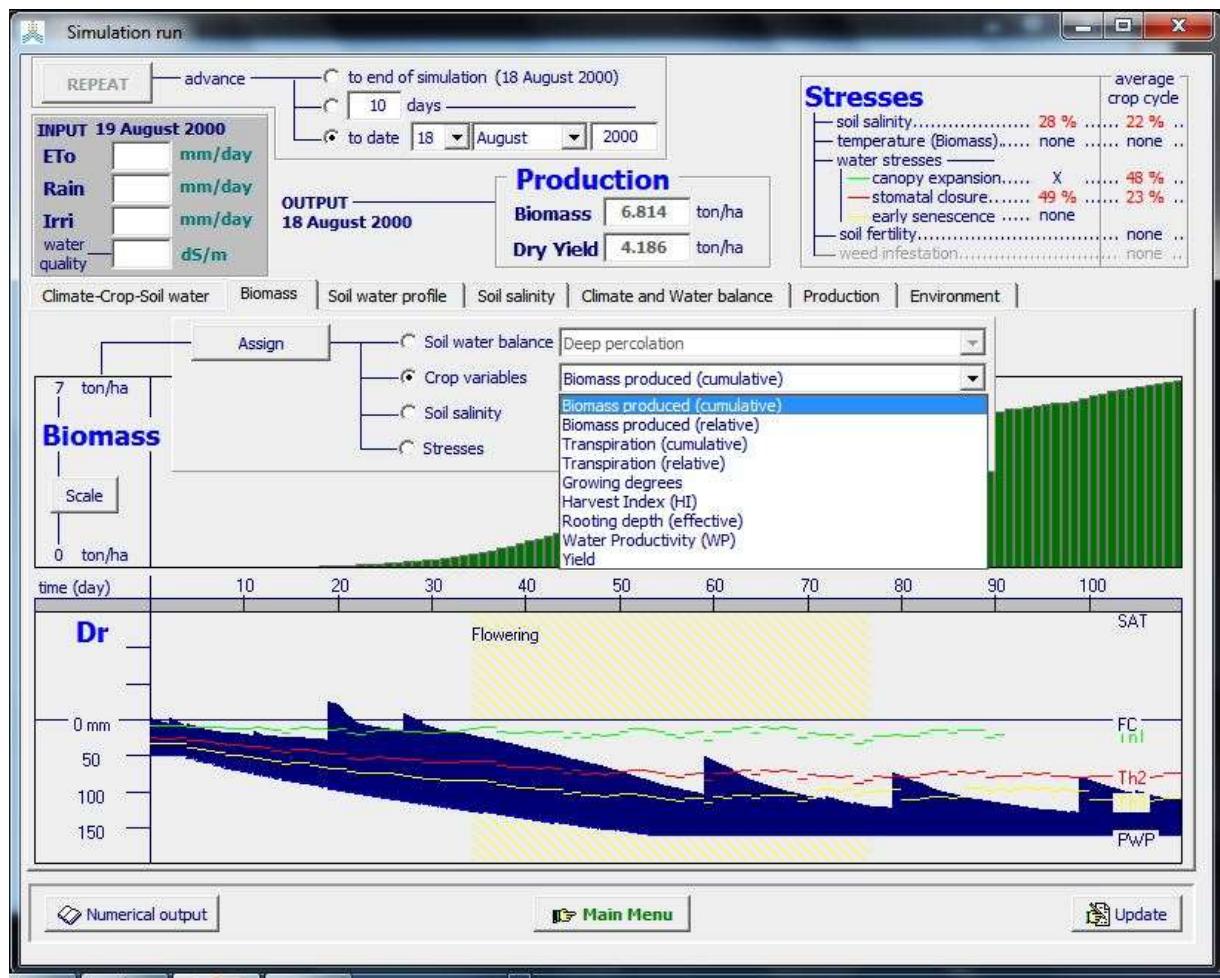


Figure 2.21c - Selection of a parameter for display in the *Simulation run* menu

- **Tabular sheet: ‘Soil water profile’**

In the soil water profile sheet of the ***Simulation run*** menu, the simulated water content in the various compartments of the soil profile is adjusted for every day of the simulation period. Lines plotting the corresponding soil water content at Field Capacity (FC), adjusted FC in the presence of a water table, at Permanent Wilting Point, at a specific percentage of TAW, or at the (upper) thresholds for deficient aeration conditions, canopy expansion, stomatal closure, and early senescence can be selected (Fig.2.21d).

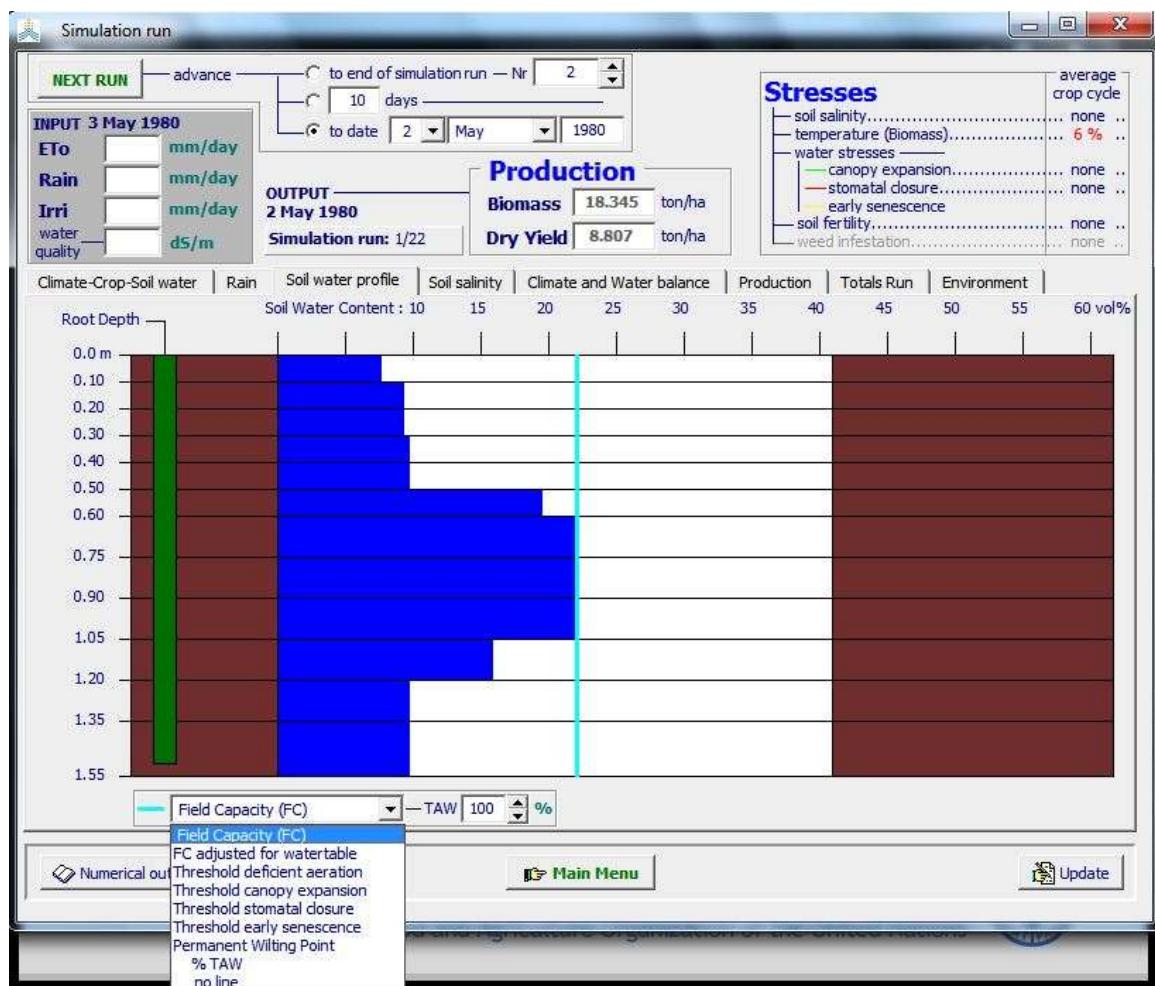


Figure 2.21d - Selection of a specific soil water content for display in the tabular sheet ‘Soil water profile’ of the *Simulation run* menu

- **Tabular sheet: ‘Soil salinity’**

In the soil salinity sheet of the ***Simulation run*** menu, the simulated soil salinity profile and the parameters of the salt balance in the soil profile and root zone are adjusted for every day of the simulation period (Fig. 2.21e).

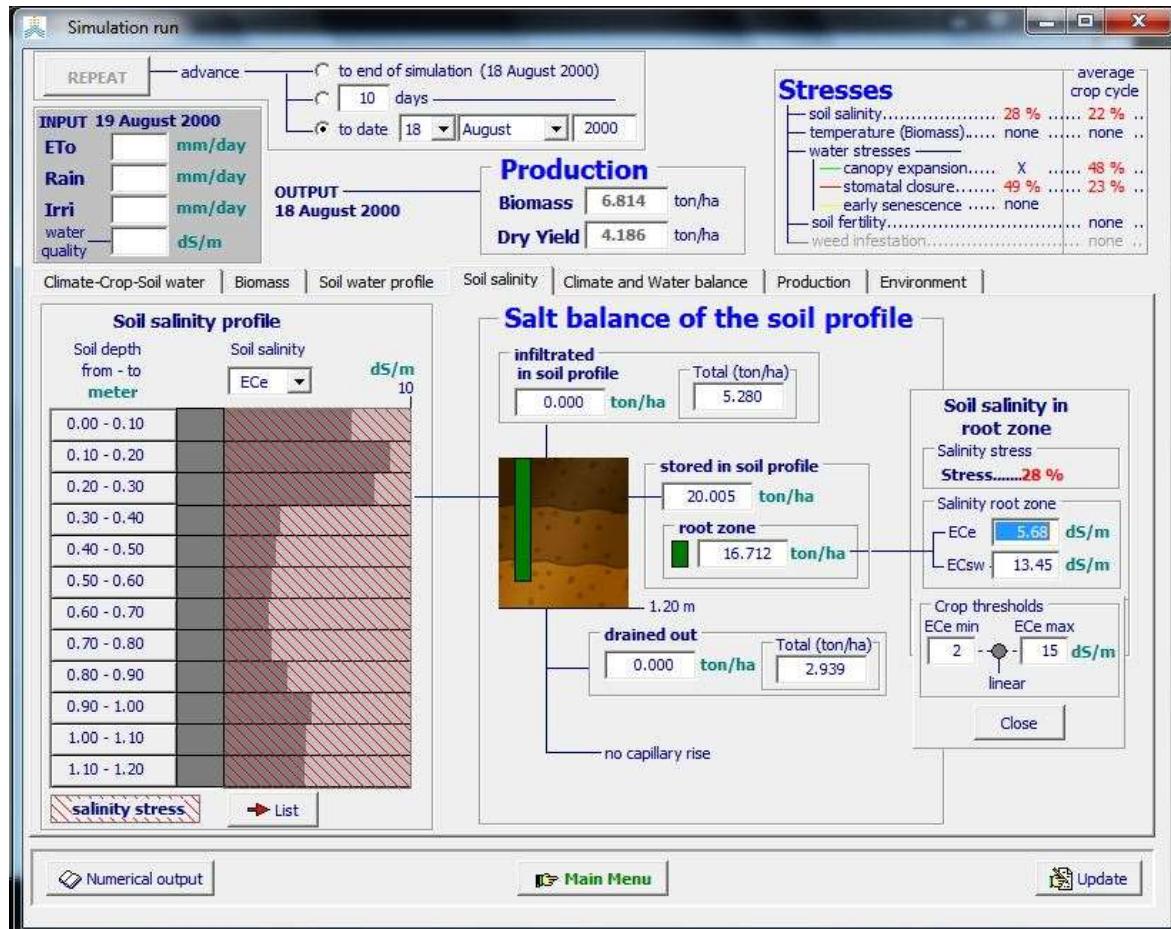


Figure 2.21e – Display of the soil salinity profile and the salt balance in the tabular sheet ‘Soil salinity’ of the *Simulation run* menu

- **Tabular sheet: ‘Climate and Water balance’**

In the Climate and Water balance sheet of the *Simulation run* menu, values are given for soil evaporation, crop transpiration, surface runoff, infiltrated water, drainage, and capillary rise. By selecting the <Irrigation events> command the irrigation events are displayed in the *Irrigation Events* menu (Fig. 2.21f).

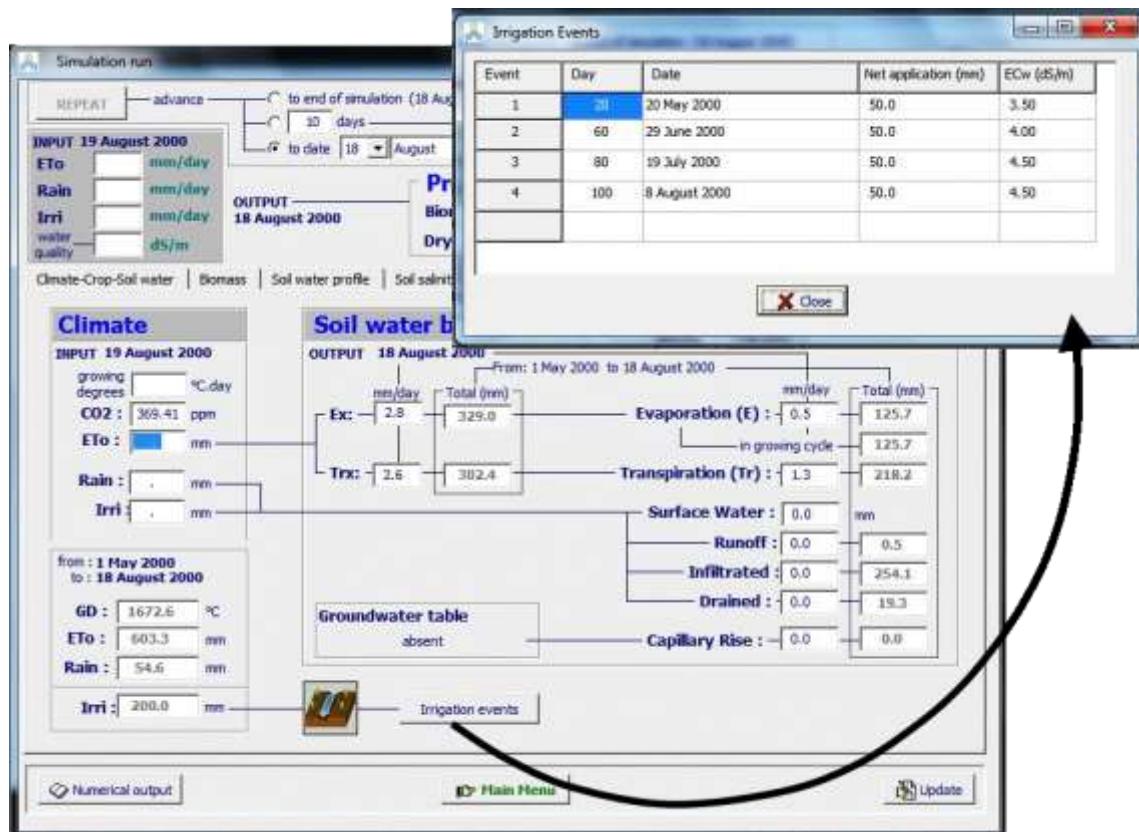


Figure 2.21f – Display of the parameters of the climate and soil water balance in the tabular sheet: ‘Climate and Water balance’ of the *Simulation run* menu and the irrigation events in the *Irrigation Events* menu

- **Tabular sheet: ‘Production’**

In the Production sheet of the ***Simulation run*** menu, information is given on the ante and post-anthesis impact of water stress on the adjustment of HI (Fig 2.21g). The simulated amount of biomass produced and the biomass that could have been produced in the absence of water, soil fertility and salinity stress are displayed as well. Information is also given on the ET water productivity (yield per unit of evapotranspired water):

$$WUE = \frac{\text{yield produced}}{\text{water evapotranspired}}$$

$$WP_{ET} = \frac{\text{kg (yield)}}{\text{m}^3 (\text{ET})}$$

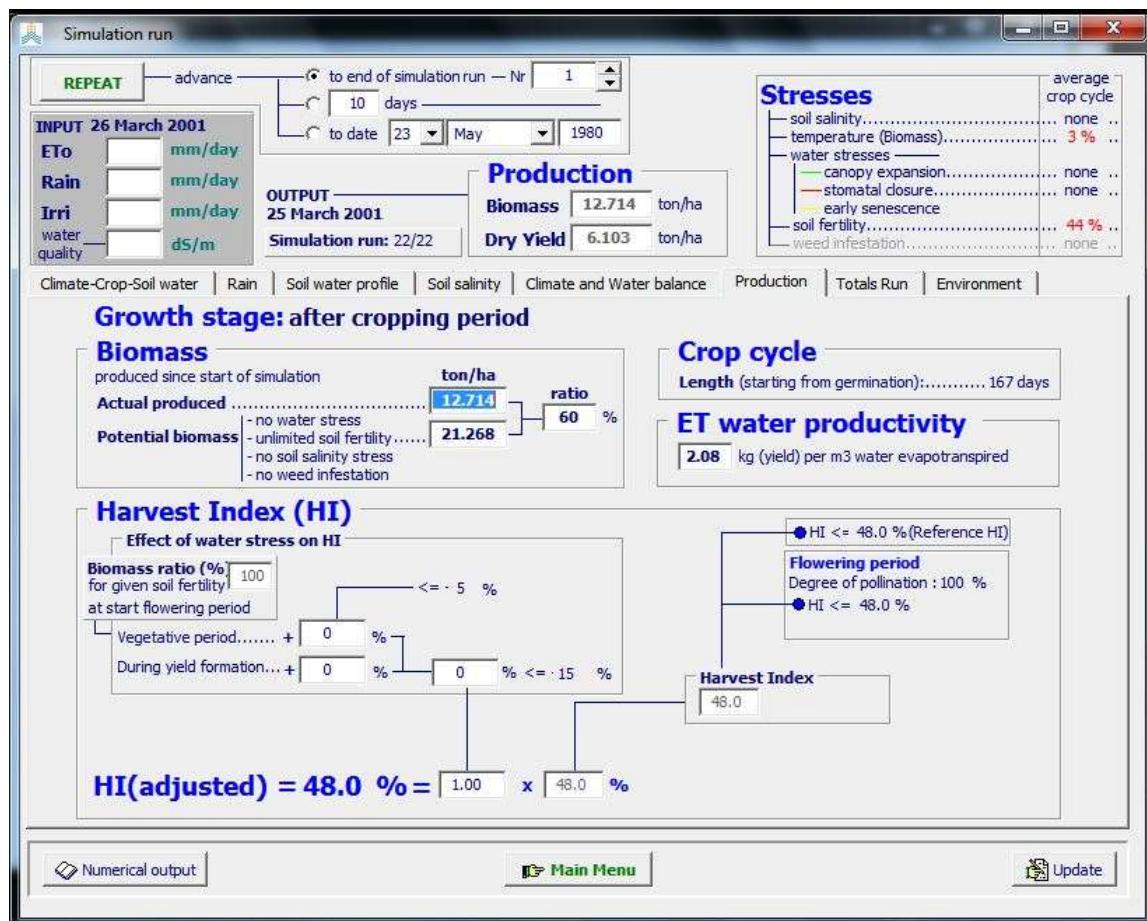


Figure 2.21g – Information on biomass production, ET water productivity, and the ante and post-anthesis impact of water stress on the adjustment of HI in the tabular sheet ‘Production’ of the *Simulation run* menu

- **Tabular sheet: ‘Totals Run’**

In the Totals Run sheet of the ***Simulation run*** menu, information is given on totals of a selected number of parameters (Tab. 2.21b) at the end of each simulation run (Fig. 2.21h).

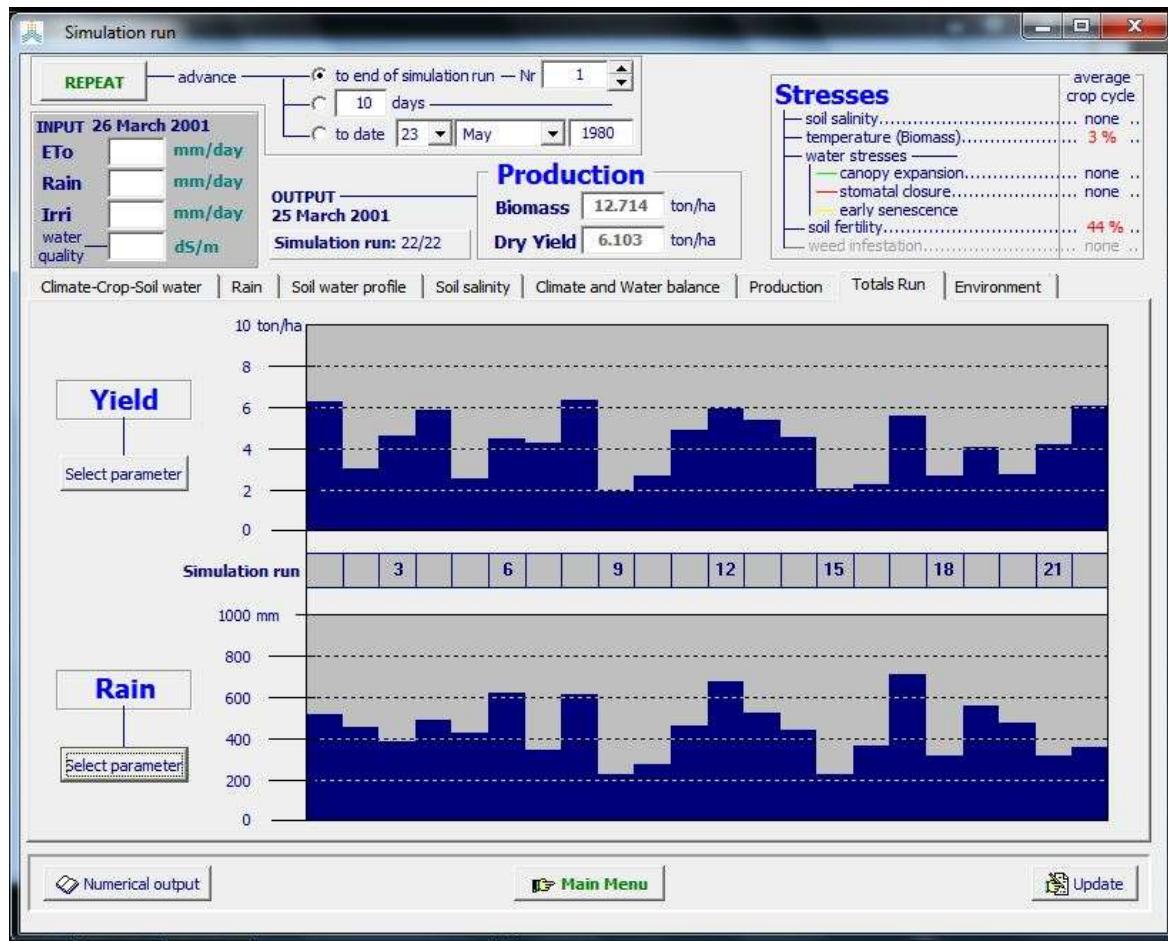


Figure 2.21h – Information on the simulated yield and total rainfall (during the simulation period) for the successive years of a multiple run project in the tabular sheet ‘Totals Run’ of the *Simulation run* menu

Table 2.21b – Parameters that can be selected for display in the tabular sheet ‘Totals Run’ of the *Simulation run* menu

| Symbol | Description | Units |
|---------------|--|-------------------|
| Rain | Rainfall | mm |
| ETo | ETo | mm |
| GD | GD | °C |
| CO2 | CO2 | ppm |
| Irri | Irrigation | mm |
| Inf | Infiltrated water | mm |
| RO | Runoff | mm |
| Drain | Deep percolation | mm |
| CR | Capillary rise | mm |
| Evap | Soil evaporation | mm |
| E/Ex | Soil evaporation (relative) | % |
| Tr | Total transpiration | mm |
| Trw | Crop transpiration | mm |
| Tr/Trx | Transpiration (relative) | % |
| SaltIN | Salt infiltrated in the soil profile | ton/ha |
| SaltOUT | Salt drained out of the soil profile | ton/ha |
| SaltUP | Salt moved upward by capillary rise | ton/ha |
| SaltProf | Salt stored salt the soil profile | ton/ha |
| Cycle | Length of crop cycle | day |
| SaltStr | Average salinity stress | % |
| FertStr | Average soil fertility stress | % |
| WeedStr | Average relative cover of weeds | % |
| TempStr | Average temperature stress (transpiration) | % |
| ExpStr | Average leaf expansion stress | % |
| StStr | Average stomatal stress | % |
| Biomass | Biomass | ton/ha |
| Brelative | Relative Biomass (Ref: optimal conditions) | % |
| HI | Harvest Index | - |
| Yield | Yield | ton/ha |
| WP(ET) | ET water productivity (kg yield per m ³ ET) | kg/m ³ |

- **Tabular sheet: ‘Environment’**

In the Simulated environment sheet of the ***Simulation run*** menu, the selected input files for the simulation run are displayed and the program settings can be checked (Fig. 2.21i). By selecting one of the icons, the corresponding characteristics for that input can be displayed.

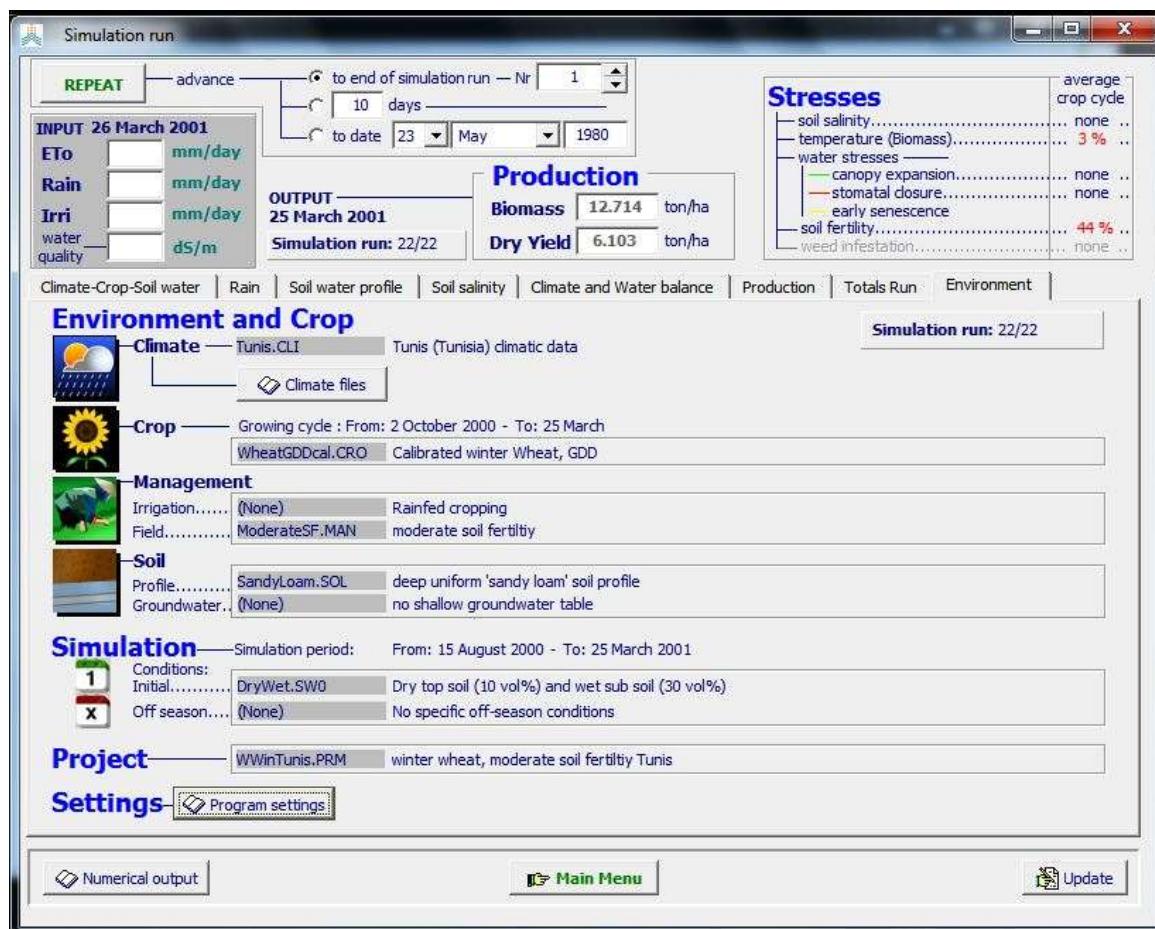


Figure 2.21i – Display of the selected input files in the tabular sheet ‘Environment’ of the *Simulation run* menu

2.21.3 Options in control panel

From the control panel at the bottom of the Simulation run menu, the user gets access to a series of other menus (Fig. 2.21j):

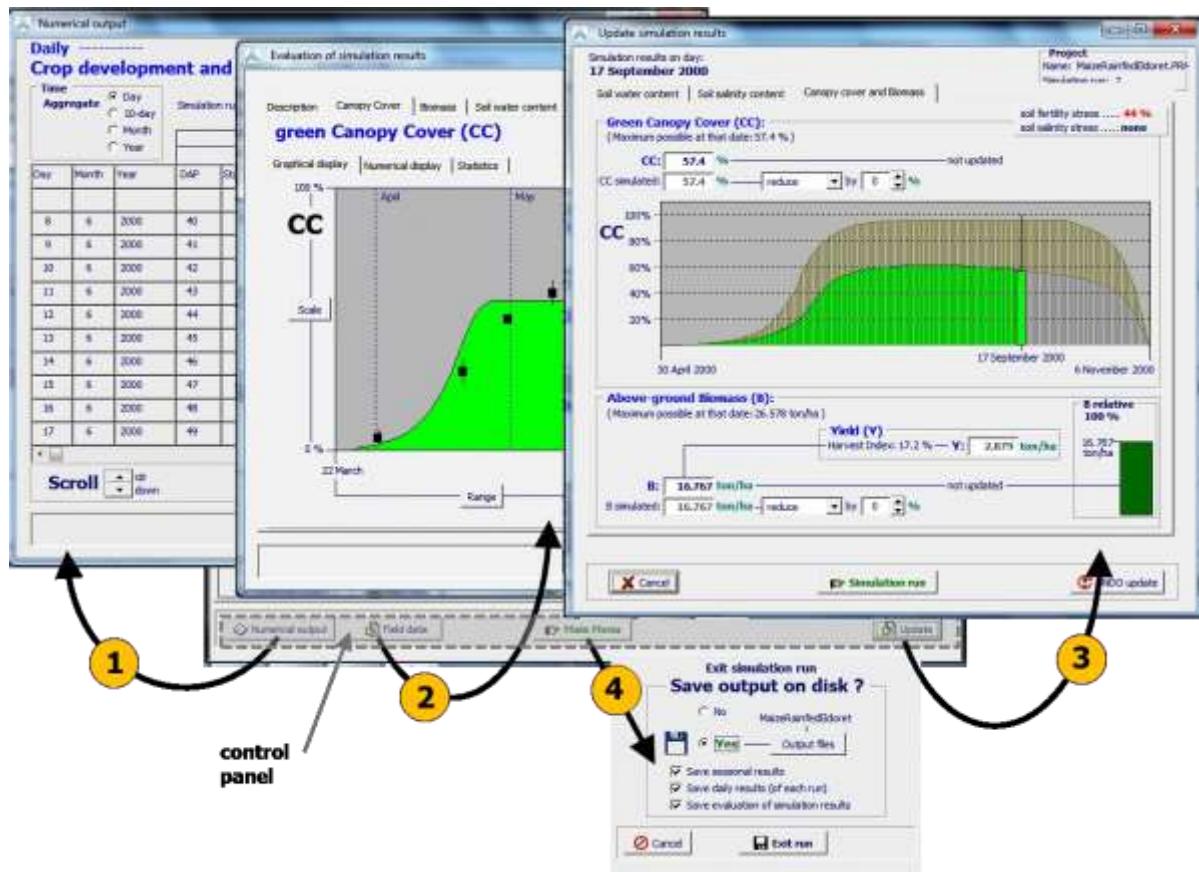


Figure 2.21j – By selecting the (1) <Numerical output>, (2) <Field data>, (3) <Update> or (4) <Main menu> command in the control panel at the bottom of the *Simulation run* menu, the user gets access to respectively the *Numerical output* menu, *Evaluation of simulation results* menu, *Update simulation results* menu and the *Exit* panel

The user can get access to:

- **Numerical output:** Simulation results are recorded in output files and the data can be displayed by selecting the <Numerical output> command;
- **Evaluation of the simulation results:** When running a simulation, users can evaluate the simulation results with the help of data stored in an field data file (see 2.20 ‘Field data’) by selecting the <Field data> command;
- **Update state variables while running a simulation:** When running a simulation, users can update some state variables by selecting the <Update> command;
- **Save simulation results in output files:** On exit of the *Simulation run* menu (select <Main menu> command), it is possible to save the output.

2.21.4 Numerical output

Simulation results are recorded in output files and the data can be displayed by selecting the <Numerical output> command in the *Simulation run* menu (Fig. 2.21j - 1). The data displayed in the *Numerical output* menu can be aggregated in 10-day, monthly or yearly data (Fig. 2.21k). See 2.25 ‘Output files’, for the list and contents of the various output files that can be displayed.

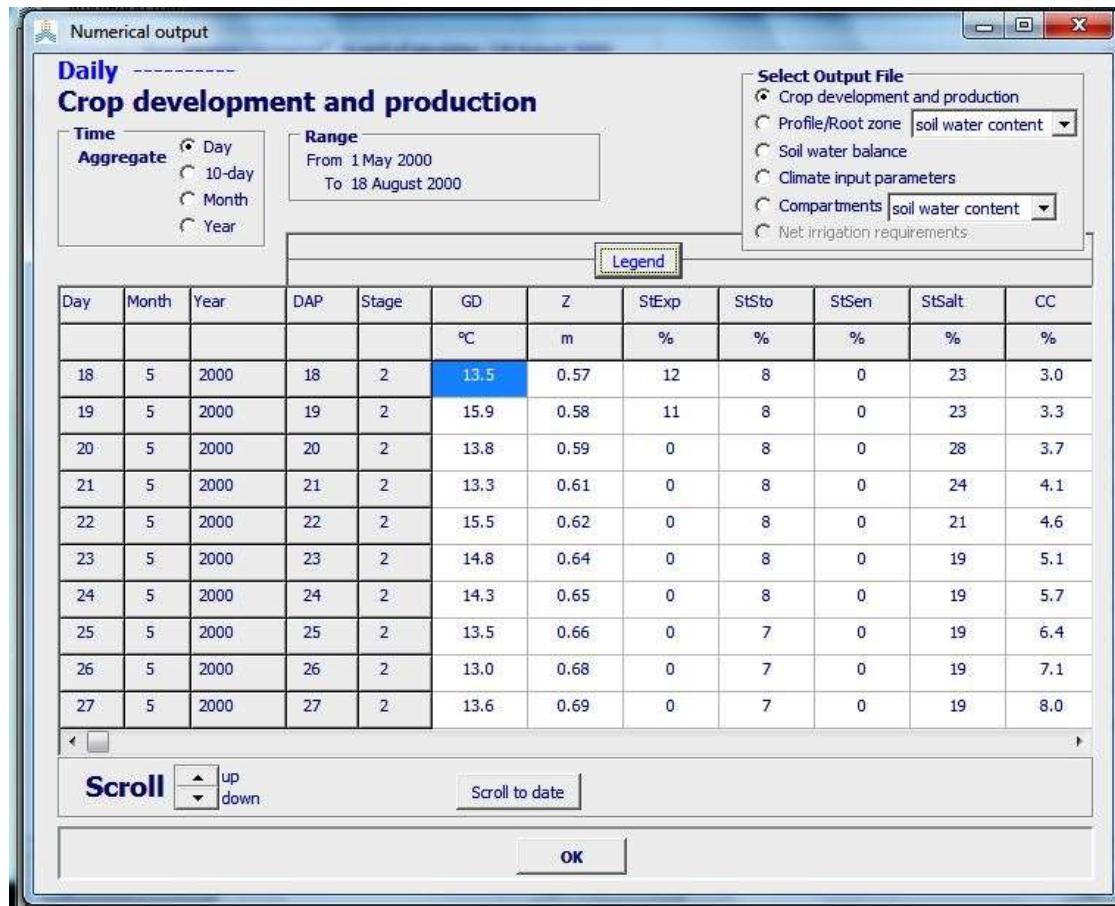


Figure 2.21k – Display of data recorded in output files

2.21.5 Evaluation of simulation results

When running a simulation, users can evaluate the simulation results with the help of data stored in an field data file (see 2.20 ‘Field data’). The user gets access to the ***Evaluation of simulation results*** menu by selecting the <Field data> command in the command panel of the ***Simulation run*** menu (Fig. 2.21j - 2).

▪ Graphical and numerical displays

For each of the 3 sets of field observations (Canopy Cover, Biomass and Soil water content) the user finds in the ***Evaluation of simulation results*** menu:

1. A graphical display where the simulated and observed (with their standard deviations) values are plotted (Fig. 2.21m);
2. A numerical display where the simulated and observed values (with their standard deviations) are displayed; and
3. Statistical indicators evaluating the simulation results (Fig. 2.21n).

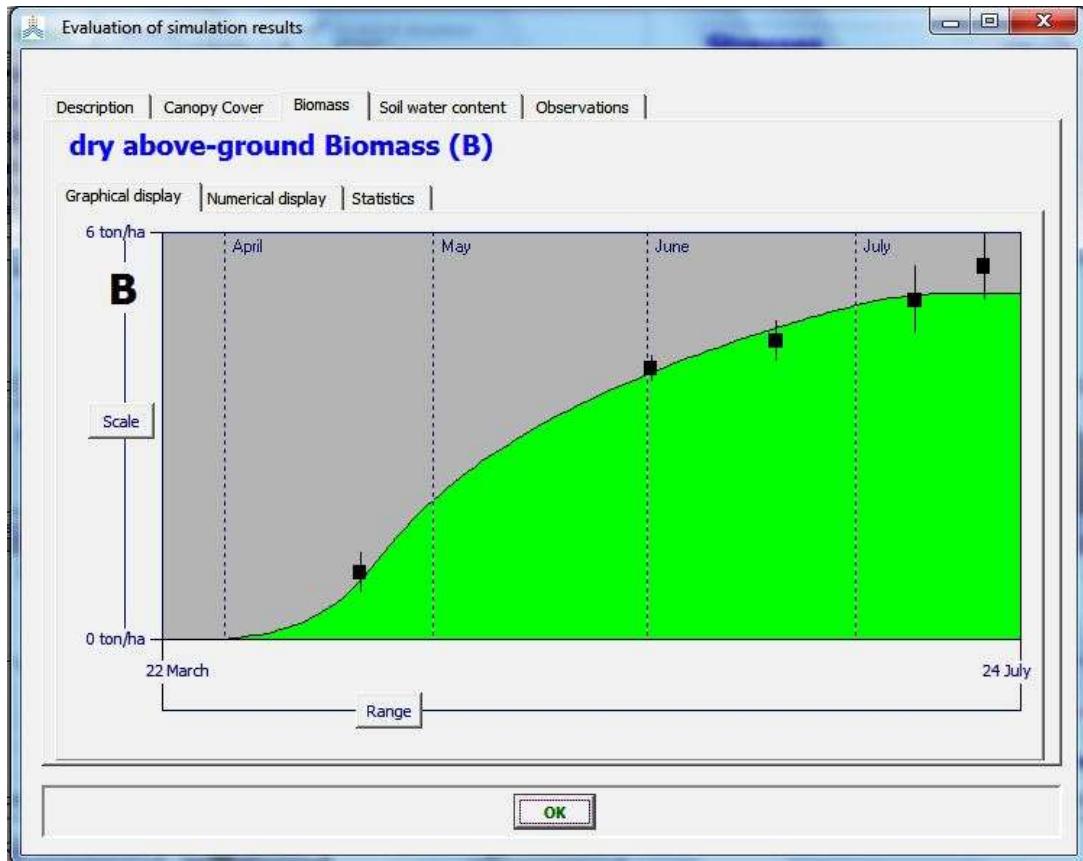


Figure 2.21m – Simulated (line) and observed (dots) dry above-ground Biomass with their standard deviations (vertical lines) in the tabular sheet ‘Biomass’ of the *Evaluation of simulation results* menu

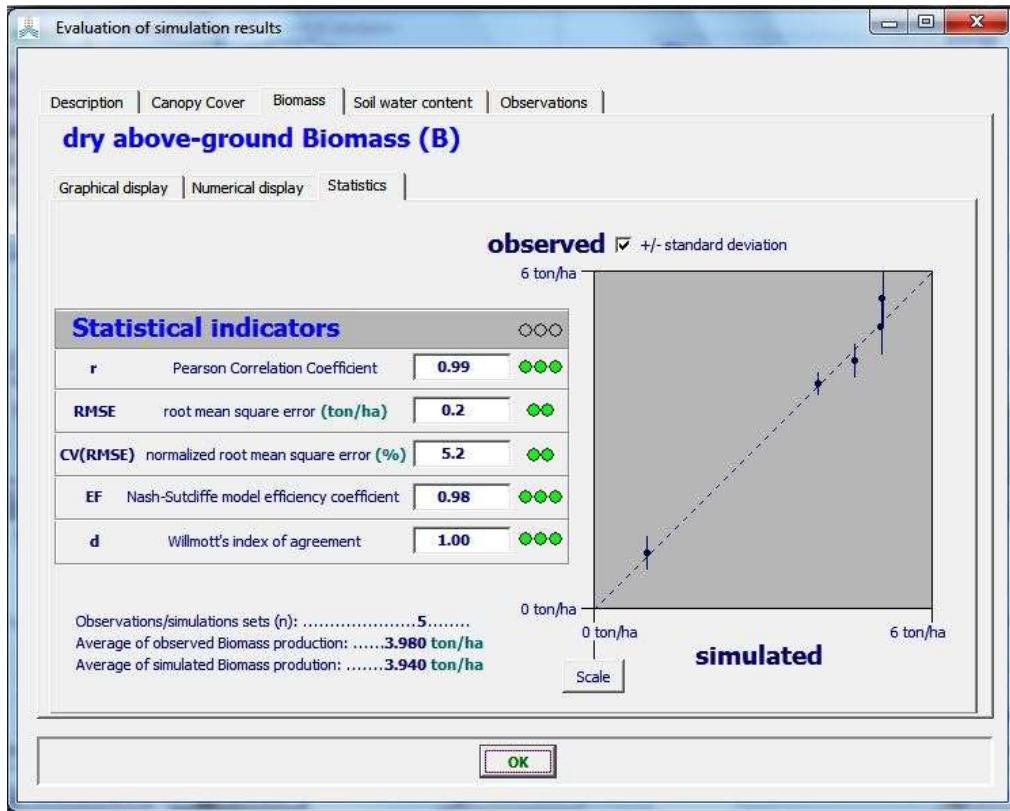


Figure 2.21n – Statistical indicators for the assessment of the simulated dry above-ground Biomass in the tabular sheet ‘Biomass’ of the *Evaluation of simulation results* menu

▪ Save results

On exit of the Simulation Run menu, the option is available to save the evaluation of the simulation results in 2 output files (see 2.21.7 ‘Output files’):

Data output file: which contain for each day of the simulation period the simulated green canopy cover (CC), biomass (B) and soil water content (SWC), and the observed field data (with their standard deviation);

Statistics output file: which contain the statics of the evaluation of the simulation results for Canopy Cover, biomass and soil water content.

▪ Statistical indicators

Evaluation of model performance is important to provide a quantitative estimate of the ability of the model to reproduce an observed variable, to evaluate the impact of calibrating model parameters and compare model results with previous reports (Krause et al., 2005). Several statistical indicators are available to evaluate the performance of a model (Loague and Green, 1991). Each has its own strengths and weaknesses, which means that the use of an ensemble of different indicators is necessary to sufficiently assess the performance of the model (Willmott, 1984; Legates and McCabe, 1999). In the equations 2.21a to 2.21e,

O_i and P_i are the observations and predictions respectively, \bar{O} and \bar{P} their averages and n the number of observations.

The statistical indicators available to assess the simulation results with field data are:

- Pearson correlation coefficient (r);
- Root mean square error (RMSE);
- Normalized root mean square error (CV(RMSE));
- Nash-Sutcliffe model efficiency coefficient (EF);
- Wilmott's index of agreement (d).

Pearson correlation coefficient (r)

The Pearson correlation coefficient ranges from -1 to 1, with values close to 1 indicating a good agreement:

$$= \left[\frac{\sum(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum(O_i - \bar{O})^2 \sum(P_i - \bar{P})^2}} \right] \quad (2.21a)$$

A major drawback of r and its squared value (r^2) is that only the dispersion is quantified, which means that a model which systematically overestimates (or underestimates) the observations can still have a good r^2 value (Krause et al., 2005). Willmott (1982) also stated that within the context of atmospheric sciences both r and r^2 are insufficient and often misleading when used to evaluate model performance. Analysis of the residual error (the difference between model predictions and observations: $P_i - O_i$) is judged to contain more appropriate and insightful information.

The correlation coefficient (r) ranges from -1 to 1, with values close to 1 indicating a good agreement. The following interpretation for r is used in AquaCrop. It is somewhat arbitrary and hence should be regarded as an indication.

| Value for r | Interpretation | Color code |
|---------------------------------|-----------------------|-------------------|
| ≥ 0.90 | Very good | ●●● |
| $0.80 - 0.89$ | Good | ●● |
| $0.70 - 0.79$ | Moderate good | ● |
| $0.50 - 0.69$ | Moderate poor | ● |
| $0 - 0.49$ | Poor | ●● |
| < 0 | Very poor | ●●● |

Root Mean Square Error (RMSE)

The root mean square error or RMSE is one of the most widely used statistical indicators (Jacovides and Kontoyiannis, 1995) and measures the average magnitude of the difference between predictions and observations. It ranges from 0 to positive infinity, with the former indicating good and the latter poor model performance. A big advantage of the RMSE is that it summarizes the mean difference in the units of P and O. It does however not differentiate between over- and underestimation.

$$RMSE = \sqrt{\frac{\sum(P_i - O_i)^2}{n}} \quad (2.21b)$$

A disadvantage of RMSE is the fact that the residual errors are calculated as squared values, which has the result that higher values in a time series are given a larger weight compared to lower values (Legates and McCabe, 1999) and that the RMSE is overly sensitive to extreme values or outliers (Moriasi et al., 2007). This is in fact a weakness of all statistical indicators where the residual variance is squared, including EF and Willmott's d which are discussed below.

Normalized Root Mean Square Error (CV(RMSE))

Because RMSE is expressed in the units of the studied variable, it does not allow model testing under a wide range of meteo-climatic conditions (Jakovides and Kontoyiannis, 1995). Therefore, RMSE can be normalized using the mean of the observed values (\bar{O}). The normalized RMSE (CV(RMSE)) is expressed as a percentage and gives an indication of the relative difference between model and observations.

$$CV(RMSE) = \frac{1}{\bar{O}} \sqrt{\frac{\sum (P_i - O_i)^2}{n}} \cdot 100 \quad (2.21c)$$

A simulation can be considered excellent if CV(RMSE) is smaller than 10%, good if between 10 and 20%, fair if between 20 and 30% and poor if larger than 30% (Jamieson, 1991).

The following interpretation for CV(RMSE) (and the corresponding RMSE) is used in AquaCrop. It is somewhat arbitrary and hence should be regarded as an indication.

| Value for NRMSE | Interpretation | Color code |
|-----------------|----------------|------------|
| $\leq 5\%$ | Very good | ●●● |
| 6 – 15% | Good | ●● |
| 16 – 25% | Moderate good | ● |
| 26 – 35% | Moderate poor | ● |
| 36 – 45% | Poor | ●● |
| > 46% | Very poor | ●●● |

Nash-Sutcliffe model efficiency coefficient (EF)

The Nash-Sutcliffe model efficiency coefficient (EF) determines the relative magnitude of the residual variance compared to the variance of the observations (Nash and Sutcliffe, 1970). Another way to look at it is to say that EF indicates how well the plot of observed versus simulated data fits the 1:1 line (Moriasi et al., 2007). EF can range from minus infinity to 1. An EF of 1 indicates a perfect match between the model and the observations, an EF of 0 means that the model predictions are as accurate as the average of the observed data and a negative EF occurs when the mean of the observations is a better prediction than the model.

$$EF = 1 - \frac{\sum (P_i - O_i)^2}{\sum (O_i - \bar{O})^2} \quad (2.21d)$$

EF is very commonly used, which means that there is a large number of reported values available in literature (Moriasi et al., 2007). However, like r^2 , EF is not very sensitive to systematic over- or underestimations by the model (Krause et al., 2005).

The Nash-Sutcliffe efficiency coefficient (EF) can range from minus infinity to 1. An EF of 1 indicates a perfect match between the model and the observations, an EF of 0 means that the model predictions are as accurate as the average of the observed data and a negative EF occurs when the mean of the observations is a better prediction than the model. The following interpretation for EF is used in AquaCrop. It is somewhat arbitrary and hence should be regarded as an indication.

| Value for EF | Interpretation | Color code |
|--------------|----------------|------------|
| ≥ 0.80 | Very good | ●●● |
| 0.60 – 0.79 | Good | ●● |
| 0.40 – 0.59 | Moderate good | ● |
| 0 – 0.39 | Moderate poor | ● |
| (-10) – 0 | Poor | ●● |
| < (-10) | Very poor | ●●● |

Willmott's index of agreement (d)

The index of agreement was proposed by Willmott (1982) to measure the degree to which the observed data are approached by the predicted data. It represents the ratio between the mean square error and the “potential error”, which is defined as the sum of the squared absolute values of the distances from the predicted values to the mean observed value and distances from the observed values to the mean observed value (Willmott, 1984). It overcomes the insensitivity of r^2 and EF to systematic over- or underestimations by the model (Legates and McCabe, 1999; Willmott, 1984). It ranges between 0 and 1, with 0 indicating no agreement and 1 indicating a perfect agreement between the predicted and observed data.

$$d = 1 - \frac{\sum (P_i - O_i)^2}{\sum (|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (2.21e)$$

A disadvantage of d is that relatively high values may be obtained (over 0.65) even when the model performs poorly, and that despite the intentions of Willmott (1982) d is still not very sensitive to systematic over- or underestimations (Krause et al., 2005).

The Willmott's index of agreement (d) ranges between 0 and 1, with 0 indicating no agreement and 1 indicating a perfect agreement between the predicted and observed data. The following interpretation for d is used in AquaCrop. It is somewhat arbitrary and hence should be regarded as an indication.

| Value for d | Interpretation | Color code |
|-------------|----------------|------------|
| ≥ 0.9 | Very good | ●●● |
| 0.80 – 0.89 | Good | ●● |
| 0.65 – 0.79 | Moderate good | ● |
| 0.50 – 0.64 | Moderate poor | ● |
| 0.25 – 0.49 | Poor | ●● |
| < 0.25 | Very poor | ●●● |

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2.21.6 Updating results when running a simulation

▪ Need for an update of simulation results

AquaCrop does not simulate:

- pests, diseases, frost, hail, ... destroying part of the green canopy cover (CC) and the above-ground biomass (B) during the season;
- subsurface horizontal water flow, moving water in or out of the soil profile (seepage). As a consequence CC, B and/or the soil water profile (θ -z) after such an event might be different from what is observed. Therefore AquaCrop offers the possibility to update CC, B and θ -z at the end of the event day by considering observations or estimates made on that day. After the update, AquaCrop resumes the simulation with the adjusted CC, B and/or θ -z.

Before such changes are made, the user should check if the mismatch between observations and simulation results is not the result of a wrong setting of non-conservative crop parameters and/or a poor description of the environment in which the crop develops. Only events not simulated in AquaCrop may justify an update. Therefore the user should assure that:

- the rainfall data is collected at or nearby the field;
- the evaporating power of the atmosphere (ETo) is correctly determined;
- the air temperature (which might affects crop development and production) is well defined;
- the crop phenology and life cycle length is fine-tuned to the environment and the crop species;
- the moment of germination or transplanting is correctly specified;
- the moment and duration of flowering is well selected in case of a determinant fruit/grain crop;
- field management, affecting soil surface run-off, reducing soil evaporation (mulches) and crop development and production (soil fertility) is well specified;
- the moment and the net application depth of the various irrigation events are correctly specified;
- the physical soil characteristics of the various soil horizons are well defined.

▪ Updating simulation results

By specifying in the advance panel, at the top left corner of the **Simulation run** menu, the date (selected option: ‘to date’) at which an update is required at the start of a simulation run, the simulation will be halted at that day (Fig. 2.21p - a). By clicking subsequently on the **<Update>** command in the menu bar at the bottom of the screen (Fig. 2.21j – 3), the user gets access to the **Update simulation results** menu. In this menu the user can change for that day, the status of the soil water content in the soil profile (Fig. 2.21q - a), the green Canopy Cover and the above-ground dry biomass (Fig. 2.21q - b). When returning to the **Simulation run** menu, any update will be considered after resuming the simulation (Fig. 2.21p - b).

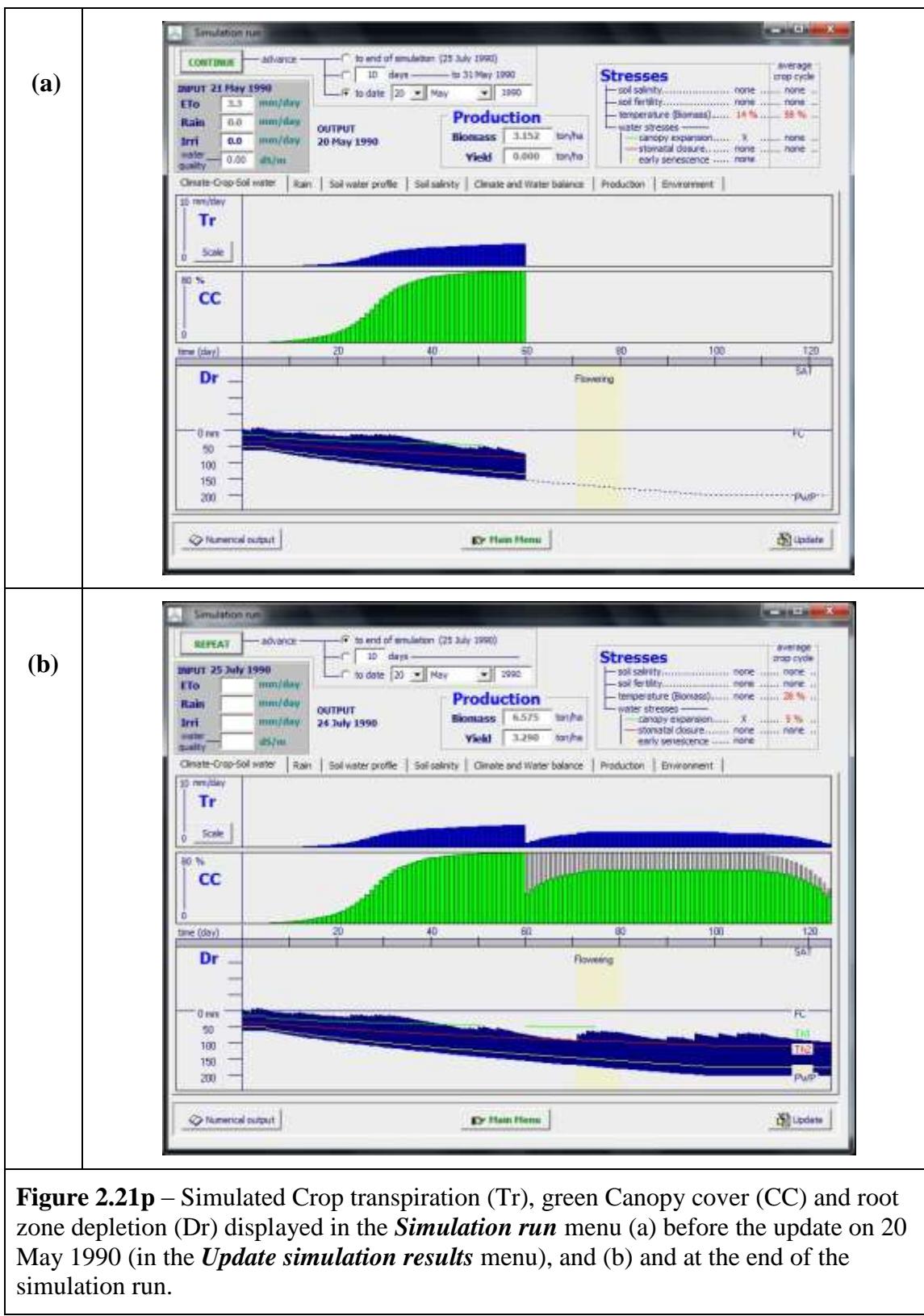


Figure 2.21p – Simulated Crop transpiration (Tr), green Canopy cover (CC) and root zone depletion (Dr) displayed in the *Simulation run* menu (a) before the update on 20 May 1990 (in the *Update simulation results* menu), and (b) and at the end of the simulation run.

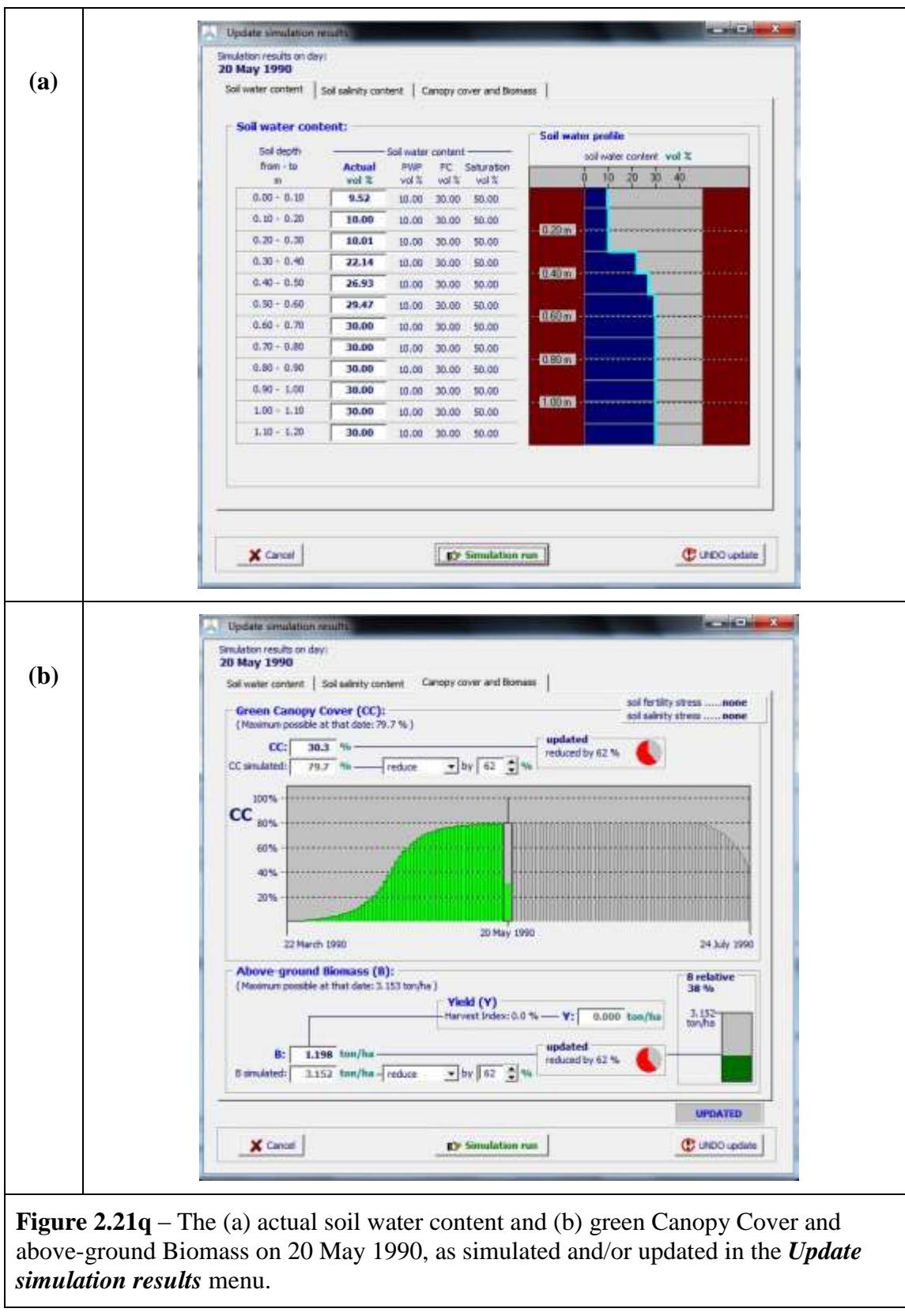


Figure 2.21q – The (a) actual soil water content and (b) green Canopy Cover and above-ground Biomass on 20 May 1990, as simulated and/or updated in the **Update simulation results** menu.

- **Guidelines for the update of CC, B and/or θ**
 - It is possible to adjust the simulated CC with a value larger than the maximum CC that can be reached on that day. However since this is the maximum CC that can be obtained under the given environmental conditions, it is advised to verify first the non-conservative parameters in the crop file (the crop phenology and life cycle length might not be fully fine-tuned to the environment), air-temperature data in the climate file (too low air temperature might have reduced the speed of canopy expansion) and/or soil fertility settings in the field management file (soil fertility stress might be different from what is assumed) before making such changes;
 - Before germination or transplanting any update of CC is disregarded. Verify, if required, the moment of germination or transplanting;
 - If the crop is a determinant fruit/grain crop (i.e. a crop in which life cycle a clear distinction is made between the vegetative and reproduction stage), AquaCrop disregard any increase in CC after mid flowering (which is the end of the vegetative stage), even when the maximum CC (CC_x) was not yet reached. Verify, if required, the moment and duration of flowering;
 - It is possible to adjust the simulated B with a value larger than the maximum B that can be produced on that day. However since this maximum B is the one that can be obtained under optimal conditions for the given weather conditions, it is advised first to verify the non-conservative parameters in the crop file (crop phenology and life cycle length might not be fully fine-tuned to the environment), and/or air temperature data in the climate file (too low air temperature might have reduced the biomass production) before making such changes;
 - Yield (Y) cannot be updated directly during the simulation run. However, by considering the displayed HI, the user can calculate the corresponding B (i.e. $Y/(0.01*HI)$) and adjust the simulated B accordingly. Note however that before the reproductive stage HI is always zero;
 - The simulated soil water contents (θ) in each of the (maximum 12) soil compartments (as displayed in the ‘Soil water profile’ tab-sheet of the ***Simulation run*** menu) can be updated. For reference the soil water content at Permanent Wilting Point (θ_{PWP}) and at saturation (θ_{SAT}) of the soil horizon at that depth, and the depth of the center of the soil compartment below soil surface are displayed. It is possible to adjust θ out of the $\theta_{PWP} - \theta_{SAT}$ range. However since θ can only fluctuate between this range, it is advised to check the physical soil characteristics of the various soil horizons before making changes out of the range. Note that at the top of the soil profile θ can drop below θ_{PWP} since the surface layer can become air dry due to soil evaporation. The soil water content at air-dry is half of the water content at permanent wilting point ($\theta_{air\ dry} = \theta_{PWP}/2$).

2.21.7 Output files

On exit of the **Simulation run** menu (select <Main menu> command, Fig 2.21j - 4), it is possible to save the output. Distinction is made between files containing daily simulation results, seasonal results and evaluation of simulation results (Fig. 2.21r). The files are stored by default in the OUTP directory of AquaCrop. By selecting the <**Output files**> command, the user can specify the files to be recorded in the **Output files** menu. To prevent that the simulation results are overwritten at each run, a different file name (an even directory) can be specified (Fig. 2.21r).

The data in the files can be retrieved in spread sheet programs for further processing and analysis.

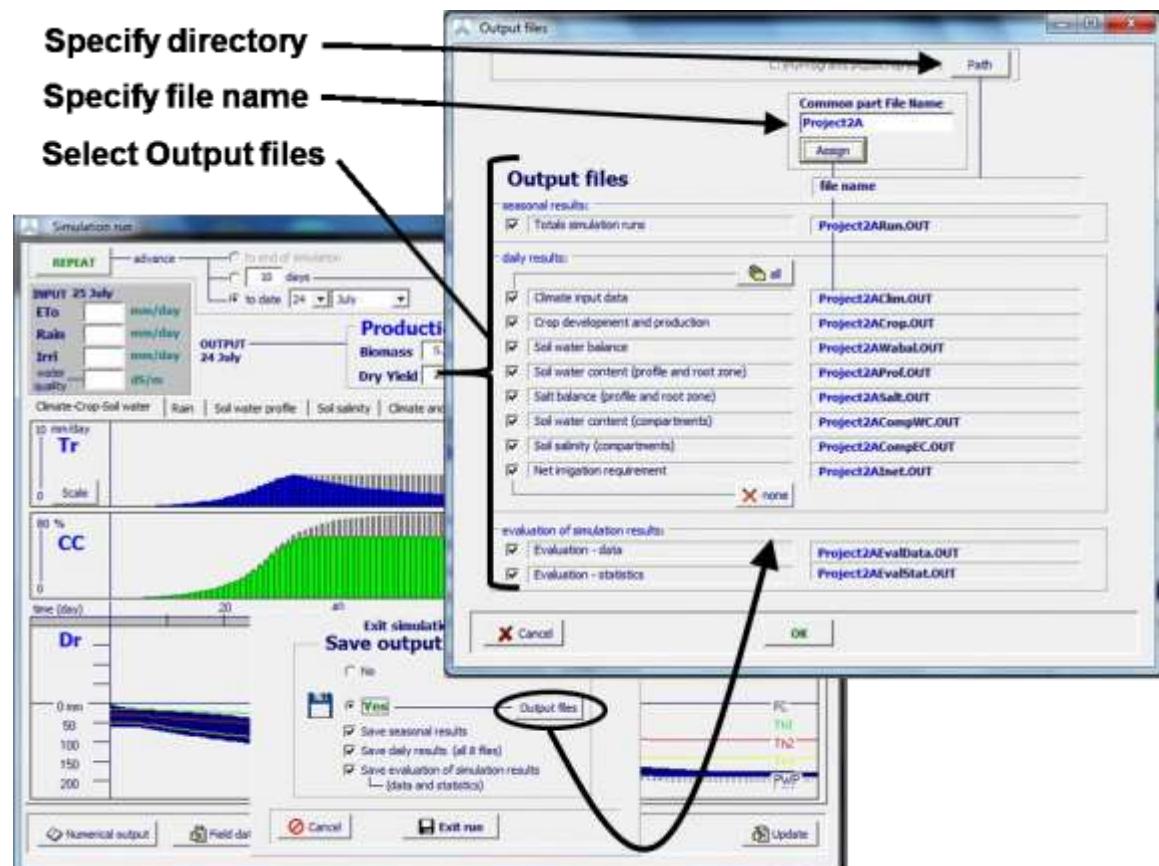


Figure 2.21r – Specification of the files to be recorded, and the path and file name for the Output files in the **Output files** menu

- **Daily results**

The output of the daily results consists of 8 files containing key variables (Tab.2.21c). In section 2.25 (Output files) the list of key variables is presented.

Table 2.21c – Default file name and content of the 8 output files with daily simulation results (see 2.25 ‘Output files’)

| Default file name | Content |
|-------------------|--|
| ProjectClim.OUT | Climate input variables |
| ProjectCrop.OUT | variables for crop development and production |
| ProjectWabal.OUT | variables for soil water balance |
| ProjectProf.OUT | variables for soil water content – Profile/Root zone |
| ProjectSalt.OUT | variables for soil salinity – Profile/Root zone |
| ProjectCompWC.OUT | variables for soil water content – Compartments |
| ProjectCompEC.OUT | variables for soil salinity – Compartments |
| ProjectInet.OUT | variables for net irrigation requirement |

- **Seasonal results**

The output of the seasonal results can be stored as well (RUN.OUT). The variables listed in the output files are described in 2.25 (Output files).

- **Evaluation of simulation results**

The evaluation of the simulation results are recorded in 2 output files (Tab2.21d).

Table 2.21d – Default file name and content of the 2 output files with evaluation of simulation results (see 2.25 ‘Output files’)

| Default file name | Content |
|---------------------|---|
| ProjectEvalData.OUT | Data output file: which contain for each day of the simulation period the simulated green canopy cover (CC), biomass (B) and soil water content (SWC), and the observed field data (with their standard deviation); |
| ProjectEvalStat.OUT | Statistics output file: which contain the statics of the evaluation of the simulation results for Canopy Cover, biomass and soil water content (see 2.21.5 ‘Evaluation of simulation results’). |

2.21.8 Training videos about applications

A set of training modules (MP4 videos) are posted in an ‘AquaCrop Training’ channel of YouTube. The modules about applications are listed in Table 2.21e.. For the playlist go to FAO AquaCrop website <http://www.fao.org/nr/water/aquacrop.html>

Table 2.21e – The training module about applications

| Video | Learning objective | Length [min:sec] |
|---|---|-------------------------|
| 06.6 Applications | Grasp the kind of applications that can be developed | - |
| – Part 1. Deficit irrigation | | 05:03 |
| – Part 2. Scenario for policy makers | | 03:06 |
| – Part 3. Improving water productivity | | 04:18 |
| – Part 4. Scenario analysis for optimizing field management | | under development |
| – Part 5. Effect of climate change | | 06:26 |
| – Part 6. Yield forecast | | 04:59 |
| – Part 7. Regional applications | | 07:41 |

2.22 Evaluation of simulation results

When the simulated crop yield differs from the observed yield, some of the input data (see 2.23 Input files) might be wrong. When examining the input, it is essential to do the checks along a sequence, which follows the order of the calculation scheme. Fig. 2.22a shows the calculation scheme of AquaCrop, together with the crop parameters and stresses governing the:

1. Simulation of green Canopy Cover (CC): The expansion, ageing, conductance and senescence of CC are key determinants of the amount of water transpired and the amount of biomass produced. CC development is described by conservative and cultivar specific parameters. Water, soil salinity and soil fertility stress can reduce CC from its potential development;
2. Simulation of crop transpiration (Tr): Tr is proportional to CC. Shortage and excess of water and soil salinity in the root zone, can reduce Tr as a result of stomatal closure;
3. Simulation of the above ground biomass production (B): B is proportional to the cumulative amount of water transpired. Temperature and soil fertility stress can reduce B;
4. Simulation of crop yield (Y): Y is calculated as the product of final B and a harvest index (HI). The actual HI is obtained by adjusting, during the simulation, the reference Harvest Index (H₀) with an adjustment factor for stress effects.

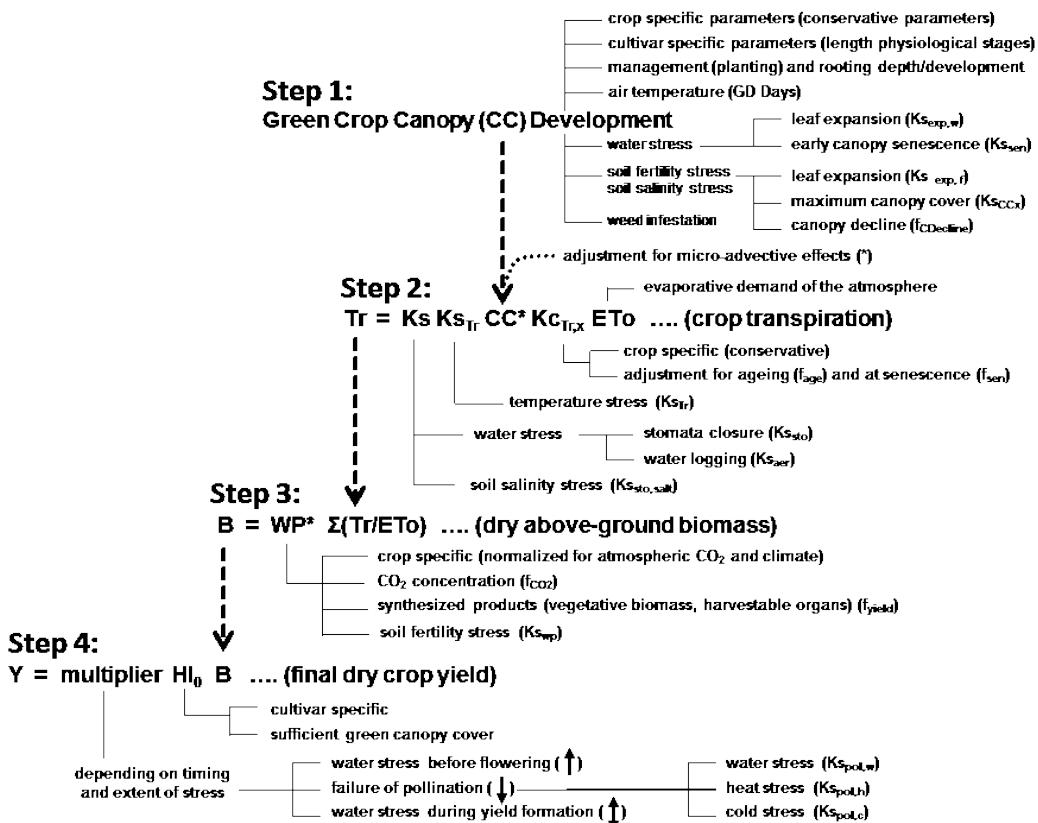


Figure 2.22a – Schematic outline of the model operation of AquaCrop

2.22.1 Green canopy cover (CC) – Step 1

Check if crop parameters are properly tuned to the environment and cultivar:

A first check should consist in verifying if the non-conservative crop parameters were properly tuned to the selected cultivar, planting mode, field management, or conditions in the soil profile as outlined in 2.10.2 ‘Tuning of crops parameters’.

Compare observed with simulated CC:

The conservative and fine-tuned non-conservative parameters of the crop file describe the potential canopy development (CC) in the absence of any stress. When soil water, soil salinity and/or soil fertility stress affects crop development, the simulated CC (CC_{sim}) will be different from its potential value. Compare therefore CC_{sim} with data collected at the field (CC_{obs}). For the study of the evolution of CC, several observations (randomly distributed throughout the field) should be taken at several times during the growing cycle. CC_{obs} can be estimated in the field by eye, by evaluating the shadowed sections on a graduated ruler placed on the soil surface around midday, or by deriving it from pictures of the canopy taken overhead with a digital camera (Tab. 2.22a).

Table 2.22a – Software and guidelines for deriving Canopy Cover (CC) from pictures

| |
|--|
| <p>Available software packages, to estimate CC from pictures:</p> <p>FREEWARE:</p> <ul style="list-style-type: none">- Green Crop Tracker http://www.flintbox.com/public/project/5470/- GIMP http://www.gimp.org/downloads/- IMAGE J http://rsb.info.nih.gov/ij/- CAN-EYE http://147.100.66.194/can_eye/index.php <p>OTHER OPTION (not freeware):</p> <ul style="list-style-type: none">- SigmaScan Pro- ENVI http://www.ittvis.com/ProductServices/ENVI.aspx- ASSESS http://www.apsnet.org/apsstore/shopapspress/Pages/43696m5.aspx- eCognition Developper http://www.ecognition.com/products/ecognition-developer- Image processing toolbox Matlab: http://www.mathworks.nl/products/image/index.html?s_tid=brdcrb |
| <p>Guidelines:</p> <ul style="list-style-type: none">- To avoid over-estimations caused by parallax distortions near the image borders, only the centres of the pictures should be analysed;- By altering thresholds in a kind of colour histogram, the ‘green’ colour of the canopy cover can be identified;- The setting of the thresholds allows to separate the image into bare soil and green matter. |

When running a simulation, observed field data (specified in the **Field data** menu) and simulation results are plotted together in the **Evaluation of simulation results** menu (see 2.21.5 ‘Evaluation of simulation results’). Next to a visual check, statistical indicators are available to evaluate the simulation. Since the development of canopy cover is affected by (i) soil fertility, (ii) soil salinity and (iii) soil water stress, a poor simulation of those stresses

in the root zone might be the reason of a poor fit between observed and simulated canopy cover:

- (i) Check if the amount of fertilizers applied in the field is in agreement with the soil fertility level (relative potential biomass production) specified in the **Field management** menu;
- (ii) Adjust if required the initial EC_e, and/or the EC_w of the irrigation water and groundwater table, if there is a mismatch between the real and simulated incoming and outgoing salts;
- (iii) The evaluation of the simulated soil water content is discussed below in section 2.22.2

2.22.2 Crop transpiration (Tr) – Step 2

Crop transpiration (Tr) is calculated by multiplying the reference evapotranspiration (ET_o) with the crop transpiration coefficient and by considering the effect of water stress with the help of water stress coefficients. The crop transpiration coefficient is proportional with the green canopy cover. The proportional factor and the thresholds and shapes of the K_s functions are conservative crop parameters and should not be adjusted.

Check reference evapotranspiration (ET_o):

AquaCrop runs with ET_o estimated with the FAO Penman-Monteith method (see 2.9 ‘Climatic data’). To check if ET_o is well calculated, the (daily) ET_o values used for simulations can be compared with the mean monthly values specified in the New_LocClim software for the particular location (Tab. 2.22b). The two sets should have the same order of magnitude.

Table 2.22b – New_LocClim: Local Climate Estimator (download from web)

| | |
|---|---|
|  | New_locClim is a software program and database, which provides estimates of average climatic conditions at locations in the world. Reference: FAO. 2005. New_locClim, Environment and Natural Resources, Working paper No. 20 (CD-ROM) |
|---|---|

Check the initial soil water content (at the start of the simulation period):

Simulations of the soil water balance are sensitive to the initial conditions. If the soil water content at the start of simulation is poorly defined, the estimated soil water content at the next days might be out of range as well. Since the simulated soil water content in the root zone strongly affects crop development (CC), transpiration (Tr), biomass production (B) and yield (Y) the initial soil water content should be well estimated. Section 2.17 ‘Initial conditions’ provides guidelines for a proper estimation of the initial soil water content.

Check the soil water balance:

Soil water content in the root zone (Wr) affects canopy development and crop transpiration. By considering the incoming and outgoing fluxes the variation of Wr during the growing season is simulated. If crop transpiration and/or canopy cover are not well simulated check:

- **the size of the root zone reservoir** which is determined by soil profile and crop characteristics. Soil type and variations of soil physical characteristics with soil depth are specified in the soil file (2.14 ‘Soil profile characteristics’). The development and

the maximum depth of the root zone are specified in the crop file (see 2.10.6 ‘Tabular sheet: Development’);

- **daily rainfall.** Since the temporal and spatial variability of rainfall is very high, the data should have been collected at or nearby the site, and preferably on a daily basis;
- **irrigation application depth and timing of the applications.** The irrigation depth refers to the net irrigation amount. Extra water applied to the field to account for conveyance losses or the uneven distribution of irrigation water on the field should not have been added;
- **surface runoff** which is determined by soil profile characteristics and field management. The Curve Number (CN), and the saturated hydraulic conductivity are specified in the soil file (2.14 ‘Soil profile characteristics’). Adjust, if required, CN by considering the slope, land use and cover. Field surface practices affecting runoff are specified in the Field management file (2.13 ‘Field management’);
- **capillary rise** which strongly depends on the depth of the groundwater table, which can vary throughout the simulation period and is specified in the Groundwater file (2.15 ‘Groundwater table characteristics’). If required, calibrate ‘capillary rise’ in the *Soil profile characteristics* menu (2.14 ‘Soil profile characteristics’).

Compare the observed with simulated soil water content retained in the root zone (Wr):

By measuring (or collecting representative soil samples) at various depths, the soil water content in the root zone can be determined (Fig. 2.20b). The quality of the simulation can be evaluated by comparing Wr_{sim} with measured soil water content at particular days throughout the growing cycle (2.20 ‘Field data’). This corresponds with an evaluation of the crop evapotranspiration, since it is the only water flux which could not be checked directly.

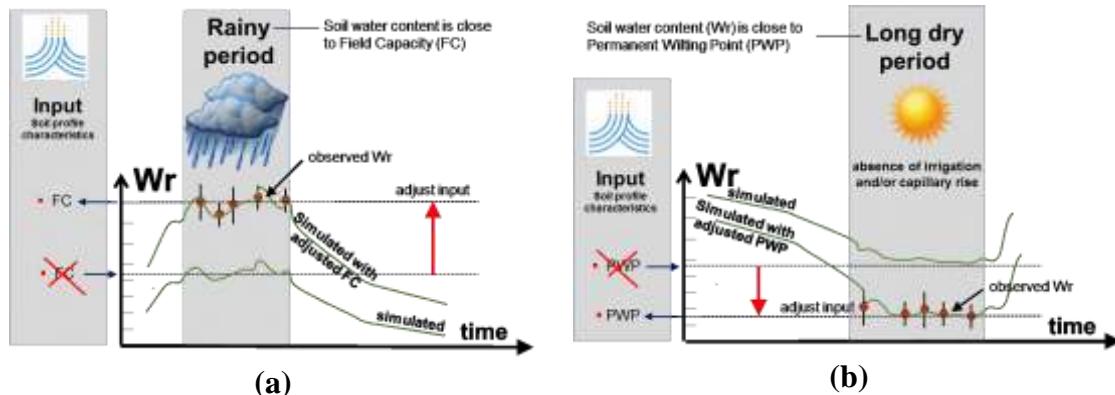


Fig. 2.22b – Comparing observed (points) with simulated (lines) soil water retained in the root zone (Wr), and the result on simulated Wr after the adjustment of (a) Field Capacity (FC) and (b) Permanent Wilting Point (PWP) in the soil profile characteristics

When running a simulation, observed field data (specified in the *Field data* menu) and simulation results are plotted together in the *Evaluation of simulation results* menu (see 2.21.5 ‘Evaluation of simulation results’). Next to a visual check, statistical indicators are available to evaluate the simulation. If the observed Wr is above or below the simulated

Wr , check the values for Field Capacity and Permanent Wilting Point specified in the soil file:

- During a rainy period, the soil water content in the root zone remains close to Field Capacity (FC). If during such a period the observed Wr is above (or below) the simulated water content in the root zone, the specified value(s) for FC in the soil file are most likely wrong (Fig. 2.22b - a).
- The soil water content in the root zone will drop close to Permanent Wilting Point (PWP) at the end of a long dry period (and in the absence of irrigation or capillary rise). If during such a dry spell the observed Wr is above (or below) the simulated water content in the root zone, the specified value(s) for PWP in the soil file are most likely wrong (Fig. 2.22b - b).

2.22.3 Above-ground biomass production (B) – Step 3

Above ground biomass production (B) is obtained by multiplying the cumulative sum of (Tr/ETo), with the normalized biomass water productivity (WP^*), and by considering cold stress. The shape and thresholds of the ‘cold stress – air temperature’ curve, together with WP^* are conservative crop parameters and should not be adjusted.

Compare observed with simulated above-ground biomass:

When running a simulation, observed field data and simulation results are plotted together. If the assessments in the previous steps, indicate a correct simulation of CC and Tr, detected differences between simulated biomass and observed biomass in the field, might be the result of:

- **poor sampling of the biomass:** Collecting field data of biomass consists in destructive sampling in a number of randomly selected small areas in the field, a few times during the growing cycle. The sampling areas should be large enough (at least 1 m²) and representative for the conditions in the field. To obtain dry above-ground biomass, the samples should stay in a well-ventilated oven for 48 hours at 65°C. Any biomass lost at the field by wind or removed by animals should be estimated, and accounted for when determining B;
- **occurrence of events not simulated by AquaCrop:** such as pests and diseases, and damage by hail storms (see 2.21.6 ‘Updating results when running a simulation’).

2.22.4 Crop yield (Y) – Step 4

Crop yield (Y) is obtained by multiplying the total above-ground biomass (B), produced at crop maturity, with a Harvest Index. If stresses developed during the growing cycle, HI has been adjusted to the stresses at run time (multiplier ≠ 1), which makes that HI differs from the reference harvest index. Conservative crop parameters and the correct simulation of the soil water balance, should guarantee a correct adjustment for HI.

Check the reference harvest index (HI_o):

If after all previous checks, the observed final yield is still different from the simulated yield, the inaccuracy might be due to the selected value for the reference harvest index

(H_{Io}). This might be the case when the simulated crop is of a different cultivar class than the crop specified in the crop file. Due to plant breeding and biotechnology, H_{Io} is likely to increase in the future. On the other hand, local land races are likely to have a smaller H_{Io} than the default specified in the crop files.

2.22.5 Training videos about the evaluation of simulation results

A set of training modules (MP4 videos) are posted in an ‘AquaCrop Training’ channel of YouTube. The modules about the evaluation of simulation results are listed in Table 2.22c. For the playlist go to FAO AquaCrop website <http://www.fao.org/nr/water/aquacrop.html>

Table 2.22c – The training module about the evaluation of simulation results

| Video | Learning objective | Length [min:sec] |
|--|--|------------------|
| 06.5 Evaluation of simulation results | Understand how to evaluate simulations with field data | - |
| – Part 1. Green canopy cover | | 12:46 |
| – Part 2. Crop transpiration | | 10:46 |
| – Part 3. Above ground biomass production, Yield | | 05:37 |

Input/Output and program settings Files

By default AquaCrop is installed in the FAO folder of the C drive:

```
C:\----|-
      |
      |
      |
      |
|- FAO -----|-
|-           |- AQUACROP -----|-
                  |          AquaCrop.EXE   |
                  |          |- IMPORT
                  |
                  |          |- OBS
                  |
                  |          |- OUTPUT
                  |
                  |- SIMUL
                      |- Default.PAR
                      |- General.PAR
                      |- Planting.PAR
                      |- Onset.PAR
                      |- Soil.PAR
                      |- Rainfall.PAR
                      |- Crop.PAR
                      |- Field.PAR
                      |- Temperature.PAR
                      |- MaunaLoa.CO2
                      |- SOILS.DIR
```

If AquaCrop is correctly installed, the AquaCrop folder should contain:

- (i) the AquaCrop.EXE file (the executable file);
- (ii) and five subdirectories:
 - **DATA** (default subdirectory for the input files);
 - **IMPORT** (default subdirectory for text files with climatic data);
 - **OBS** (default subdirectory for the field observations files);
 - **OUTP** (default subdirectory for the output files);
 - **SIMUL** (subdirectory for simulation purposes, containing between other files the MaunaLoa.CO2 file, files with default project settings (*.PAR), and SOILS.DIR (a file with default values for soil characteristics).

2.23 Input files

AquaCrop uses a relative small number of explicit parameters and largely intuitive input variables. Those are either widely available or require just simple methods for their determination. Input consists of weather data, crop and soil characteristics, and management practices that define the environment in which the crop will develop. Soil characteristics are divided into soil profile and groundwater characteristics and Management practices into field management and irrigation management practices (Fig.2.23a).

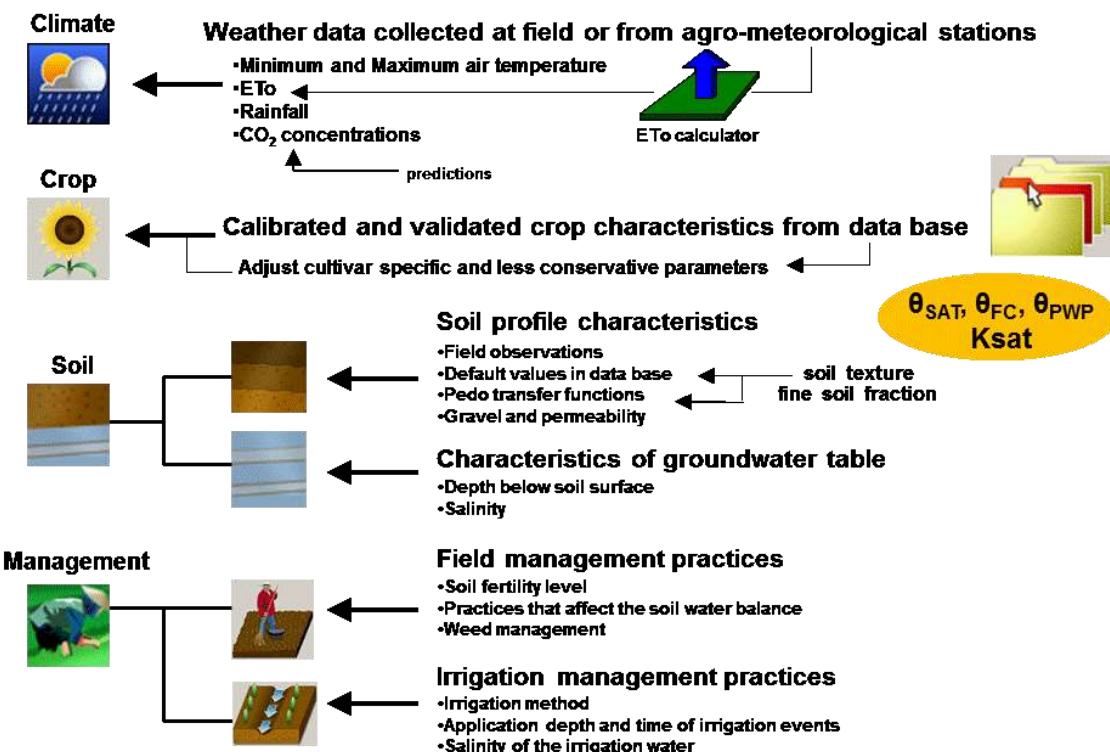


Figure 2.23a – Required input data for AquaCrop

The input is stored in text files which are retrieved through the user-interface. Input files contain the characteristics of the crop, of the environment (climate, management, soil) in which the crop is cultivated, and of the conditions outside the growing period and at the start of the simulation run. By default the input files are stored in the DATA subdirectory of the AquaCrop folder. Distinction is made between:

- Climate files (*.CLI) which contains the names of a set of files containing
 - o air temperature data (*.Tnx),
 - o reference evapotranspiration data (*.ETo),
 - o rainfall data (*.PLU), and
 - o atmospheric CO₂ data (*.CO2);
- Crop files (*.CRO) containing crop characteristics;

- Irrigation files (*.IRR) containing, apart from the irrigation method, (i) information for the calculation of the net irrigation requirement, (ii) the timing, applied irrigation amounts and the irrigation water quality of an irrigation schedule, or (iii) information for generating irrigation schedules;
- Field management files (*.Man) containing characteristics of the field on which the crop is cultivated;
- Soil profile files (*.SOL) containing characteristics of the soil profile;
- Groundwater files (*.GWT) containing characteristics of the groundwater table;
- Files with the specific conditions in the soil profile at the start of the simulation period (*.SW0);
- Files with off-season field management conditions (*.OFF).

Project files contain all the required information for a simulation run. Distinction is made between:

- Single run project files (*.PRO) containing information on the growing and simulation period, the settings of program parameters, and the names of the set of input files describing the environment, and the initial and off-season conditions;
- Multiple runs project files (*.PRM) containing information on the settings of program parameters and on the growing and simulation period, names of the set of input files describing the environment, and the initial and off-season conditions for each of the runs.

Also field observations can be stored in text files and retrieved through the user-interface for the evaluation of simulations results. By default the field observations files are stored in the OBS subdirectory of the AquaCrop folder.

- Files with field observations (*.OBS).

Also climatic data can be stored in text files and imported through the user-interface for calculating ETo and creating Tnx, ETo and PLU files. By default the text files with climatic data are stored in the IMPORT subdirectory of the AquaCrop folder.

- Text files with climatic data (*.TXT).

2.23.1 Climate file (*.CLI)

A climate file (Tab. 2.23a and 2.23b, Fig. 2.9a) contains next to its description and the reference of the AquaCrop version, the names of the air temperature file (*.Tnx), ETo file (*.ETo), rainfall file (*.PLU), and CO₂ file (*.CO2).

Table 2.23a – Structure of a Climate file (files with extension CLI)

| Line | Description | Format |
|------|---|----------------------|
| 1 | First line is a description of the file content | String of characters |
| 2 | Version number of AquaCrop | Real (1 digit) |
| 3 | The name of the air temperature file (*.TMP) | String of characters |
| 4 | The name of the ETo file (*.ETo) | String of characters |
| 5 | The name of the rainfall file (*.PLU) | String of characters |
| 6 | The name of the CO ₂ file (*.CO2) | String of characters |

Table 2.23b – Example of a climate file (files with extension CLI)

| |
|---|
| Ankara daily data 1 Jan 2000 - 13 July 2007 |
| 5.0 : AquaCrop Version (October 2015) |
| Ankara00-07.Tnx |
| Ankara00-07.ETo |
| Ankara00-07.PLU |
| MaunaLoa.CO2 |

To avoid confusion between the air temperature files in AquaCrop and Windows temporary files (both files have the extension ‘.TMP’), the extension of air temperature files in AquaCrop is changed from ‘.TMP’ to ‘.Tnx’. Due to restrictions in the transfer of Windows temporary files between computers, sending AquaCrop air temperature files with extension ‘.TMP’ as attachment in e-mails, was not possible.

Since version 5.0, newly created air temperature files in AquaCrop get automatically the extension ‘.Tnx’. Nevertheless, previously created air temperature files with extension ‘.TMP’ can still be used in AquaCrop. Files with extension ‘.TMP’ or ‘.Tnx’ in the data base of AquaCrop can be used and are recognized as air temperature files.

2.23.2 Temperature (*.Tnx), ETo (*.ETo) and rainfall (*.PLU) files

Temperature (Tab. 2.23c and 2.23d), ETo (Tab. 2.23e and 2.23f) and Rainfall files (Tab. 2.23g and 2.23h) have all the same structure which consists of:

- 5 lines containing information required by the program;
- an empty line to separate the information from the records;
- 2 lines for the title of the records;
- list of records (1 line for each daily, 10-daily or monthly record). The records are the daily, mean 10-daily or monthly minimum and maximum air temperature in degrees Celsius, the daily, mean 10-daily or monthly ETo in mm/day and the total daily, 10-daily or monthly rainfall data in mm. The data may consists of integers or reals with 1 digit (1/10 of a degree or a millimeter).

▪ Daily, 10-day and Monthly weather data

In the absence of daily data, the input (Air Temperature, and/or ETo) may also consists of 10-day or monthly data. At run time an interpolation procedure is used to obtain daily temperature and/or ETo data from the 10-day or monthly means.

For rainfall, with its extremely heterogeneous distribution over time, the use of long-term mean data is not recommended. In case no daily rainfall data is available, 10-day and monthly data can be used as input. Since it is highly unlikely that rainfall is homogenously distributed over all the days of the 10-day period or month, AquaCrop uses at run time procedures to determine the amount of rainfall that is (i) lost by surface runoff, (ii) stored in the top soil as effective rainfall, (iii) lost by deep percolation and (iv) by soil evaporation.

▪ Average weather data

If the meteorological data consists of averages of several years, the data should not be linked to a specific year and the year has not to be specified (Tab. 2.23i). Since the weather data is not linked to a specific year, the data can be used for any year.

Table 2.23c – Structure of an air temperature file (files with extension TMP)

| Line | Description | Format |
|-------------|--|----------------------------------|
| 1 | First line is a description of the file content | String of characters |
| 2 | A number (1 to 3) used as a code to specify the time aggregation of the weather data: 1 : Daily weather data 2 : 10-day weather data 3 : monthly weather data | Integer |
| 3 | First day of record (1, 11 or 21 for 10-day or 1 for months) | Integer |
| 4 | First month of record | Integer |
| 5 | First year of record (1901 if the characteristics are not linked to a specific year) | Integer |
| 6 | Empty line | - |
| 7 | Title of variables ('Tmin (°C) TMax (°C)') | String of characters |
| 8 | Dotted line ('=====') | String of characters |
| 9 | For each day 10-day or month of the record: - (average) minimum air temperature (°C) - (average) maximum air temperature (°C) | Real (1 digit) Real (1 digit) |

Table 2.23d – Example of an air temperature file (files with extension TMP)

| | |
|--|--|
| Daily air temperature data of Location (Country) | |
| 1 | : Daily records (1=daily, 2=10-daily and 3=monthly data) |
| 1 | : First day of record (1, 11 or 21 for 10-day or 1 for months) |
| 1 | : First month of record |
| 2000 | : First year of record (1901 if not linked to a specific year) |
| Tmin (°C) TMax (°C) | |
| ===== | |
| 7.0 | 15.0 |
| 8.0 | 16.0 |
| 9.0 | 18.0 |
| ... | ... |

Table 2.23e – Structure of an ETo file (files with extension ETo)

| Line | Description | Format |
|-------------|--|----------------------|
| 1 | First line is a description of the file content | String of characters |
| 2 | A number (1 to 3) used as a code to specify the time aggregation of the weather data: 1 : Daily weather data 2 : 10-day weather data 3 : monthly weather data | Integer |
| 3 | First day of record (1, 11 or 21 for 10-day or 1 for months) | Integer |
| 4 | First month of record | Integer |
| 5 | First year of record (1901 if the characteristics are not linked to a specific year) | Integer |
| 6 | Empty line | - |
| 7 | Title of variables ('Average ETo (mm/day)') | String of characters |
| 8 | Dotted line ('=====') | String of characters |
| 9 | Average ETo (mm/day) for each day, 10-day or month of the record | Real (1 digit) |

Table 2.23f – Example of an ETo file (files with extension ETo)

Daily reference evapotranspiration (ETo) of Location (Country)
 1 : Daily records (1=daily, 2=10-daily and 3=monthly data)
 1 : First day of record (1, 11 or 21 for 10-day or 1 for months)
 1 : First month of record
 2000 : First year of record (1901 if not linked to a specific year)

Average ETo (mm/day)
=====

| |
|-----|
| 1.0 |
| 1.1 |
| 1.2 |
| ... |

Table 2.23g – Structure of a Rainfall file (files with extension PLU)

| Line | Description | Format |
|-------------|--|----------------------|
| 1 | First line is a description of the file content | String of characters |
| 2 | A number (1 to 3) used as a code to specify the time aggregation of the weather data: 1 : Daily weather data 2 : 10-day weather data 3 : monthly weather data | Integer |
| 3 | First day of record (1, 11 or 21 for 10-day or 1 for months) | Integer |
| 4 | First month of record | Integer |
| 5 | First year of record (1901 if the characteristics are not linked to a specific year) | Integer |
| 6 | Empty line | - |
| 7 | Title of variables ('Total Rain (mm)') | String of characters |
| 8 | Dotted line ('=====') | String of characters |
| 9 | Total Rain (mm) for each day, 10-day or month of the record | Real (1 digit) |

Table 2.23h – Example of an Rainfall file (files with extension PLU)

| | |
|--------------------------------------|--|
| Daily rainfall of Location (Country) | |
| 1 | : Daily records (1=daily, 2=10-daily and 3=monthly data) |
| 1 | : First day of record (1, 11 or 21 for 10-day or 1 for months) |
| 1 | : First month of record |
| 2000 | : First year of record (1901 if not linked to a specific year) |
| Total Rain (mm) | |
| ===== | |
| | 0.0 |
| | 0.0 |
| | 16.6 |
| | ... |
| | ... |

Table 2.23i – Example of an ETo file (file with extension ETo) with mean monthly climatic data not linked to a specific year

| |
|---|
| Mean monthly ETo for Axum (Ethiopia) |
| 3 : Monthly records (1=daily, 2=10-daily and 3=monthly data) |
| 1 : First day of record (1, 11 or 21 for 10-day or 1 for months) |
| 1 : First month of record |
| 1901 : First year of record (1901 if not linked to a specific year) |
| Average ETo (mm/day) |
| ===== |
| 3.4 |
| 3.5 |
| 4.6 |
| 4.9 |
| 5.4 |
| 4.8 |
| 3.5 |
| 3.2 |
| 4.1 |
| 4.2 |
| 3.4 |
| 3.0 |

2.23.3 CO2 file (*.CO2)

A CO2 file contains mean annual atmospheric CO₂ data (in ppm) for a series of years arranged in chronological order (Tab. 2.23j and 2.23k). The following rules apply (Fig. 2.23c, 2.23d):

- for years not specified in the file, AquaCrop will derive at run time the CO₂ concentration by linear interpolation between the specified CO₂ values for an earlier and later year;
- for years out of the listed range, the atmospheric CO₂ concentration is assumed to be equal to the specified value of the first year (for earlier years) or the specified value of the last year (for later years).

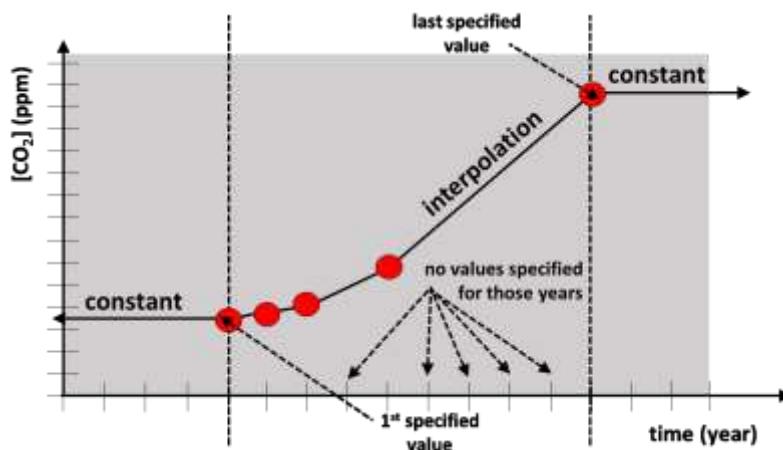


Figure 2.23c – Rules applicable in CO2 file

Table 2.23j – Structure of a CO2 file (files with extension CO2)

| Line | Description | Format |
|------------------|--|----------------------------|
| 1 | First line is a description of the file content | String of characters |
| 2 | Title of variables ('Year CO2 (ppm by volume)') | String of characters |
| 3 | Dotted line ('=====') | String of characters |
| 4 and next | For each record specify: - year - corresponding [CO2] in ppm by volume | Integer Real (2 digits) |

AquaCrop uses as default the data from the MaunaLoa.CO2 (stored in the SIMUL subdirectory) which contains the mean annual atmospheric CO₂ concentration measured at Mauna Loa Observatory since 1958 (Tab. 2.23m). For earlier years, data obtained from firn and ice samples close to the coast of Antarctica¹ are used, and for future estimates an increase of 2.0 ppm is assumed (following Pieter Hans (NOAA) - personal communication, December 2007).

¹ David Etheridge et al. (1996), J. Geophys. Research vol. 101, 4115-4128

Table 2.23k – Example of a CO2 file (files with extension CO2)

| Default atmospheric CO2 concentration from 1902 to 2099 | |
|---|---------------------|
| Year | CO2 (ppm by volume) |
| 1902 | 297.4 |
| 1905 | 298.2 |
| 1912 | 300.7 |
| 1915 | 301.3 |
| 1924 | 304.5 |
| ... | ... |
| ... | ... |
| 2010 | 389.90 |
| 2011 | 391.65 |
| 2020 | 409.57 |
| 2099 | 567.57 |

Table 2.23m – The default CO2 concentrations in ppm in the MaunaLoa.CO2 file

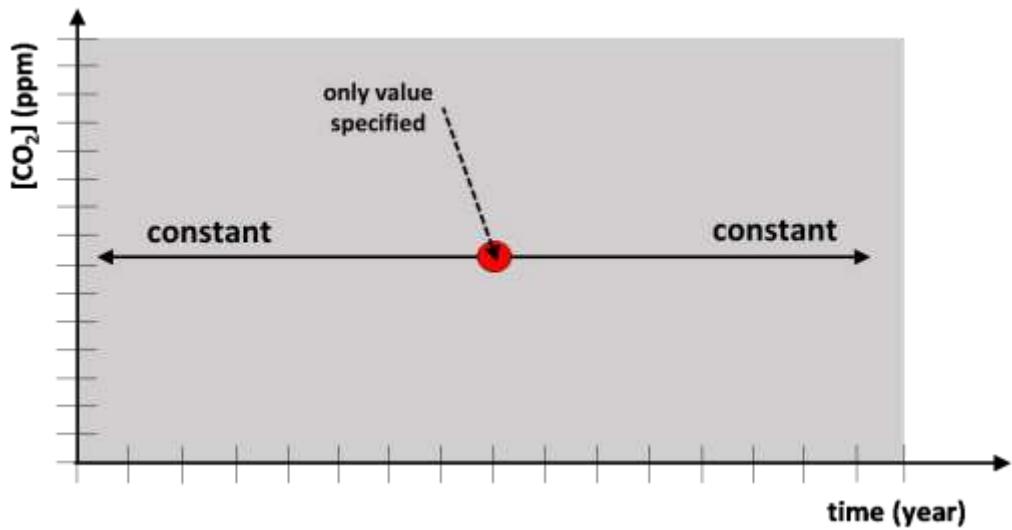
| Year | Annual Mean [CO ₂] | Year | Annual Mean [CO ₂] | Year | Annual Mean [CO ₂] |
|------|--------------------------------|------|--------------------------------|------|--------------------------------|
| 1902 | 297.40 | 1967 | 322.16 | 1993 | 356.10 |
| 1905 | 298.20 | 1968 | 323.04 | 1994 | 358.83 |
| 1912 | 300.70 | 1969 | 324.62 | 1995 | 360.82 |
| 1915 | 301.30 | 1970 | 325.68 | 1996 | 362.61 |
| 1924 | 304.50 | 1971 | 326.32 | 1997 | 363.73 |
| 1926 | 305.00 | 1972 | 327.45 | 1998 | 366.70 |
| 1929 | 305.20 | 1973 | 329.68 | 1999 | 368.38 |
| 1932 | 307.80 | 1974 | 330.18 | 2000 | 369.55 |
| 1934 | 309.20 | 1975 | 331.11 | 2001 | 371.14 |
| 1936 | 307.90 | 1976 | 332.04 | 2002 | 373.28 |
| 1938 | 310.50 | 1977 | 333.83 | 2003 | 375.80 |
| 1939 | 310.10 | 1978 | 335.40 | 2004 | 377.52 |
| 1940 | 310.50 | 1979 | 336.84 | 2005 | 379.80 |
| 1944 | 309.70 | 1980 | 338.75 | 2006 | 381.90 |
| 1948 | 310.70 | 1981 | 340.11 | 2007 | 383.79 |
| 1953 | 311.90 | 1982 | 341.45 | 2008 | 385.60 |
| 1954 | 314.10 | 1983 | 343.05 | 2009 | 387.43 |
| 1958 | 315.29 | 1984 | 344.65 | 2010 | 389.90 |
| 1959 | 315.97 | 1985 | 346.12 | 2011 | 391.65 |
| 1960 | 316.91 | 1986 | 347.42 | 2012 | 393.85 |
| 1961 | 317.64 | 1987 | 349.19 | 2013 | 396.52 |
| 1962 | 318.45 | 1988 | 351.57 | 2014 | 398.65 |
| 1963 | 318.99 | 1989 | 352.12 | 2015 | 400.83 |
| 1964 | 319.62 | 1990 | 354.39 | 2016 | 404.21 |
| 1965 | 320.04 | 1991 | 355.61 | 2020 | 412.21 |
| 1966 | 321.38 | 1992 | 356.45 | 2099 | 570.21 |

When the effect of a specific [CO₂] on crop production has to be tested for a number of successive years, the content of the CO₂ file can be specified as shown in Table 2.23n. In the example it is assumed that the specified CO₂ concentration corresponds to 550 ppm.

For all years, AquaCrop will assume that the CO₂ concentration remains constant (550 ppm).

Table 2.23n – Example of a CO2 file containing only one specific annual atmospheric [CO₂] for testing its effect on crop production in any year of the simulation period.

| Constant CO ₂ concentration of 550 ppm | |
|---|---------------------------------|
| Year | CO ₂ (ppm by volume) |
| 2050 | 550 |



**Figure 2.23d – Rules applicable in CO₂ file when only one value is specified
(example of Tab. 2.23n)**

2.23.4 Crop file (*.CRO)

Crop parameters describing its development, evapotranspiration, production (biomass and yield), and its response to soil water, temperature, salinity and fertility stress, are stored in crop files (files with extension CRO). To assure that there is no conflict in the data, and the data is in the correct range, crop files are best created with the user interface. An example of a crop file is given in Table 2.23p.

Table 2.23p – Example of crop file (Default.CRO)

| | |
|----------------|--|
| a generic crop | |
| 6.0 | : AquaCrop Version (March 2017) |
| 1 | : File not protected |
| 2 | : fruit/grain producing crop |
| 1 | : Crop is sown |
| 1 | : Determination of crop cycle : by calendar days |
| 1 | : Soil water depletion factors (p) are adjusted by ETo |
| 5.5 | : Base temperature (°C) below which crop development does not progress |
| 30.0 | : Upper temperature (°C) above which crop development no longer increases with an increase in temperature |
| -9 | : Total length of crop cycle in growing degree-days |
| 0.25 | : Soil water depletion factor for canopy expansion (p-exp) - Upper threshold |
| 0.60 | : Soil water depletion factor for canopy expansion (p-exp) - Lower threshold |
| 3.0 | : Shape factor for water stress coefficient for canopy expansion (0.0 = straight line) |
| 0.50 | : Soil water depletion fraction for stomatal control (p - sto) - Upper threshold |
| 3.0 | : Shape factor for water stress coefficient for stomatal control (0.0 = straight line) |
| 0.85 | : Soil water depletion factor for canopy senescence (p - sen) - Upper threshold |
| 3.0 | : Shape factor for water stress coefficient for canopy senescence (0.0 = straight line) |
| 0 | : Sum(ETo) during stress period to be exceeded before senescence is triggered |
| 0.90 | : Soil water depletion factor for pollination (p - pol) - Upper threshold |
| 5 | : Vol% for Anaerobic point (* (SAT - [vol%]) at which deficient aeration occurs *) |
| 50 | : Considered soil fertility stress for calibration of stress response (%) |
| 2.16 | : Shape factor for the response of canopy expansion to soil fertility stress |
| 0.79 | : Shape factor for the response of maximum canopy cover to soil fertility stress |
| 1.67 | : Shape factor for the response of crop Water Productivity to soil fertility stress |
| 1.67 | : Shape factor for the response of decline of canopy cover to soil fertility stress |
| -9 | : dummy - Parameter no Longer required |
| 8 | : Minimum air temperature below which pollination starts to fail (cold stress) (°C) |
| 40 | : Maximum air temperature above which pollination starts to fail (heat stress) (°C) |
| 11.1 | : Minimum growing degrees required for full crop transpiration (°C - day) |
| 2 | : Electrical Conductivity of soil saturation extract at which crop starts to be affected by soil salinity (dS/m) |
| 12 | : Electrical Conductivity of soil saturation extract at which crop can no longer grow (dS/m) |
| -9 | : Dummy - no longer applicable |
| 25 | : Calibrated distortion (%) of CC due to salinity stress (Range: 0 (none) to +100 (very strong)) |
| 100 | : Calibrated response (%) of stomata stress to ECsw (Range: 0 (none) to +200 (extreme)) |
| 1.10 | : Crop coefficient when canopy is complete but prior to senescence (KcTr,x) |
| 0.150 | : Decline of crop coefficient (%/day) as a result of ageing, nitrogen deficiency, etc. |

| | |
|-----------|---|
| 0.30 | : Minimum effective rooting depth (m) |
| 1.00 | : Maximum effective rooting depth (m) |
| 15 | : Shape factor describing root zone expansion |
| 0.048 | : Maximum root water extraction (m ³ water/m ³ soil.day) in top quarter of root zone |
| 0.012 | : Maximum root water extraction (m ³ water/m ³ soil.day) in bottom quarter of root zone |
| 50 | : Effect of canopy cover in reducing soil evaporation in late season stage |
| 6.50 | : Soil surface covered by an individual seedling at 90 % emergence (cm ²) |
| 6.50 | : Canopy size of individual plant (re-growth) at 1st day (cm ²) |
| 185000 | : Number of plants per hectare |
| 0.15000 | : Canopy growth coefficient (CGC): Increase in canopy cover (fraction soil cover per day) |
| -9 | : Maximum decrease of Canopy Growth Coefficient in and between seasons - Not Applicable |
| -9 | : Number of seasons at which maximum decrease of Canopy Growth Coefficient is reached - Not Applicable |
| -9.0 | : Shape factor for decrease Canopy Growth Coefficient - Not Applicable |
| 0.80 | : Maximum canopy cover (CCx) in fraction soil cover |
| 0.12750 | : Canopy decline coefficient (CDC): Decrease in canopy cover (in fraction per day) |
| 5 | : Calendar Days: from sowing to emergence |
| 100 | : Calendar Days: from sowing to maximum rooting depth |
| 110 | : Calendar Days: from sowing to start senescence |
| 125 | : Calendar Days: from sowing to maturity (length of crop cycle) |
| 70 | : Calendar Days: from sowing to flowering |
| 10 | : Length of the flowering stage (days) |
| 1 | : Crop determinancy linked with flowering |
| 50 | : Excess of potential fruits (%) |
| 50 | : Building up of Harvest Index starting at flowering (days) |
| 17.0 | : Water Productivity normalized for ET ₀ and CO ₂ (WP*) (gram/m ²) |
| 100 | : Water Productivity normalized for ET ₀ and CO ₂ during yield formation (as % WP*) |
| 50 | : Crop performance under elevated atmospheric CO ₂ concentration (%) |
| 50 | : Reference Harvest Index (HI ₀) (%) |
| 5 | : Possible increase (%) of HI due to water stress before flowering |
| 10.0 | : Coefficient describing positive impact on HI of restricted vegetative growth during yield formation |
| 8.0 | : Coefficient describing negative impact on HI of stomatal closure during yield formation |
| 15 | : Allowable maximum increase (%) of specified HI |
| -9 | : GDDays: from sowing to emergence |
| -9 | : GDDays: from sowing to maximum rooting depth |
| -9 | : GDDays: from sowing to start senescence |
| -9 | : GDDays: from sowing to maturity (length of crop cycle) |
| -9 | : GDDays: from sowing to flowering |
| -9 | : Length of the flowering stage (growing degree days) |
| -9.000000 | : CGC for GDDays: Increase in canopy cover (in fraction soil cover per growing-degree day) |
| -9.000000 | : CDC for GDDays: Decrease in canopy cover (in fraction per growing-degree day) |
| -9 | : GDDays: building-up of Harvest Index during yield formation |

2.23.5 Irrigation file (*.IRR)

The irrigation method, the percentage of the soil surface wetted by the irrigation, and (i) the timing, net application depth and water quality of the irrigation events or (ii) rules to generate irrigation events, or (iii) rules to determine net irrigation requirement, are specified in an irrigation file (files with extension IRR). Various irrigation modes are considered in AquaCrop:

- (i) specification of irrigation events (example Tab. 2.23q - 3);
- (ii) generation of an irrigation schedule (example Tab. 2.23q - 4);
- (iii) determination of net irrigation water requirement (example Tab. 2.23q - 5).

Each mode requires particular data that need to be specified (Table 2.23q - 1). In the absence of an irrigation file, rainfed cropping is assumed when running a simulation.

Table 2.23q - 1. – Structure of the irrigation file (files with extension IRR)

| Line | Description | Format |
|------|---|----------------------|
| 1 | First line is a description of the file content | String of characters |
| 2 | Version number of AquaCrop | Real (1 digit) |
| 3 | A number (1 to 5) used as a code to specify the irrigation method: 1 : Sprinkler irrigation 2 : Surface irrigation: Basin 3 : Surface irrigation: Border 4 : Surface irrigation: Furrow 5 : Drip irrigation Default = 1 | Integer |
| 4 | Percentage of soil surface wetted by irrigation. This percentage is generally closely linked with the irrigation method. Indicative values for the percentage of soil surface wetted for various irrigation methods are presented in Table 2.23q - 2. Default = 100 | Integer |
| 5 | A number (1 to 3) used as a code to specify the irrigation mode: 1 : Specification of irrigation events; 2 : Generation of an irrigation schedule; 3 : Determination of net irrigation water requirement; | Integer |
| | Code = 1 (in line 5): Specification of irrigation events (Example Table 2.23q - 3) | |
| 6 | Empty line | - |
| 7 | Title ('Day Depth (mm) ECw (dS/m)') | String of characters |
| 8 | Dotted line ('=====') | String of characters |
| 9 | For the 1 st irrigation event: – The number of days after sowing/planting | Integer |

| | | |
|--|--|-------------------------------|
| | <ul style="list-style-type: none"> – The net irrigation application depth (mm) – The Electrical Conductivity (dS/m) of the irrigation water <p>The net irrigation application depth refers to the net irrigation amount. Extra water applied to the field to account for conveyance losses or the uneven distribution of irrigation water on the field should not be added.</p> | Integer Real (1 digit) |
| 10.. | Repeat for each successive irrigation event | |
| Code = 2 (in line 5): Generation of an irrigation schedule (Example Table 2.23q - 4) | | |
| 6 | A number (1 to 3) used as a code to specify the time criterion: 1 : Fixed interval; 2 : Allowable depletion (mm water); 3 : Allowable depletion (% of RAW); 4: Keep a minimum level of surface water layer between soil bunds | Integer |
| 7 | A number (1 to 2) used as a code to specify the depth criterion: 1 : Back to Field Capacity; 2 : Fixed net application depth. | Integer |
| 8 | Empty line | - |
| 9 | Title ('From day ... ECw (dS/m)') | String of characters |
| 10 | Dotted line ('=====') | String of characters |
| 11 | For the 1 st rule: <ul style="list-style-type: none"> – The number of days after sowing/planting from which the rule is valid (has to be 1 for the 1st rule); – Value linked with the time criterion: <ul style="list-style-type: none"> ○ the fixed interval (days) between irrigations (for example 10 days); ○ the amount of water (mm) that can be depleted from the root zone (the reference is soil water content at field capacity) before an irrigation has to be applied (for example 30 mm); or ○ the percentage of RAW that can be depleted before irrigation water has to be applied (for example 100 %); ○ the minimum depth (mm) of surface water that should be maintained (between the soil bunds). – Value linked with the depth criterion: | Integer Integer Integer |

| | | |
|------|---|----------------|
| | <ul style="list-style-type: none"> ○ Extra water on top of the amount of irrigation water required to bring the root zone back to Field Capacity. The specified value can be zero (exact back to FC), positive (an over-irrigation) or negative (an under-irrigation); or ○ The fixed net irrigation application depth. <p>– The Electrical Conductivity (dS/m) of the irrigation water.</p> <p>The fixed net irrigation application depth refers to the net irrigation amount. Extra water applied to the field to account for conveyance losses or the uneven distribution of irrigation water on the field should not be added.</p> <p>The values specified remain valid till the date for which a new rule (in the next line) is specified or to the end of the cropping period when no values at later dates are specified</p> | Real (1 digit) |
| 12.. | If applicable specifies values for 2 nd , 3 rd , 4 th , .. rule | |
| | Code = 3 (in line 5): Determination of net irrigation requirement. (Example Table 2.23q -5) | |
| 6 | <p>The depletion (% RAW) below which the soil water content in the root zone may not drop (0 % RAW corresponds to Field Capacity).</p> <p>The total amount of irrigation water required to keep the water content in the soil profile above the specified threshold is the net irrigation water requirement for the period. The net requirement does not consider extra water that has to be applied to the field to account for conveyance losses or the uneven distribution of irrigation water on the field.</p> | Integer |

Table 2.23q – 2. – Indicative values for soil surface wetted for various irrigation methods

| Irrigation method | Soil surface wetted (%) |
|-------------------|-------------------------|
|-------------------|-------------------------|

| | |
|--|----------|
| Sprinkler irrigation | 100 |
| Basin irrigation | 100 |
| Border irrigation | 100 |
| Furrow irrigation (every furrow), narrow bed | 60 – 100 |
| Furrow irrigation (every furrow), wide bed | 40 – 60 |
| Furrow irrigation (alternated furrows) | 30 – 50 |
| Trickle/Drip - Micro irrigation | 15 – 40 |
| Subsurface drip irrigation | 0 |

Table 2.23q – 3. – Example of an irrigation file (file with extension IRR) in which irrigation events of an irrigation schedule are specified

| | | |
|---------------------------|---|------------|
| given irrigation schedule | | |
| 5.0 | : AquaCrop Version (October 2015) | |
| 1 | : Sprinkler irrigation | |
| 100 | : Percentage of soil surface wetted by irrigation | |
| 1 | : Irrigation schedule | |
| Day | Depth (mm) | ECw (dS/m) |
| ===== | | |
| 10 | 50 | 1.5 |
| 20 | 50 | 1.5 |
| 30 | 50 | 1.5 |
| 40 | 50 | 1.5 |
| 50 | 50 | 1.5 |
| 60 | 50 | 1.5 |
| 80 | 50 | 1.5 |

Table 2.23q – 4. – Example of an irrigation file (file with extension IRR) in which rules for the generation of an irrigation schedule are specified

| | | | |
|--|---|------------------------|--------------------------------|
| Generation of irrigation schedule | | | |
| 5.0 | : AquaCrop Version (October 2015) | | |
| 1 | : Sprinkler irrigation | | |
| 100 | : Percentage of soil surface wetted by irrigation | | |
| 2 | : Generate irrigation schedule | | |
| 1 | : Time criterion = fixed intervals | | |
| 2 | : Fixed application depth | | |
| From day | Interval (days) | Application depth (mm) | ECw (dS/m) |
| ===== | | | |
| ==== | | | |
| 1 | 40 | 40 | 0.4 |
| 41 | 7 | 40 | 0.6 |
| 116 | 100 | 40 | 0.8 |
| Generated irrigation schedules as defined in above Table: | | | |
| no | irrigation interval: 7 days | no | |
| irrigation | applied irrigation amount: 40 mm | irrigation | |
| DNr 1 22 March sowing | DNr 41 1 May | DNr 116 15 July | DNr 125 24 July maturity |

Table 2.23q – 5. – Example of an irrigation file (file with extension IRR) in which the request for the determination of the Net irrigation water requirement is specified

| |
|---|
| Determination of Net irrigation requirement |
| 5.0 : AquaCrop Version (October 2015) |
| 1 : Sprinkler irrigation |
| 100 : Percentage of soil surface wetted by irrigation |
| 3 : Determination of Net Irrigation requirement |
| 50 : Allowable depletion of RAW (%) |

2.23.6 Field management file (*.MAN)

The type of mulches and the fraction of soil surface covered by the mulches, the soil fertility level, practices that affect the surface run-off (soil bunds and field surface practices), and weed infestation are specified in the field management file (files with extension MAN). The content of the field management file is given in Table 2.23r - 1, and an example in Table 2.23r - 3.

In the absence of a field management file, no specific field management conditions are considered. It is assumed that soil fertility is unlimited, that field surface practices do not affect soil evaporation or surface run-off, and that weed management is perfect.

Table 2.23r – 1. – Structure of the field management file (files with extension ‘MAN’)

| Line | Description | Format |
|------|---|----------------------|
| 1 | First line is a description of the file content | String of characters |
| 2 | Version number of AquaCrop | Real (1 digit) |
| 3 | Percentage (%) of ground surface covered by mulches in the growing period | Integer |
| 4 | Effect (%) of mulches on the reduction of soil evaporation, which depends on the type of mulches (see Table 2.23r - 2) | Integer |
| 5 | Degree of soil fertility stress (%) The effect of the selected soil fertility stress on crop production depends on calibration since the biomass – stress relationship (calibrated in the Crop characteristic menu), determines the corresponding biomass production that can be expected under well watered conditions for the selected soil fertility stress. The expected biomass production is expressed as a percentage of the maximum biomass production for unlimited soil fertility. In the absence of a calibration, the adjustment of biomass production to the specified soil fertility stress will not be simulated. | Integer |
| 6 | Height (m) of soil bunds | Real (2 digits) |
| 7 | A number (0 to 1) used as a code to specify if surface runoff is affected/prevented by field surface practices: 0 : surface runoff is not affected 1 : surface runoff is affected or completely prevented (Default = 0) | Integer |
| 8 | Percent increase/decrease of soil profile CN value (is zero (not applicable) when surface runoff is not affected or completely prevented by surface practices) | Integer |
| 9 | Relative cover of weeds (%) | Integer |

| | | |
|----|--|-----------------|
| 10 | Increase/decrease of relative cover of weeds in mid-season (%) | Integer |
| 11 | shape factor of the CC expansion function in a weed infested field | Real (2 digits) |

Table 2.23r – 2. – Effect of mulches on the reduction of soil evaporation

| Type of mulches | Effect on reduction of soil evaporation |
|--|---|
| Synthetic plastic mulches (completely reducing the evaporation of water from the soil surface) | 100 % |
| Organic mulches, which consists of unincorporated plant residues or foreign material imported to the field such as a straw | 50 % |
| User specified mulches | 10 ... 100 % |

Table 2.23r – 3. – Example of field management file

| | |
|---|--|
| soil fertility stress, organic mulches, practices preventing runoff, weed infestation | |
| 6.0 | : AquaCrop Version (March 2016) |
| 80 | : percentage (%) of ground surface covered by mulches IN growing period |
| 50 | : effect (%) of mulches on reduction of soil evaporation |
| 57 | : Degree of soil fertility stress (%) - Effect is crop specific |
| 0.00 | : height (m) of soil bunds |
| 1 | : surface runoff affected or completely prevented by field surface practices |
| 0 | : N/A (surface runoff is not affected or completely prevented) |
| 20 | : relative cover of weeds at canopy closure (%) |
| 25 | : increase of relative cover of weeds in mid-season (+%) |
| -0.01 | : shape factor of the CC expansion function in a weed infested field |

2.23.7 Soil profile file (*.SOL)

Major physical characteristics of the successive soil horizons of the soil profile are specified in a soil profile file (files with extension ‘SOL’). Up to 5 soil horizons can be specified.

▪ Structure and example of SOL files

The structure and an example of a SOL file are given in Tables 2.23s - 1 and 2.23s – 2.

Table 2.23s – 1. – Structure of the Soil profile file (files with extension SOL)

| Line | Description | Format |
|------|--|---|
| 1 | First line is a description of the file content | String of characters |
| 2 | Version number of AquaCrop | Real (1 digit) |
| 3 | CN: the Curve Number (dimensionless) | Integer |
| 4 | REW: The Readily evaporable water from top layer (mm) | Integer |
| 5 | Number of soil horizons | Integer |
| 6 | Variable no longer applicable | - 9 |
| 7 | Line with symbols for the soil physical characteristics | |
| 8 | Line with units for the soil physical characteristics | |
| 9 | Soil physical characteristics for soil horizon 1: - thickness of the soil horizon (m) - soil water content at saturation (vol%) - soil water content at Field Capacity (vol%) - soil water content at Permanent Wilting Point (vol%) - saturated hydraulic conductivity (mm/day) - penetrability (%) for root zone expansion rate - mass percentage (%) of the gravel fraction - parameter ‘a’ for estimation of capillary rise - parameter ‘b’ for estimation of capillary rise - description | Real (2 digits) Real (1 digit) Real (1 digit) Real (1 digit) Real (1 digit) Integer Integer Real (6 digits) Real (6 digits) String of characters |
| 10 | Soil physical characteristics for soil horizon 2 (if present) | as for line 9 |
| 11 | Soil physical characteristics for soil horizon 3 (if present) | as for line 9 |
| 12 | Soil physical characteristics for soil horizon 4 (if present) | as for line 9 |
| 13 | Soil physical characteristics for soil horizon 5 (if present) | as for line 9 |

Table 2.23s – 2. – Example of soil profile file with 3 horizons

| Three layered loamy soil | | | | | | | | | |
|--------------------------|-----|----|----|------|---------------|--------|-----|-----|--|
| 6.0 | | | | | | | | | : AquaCrop Version (March 2017) |
| 46 | | | | | | | | | : CN (Curve Number) |
| 7 | | | | | | | | | : Readily evaporable water from top layer (mm) |
| 3 | | | | | | | | | : number of soil horizons |
| -9 | | | | | | | | | : variable no longer applicable |
| Thickness | Sat | FC | WP | Ksat | Penetrability | Gravel | CRa | CRb | description |

| --- (m) - | ---- (vol %) ----- | (mm/day) | (%) | (%) | | | |
|-----------|--------------------|----------|------|--------|-----|----|-------------------------------|
| - | | | | | | | |
| 0.30 | 41.0 | 22.0 | 10.0 | 1200.0 | 100 | 30 | -0.323200 0.219363 sandy loam |
| 0.50 | 46.0 | 31.0 | 15.0 | 500.0 | 100 | 0 | -0.453600 0.837340 loam |
| 2.00 | 46.0 | 33.0 | 13.0 | 575.0 | 85 | 0 | -0.446850 0.904118 silt loam |

- **Indicative values for soil physical soil characteristics**

Indicative values are presented and discussed in section 2.14.2 ‘Indicative values for soil physical characteristics’

The total porosity (assumed to be similar to the soil water content at saturation SAT) can also be derived from the soil bulk density of the soil horizon:

$$SAT = 100 \frac{(\rho_p - \rho_b)}{\rho_p} \quad (\text{Eq. 2.23s - 1})$$

| | | |
|-------|----------|---|
| where | SAT | soil water content at saturation [vol%] |
| | ρ_p | particle density [2.65 Mg/m ³] |
| | ρ_b | bulk density of the soil [Mg/m ³] |

- **‘a’ and ‘b’ parameters for estimating capillary rise**

The maximum possible capillary rise for each soil horizon is calculated with an exponential equation. The default ‘a’ and ‘b’ parameters, describing the capillary rise, are obtained by (i) considering the class of the soil type and (ii) the saturated hydraulic conductivity:

1. The class of the soil type for each of the soil horizons is obtained by comparing the volumetric water content at saturation (SAT), field capacity (FC) and permanent wilting point (PWP) of the soil horizon with the expected ranges of those soil water contents (Table 2.23s - 3). Four classes are distinguished: I. sandy soils; II. Loamy soils; III Sandy clayey soils; and IV Silty clayey soils;
2. The a and b soil parameters for each soil horizon are obtained with Eq. 2.23s - 2 and 2.23s - 3 by considering (i) the soil class of the soil horizon and (ii) the saturated hydraulic conductivity (Ksat in mm/day) for that soil horizon (Table 2.23s - 4 and 2.23s - 5).

Table 2.23s – 3. – Calculation procedure for the soil class

```

IF (SATvolPro <= 55)
THEN BEGIN
  IF (PWPvolPro >= 20)
    THEN BEGIN
      IF ((SATvolPro >= 49) AND (FCvolPro >= 40))
        THEN NumberSoilClass := 4 // silty clayey soils
        ELSE NumberSoilClass := 3 // sandy clayey soils
      END
    ELSE BEGIN
      IF (FCvolPro < 23)
        THEN NumberSoilClass := 1 // sandy soils
      ELSE BEGIN
        IF ((PWPvolPro > 16) AND (Ksatmm < 100))
          THEN NumberSoilClass := 3 // sandy clayey soils
        ELSE BEGIN
          IF ((PWPvolPro < 6) AND (FCvolPro < 28)
            AND (Ksatmm > 750))
            THEN NumberSoilClass := 1 // sandy soils
          ELSE NumberSoilClass := 2 // loamy soils
        END;
      END;
    END;
  END;
END;

```

```

        END;
    END
ELSE NumberSoilClass := 4; // silty clayey soils

```

Table 2.23s – 4. – Equation 2a and 2b for the 4 soil Classes with indication of the considered range for the saturated hydraulic conductivity (K_{sat})

| Soil Class | Range K_{sat} $\text{mm} \cdot \text{day}^{-1}$ | a (Eq. 2.23s - 2) | b (Eq. 2.23s - 3) |
|--|---|-------------------------------------|---------------------------------|
| I. Sandy soils sand, loamy sand, sandy loam | 200 to 2000 | $-0.3112 - 10^{-5} K_{sat}$ | $-1.4936 + 0.2416 \ln(K_{sat})$ |
| II. Loamy soils loam, silt loam, silt | 100 to 750 | $-0.4986 + 9 \cdot 10^{-5} K_{sat}$ | $-2.1320 + 0.4778 \ln(K_{sat})$ |
| III. Sandy clayey soils sandy clay, sandy clay loam, clay loam | 5 to 150 | $-0.5677 - 4 \cdot 10^{-5} K_{sat}$ | $-3.7189 + 0.5922 \ln(K_{sat})$ |
| IV. Silty clayey soils silty clay loam, silty clay, clay | 1 to 150 | $-0.6366 + 8 \cdot 10^{-4} K_{sat}$ | $-1.9165 + 0.7063 \ln(K_{sat})$ |

Table 2.23s – 5. – Calculation procedure for ‘a’ and ‘b’ parameters for the 4 soil classes

```

CASE SoilClass OF
    1 : BEGIN // sandy soils
        aParam := -0.3112 - KsatMM/100000;
        bParam := -1.4936 + 0.2416*LN(KsatMM);
        END;
    2 : BEGIN // loamy soils
        aParam := -0.4986 + 9*KsatMM/100000;
        bParam := -2.1320 + 0.4778*LN(KsatMM);
        END;
    3 : BEGIN // sandy clayey soils
        aParam := -0.5677 - 4*KsatMM/100000;
        bParam := -3.7189 + 0.5922*LN(KsatMM);
        END;
    else BEGIN // silty clayey soils
        aParam := -0.6366 + 8*KsatMM/10000;
        bParam := -1.9165 + 0.7063*LN(KsatMM);
        END;
    end;

```

- **CN: Curve number (dimensionless)**

The Curve Number (CN) is required for the simulation of the surface runoff and its value refers to the value for antecedent moisture class II (AMC II).

The Curve Number of a soil is a function of its type, slope, land use, cover and the relative wetness of the top soil. If not given as input it can be derived from the saturated hydraulic conductivity (K_{sat}) of the top soil horizon (see 2.14.3 ‘Characteristics of the soil surface layer’, Tab. 2.14b).

- **REW: Readily Evaporable Water (mm)**

REW expresses the maximum amount of water (mm) that can be extracted by soil evaporation from a thinly soil surface layer in stage I.

REW is derived from the soil water content at Field Capacity (FC) and Permanent Wilting Point (PWP) of the top soil horizon (both expressed as volume %):

$$0 \leq REW = 10(FC - PWP/2)Z_{e, surf} \leq 15 \quad (\text{Eq. 2.23s - 4})$$

where FC volume water content at field capacity [vol%];
 PWP volume water content at permanent wilting point [vol%];
 $Z_{e, surf}$ thickness of the evaporating soil surface layer in direct contact with the atmosphere [0.040 m].

The calculation procedure is presented in Table 2.23s - 6.

Table 2.23s – 6. – Calculation procedure for REW

```
CONST Zsurflayer = 0.04; // meter
REW := ROUND(10 * (FC - (PWP/2)) * Zsurflayer);
IF (REW < 0) THEN REW := 0; // minimum value
IF (REW > 15) THEN REW := 15; // maximum value
```

2.23.8 Groundwater file (*.GWT)

Characteristics of the groundwater table are specified in the groundwater file (files with extension GWT). The considered characteristics of the groundwater table are (i) its depth below the soil surface and (2) its salinity. The characteristics can be constant or may vary throughout the year. The description of the content and examples are given in Table 2.23t – 1 to 2.23t – 4.

In the absence of a groundwater file, no shallow groundwater table is assumed when running a simulation.

Table 2.23t – 1. – Structure of the Groundwater file (files with extension GWT)

| Line | Description | Format |
|------|---|--|
| 1 | First line is a description of the file content | String of characters |
| 2 | Version number of AquaCrop | Real (1 digit) |
| 3 | A number (0, 1 or 2) used as a code to specify the presence and its variation in time of the groundwater table: 0: code indicating that there is no groundwater table; 1: code indicating that the characteristics are constant 2: code indicating that the characteristics are variable | Integer |
| | Code = 0 (in line 3): No groundwater table no further lines are required (Example Table 2.23t - 2) | |
| | Code = 1 (in line 3): Groundwater table at fixed depth and with constant salinity 4 extra lines are required (Example Table 2.23t - 3) | |
| 4 | Empty line | - |
| 5 | Title of variables ('Day Depth (m) ECw (dS/m)') | String of characters |
| 6 | Dotted line ('=====') | String of characters |
| 7 | – The day number from which the characteristics of the groundwater table are valid (has to be from the first day since the characteristics are constant); – The depth (m) of the groundwater table below the soil surface; – The salinity of the groundwater table expressed by the electrical conductivity of the water (ECw) in deciSiemens per meter (dS/m). | Integer Real (2 digits) Real (1 digit) |
| | Code = 2 (in line 3): Variable groundwater table extra lines are required (Example Table 2.23t - 4) | |
| 4 | first day of observations | Integer |
| 5 | first month of observations | Integer |
| 6 | first year of observations (1901 if the characteristics are not linked to a specific year) | Integer |

| | | |
|------|--|--|
| 7 | Empty line | - |
| 8 | Title of variables ('Day Depth (m) ECw (dS/m)') | String of characters |
| 9 | Dotted line ('=====') | String of characters |
| 10 | Specify for the first observation: – The day number from which the characteristics of the groundwater table are valid (with reference to the date specified in line 4 (DD), 5 (MM) and 6 (YYYY)); – The depth (m) of the groundwater table below the soil surface; – The salinity of the groundwater table expressed by the electrical conductivity of the water (ECw) in deciSiemens per meter (dS/m). | Integer Real (2 digits) Real (1 digit) |
| 11 | Specify for the next observation: – The day number; – The depth (m); – The salinity (dS/m). | Integer Real (2 digits) Real (1 digit) |
| 12.. | Etc. | |

Table 2.23t – 2. – Example of No groundwater table

no shallow groundwater table

5.0 : AquaCrop Version (October 2015)

0 : no groundwater table

In a groundwater file, the user can specify explicitly that there is no groundwater table or too deep to result in capillary rise to the top soil (as in the example presented in Table 2.23t - 2). However, there is no need to create such a file, since in the absence of a groundwater file, AquaCrop will assume when running a simulation, that the groundwater table is absent or too deep to result in capillary rise.

Table 2.23t – 3. – Example of a groundwater table at fixed depth and with constant salinity

constant groundwater table at 1.50 m and with salinity level of 1.5 dS/m

5.0 : AquaCrop Version (October 2015)

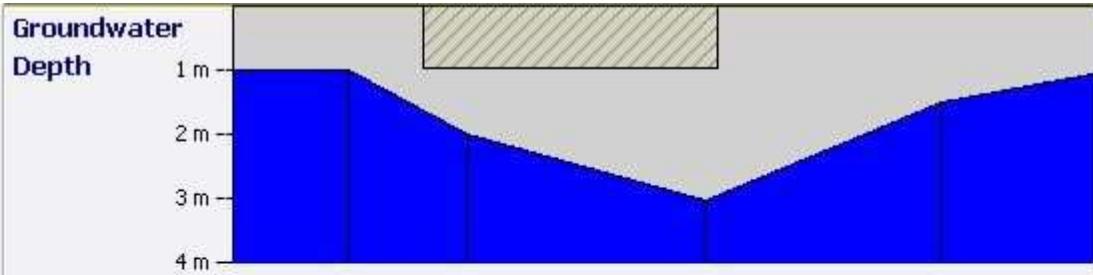
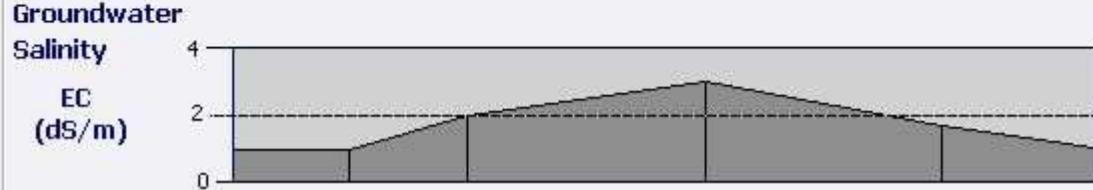
1 : groundwater table at fixed depth and with constant salinity

Day Depth (m) ECw (dS/m)

=====

| | | |
|---|------|-----|
| 1 | 1.50 | 1.5 |
|---|------|-----|

Table 2.23t – 4. – Example of a ground water table with variable depth and/or variable soil salinity

| variable groundwater table for year 2000 | | |
|--|-----------|------------|
| 5.0 : AquaCrop Version (October 2015) | | |
| 2 : variable groundwater table | | |
| 1 : first day of observations | | |
| 1 : first month of observations | | |
| 2000 : first year of observations (1901 if not linked to a specific year) | | |
| Day | Depth (m) | ECw (dS/m) |
| 50 | 1.00 | 1.0 |
| 100 | 2.00 | 2.0 |
| 200 | 3.00 | 3.0 |
| 300 | 1.50 | 1.7 |
| 400 | 0.80 | 0.7 |
| 500 | 1.50 | 0.5 |
|  | | |
|  | | |
| At run time, AquaCrop will derive the depth and water quality of the groundwater table for each day, by linear interpolation between the specified values. For moments out of the listed period, the depth and soil water quality is assumed to be equal to the 1 st value in the list (for earlier dates) or the last value in the list (for later dates). | | |

2.23.9 File with initial conditions (*.SW0)

The soil water content and soil salinity in the soil profile at the start of the simulation run are specified in the files with the initial conditions (files with extension SW0). If the field is surrounded by soil bunds the depth of the water layer on top of the soil surface and its water quality at the start of the simulation run are specified as well in the SW0 file. The soil salinity is given by the Electrical Conductivity of the saturated soil-paste extract (ECe). The quality of the water between the soil bunds is given by its Electrical Conductivity (ECw). Both ECe and ECw are expressed in dS/m. The structure and examples of SW0 files are given in Table 2.23u -1 to 2.23u - 5.

In the absence of a file with initial conditions, it is assumed that in the soil profile (i) the soil water content is at field capacity and (ii) salts are absent at the start of the simulation.

Table 2.23u – 1. – Structure of the file with initial conditions (files with extension SW0)

| Line | Description | Format |
|------|---|----------------------|
| 1 | First line is a description of the file content | String of characters |
| 2 | Version number of AquaCrop | Real (1 digit) |
| 3 | Canopy Cover (%) at start of the simulation period. If undefined (-9.00), the maximum canopy cover that could have been reached without water stress at the start of the simulation period is assumed. | Real (2 digits) |
| 4 | Biomass produced (ton/ha) before the start of the simulation period | Real (3 digits) |
| 5 | Effective rooting depth (m) at start of the simulation period. If undefined (-9.00), the maximum effective rooting depth that could have been reached without water stress at the start of the simulation period is assumed. | Real (2 digits) |
| 6 | Water layer (mm) stored between soil bunds (if present) | Real (1 digit) |
| 7 | Electrical conductivity (dS/m) of water layer stored between soil bunds (if present) | Real (2 digits) |
| 8 | A number (0 or 1) used as a code to specify if the initial conditions are specified for specific layers, or at particular depths of the soil profile: 0: code indicating that the data are specified for specific layers (Example Table 2.23u – 2, and 3); 1: code indicating that the data are specified at particular depths of the soil profile (Example Table 2.23u – 4 and 5). | Integer |
| 9 | Number of different layers/depth considered (Maximum = 12) | Integer |
| 10 | Empty line | - |
| 11 | Title (list of parameters) | String of characters |
| 12 | Dotted line ('-----') | String of characters |

| | | |
|---|--|---|
| | Code = 0 (in line 8): For specific soil layers (Example Table 2.23u – 2, and 3) | |
| 13 | For the 1 st soil layer: – Thickness of the soil layer in meter – Soil water content in volume % – Soil salinity (ECe) in dS/m | Real (2 digits) Real (2 digits) Real (2 digits) |
| 14 .. | Repeat for each soil layer | |
| Code = 1 (in line 8): At particular soil depths (Example Table 2.23u – 4 and 5) | | |
| 13 | At the 1 st soil depth: – Soil depth in meter – Soil water content in volume % – Soil salinity (ECe) in dS/m | Real (2 digits) Real (2 digits) Real (2 digits) |
| 14 .. | Repeat for each soil depth | |

Table 2.23u – 2. – Example for water stored between bunds

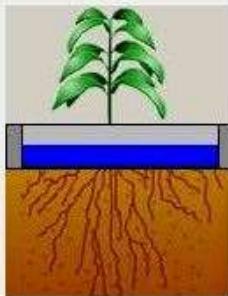
| |
|--|
| uniform silty soil at saturation with water between soil bunds |
| 5.0 : AquaCrop Version (October 2015) |
| -9.00 : initial canopy cover that can be reached without water stress will be used as default |
| 0.000 : biomass (ton/ha) produced before the start of the simulation period |
| -9.00 : initial effective rooting depth that can be reached without water stress will be used as default |
| 150.0 : water layer (mm) stored between soil bunds (if present) |
| 0.00 : electrical conductivity (dS/m) of water layer stored between soil bunds (if present) |
| 0 : soil water content specified for specific layers |
| 1 : number of layers considered |
| Thickness layer (m) Water content (vol%) ECe (dS/m) |
| ===== |
| 4.00 43.00 0.00 |
| soil bunds |
| Water on top of (paddy) field |
| Bund height 0.30 m |
| Water depth <input type="text" value="150"/> mm |
| Water quality <input type="text" value="0.00"/> dS/m |
|  |

Table 2.23u – 3. – Example of initial conditions specified for specific soil layers

| Soil water and salinity content in Field AZ123 on 21 March 2010 | | | | |
|--|----------------------|------------|--|--|
| 5.0 : AquaCrop Version (October 2015) | | | | |
| -9.00 : initial canopy cover that can be reached without water stress will be used as default | | | | |
| 0.000 : biomass (ton/ha) produced before the start of the simulation period | | | | |
| -9.00 : initial effective rooting depth that can be reached without water stress will be used as default | | | | |
| 0.0 : water layer (mm) stored between soil bunds (if present) | | | | |
| 0.00 : electrical conductivity (dS/m) of water layer stored between soil bunds (if present) | | | | |
| 0 : soil water content specified for specific layers | | | | |
| 3 : number of layers considered | | | | |
| Thickness layer (m) | Water content (vol%) | ECe (dS/m) | | |
| 0.40 | 30.00 | 1.00 | | |
| 0.40 | 20.00 | 2.00 | | |
| 0.40 | 18.00 | 2.50 | | |

| layer(s) considered | | |
|---------------------------------------|--------------------|---------------|
| thickness from - to | Soil water content | Soil salinity |
| m m | vol % | dS/m |
| 1 0.40 0.00 - 0.40 30.00 1.00 | | |
| 2 0.40 0.40 - 0.80 20.00 2.00 | | |
| 3 0.40 0.80 - 1.20 18.00 2.50 | | |

Soil water profile
Soil salinity profile

Soil water profile

soil water content vol %

0 10 20 30

0.20 m
0.40 m
0.60 m
0.80 m
1.00 m

0 10 20 30

0.20 m
0.40 m
0.60 m
0.80 m
1.00 m

Table 2.23u – 4. – Example of initial conditions specified at particular soil depths

Observed soil water and salinity content in Field AZ123 on March 2010 at particular depths

- 5.0 : AquaCrop Version (October 2015)
- 9.00 : initial canopy cover that can be reached without water stress will be used as default
- 0.000 : biomass (ton/ha) produced before the start of the simulation period
- 9.00 : initial effective rooting depth that can be reached without water stress will be used as default
- 0.0 : water layer (mm) stored between soil bunts (if present)
- 0.00 : electrical conductivity (dS/m) of water layer stored between soil bunts (if present)
- 1 : soil water content specified at particular depths
- 3 : number of soil depths considered

| Soil depth (m) | Water content (vol%) | ECe (dS/m) |
|----------------|----------------------|------------|
| 0.20 | 30.00 | 1.00 |
| 0.60 | 20.00 | 2.00 |
| 1.00 | 18.00 | 2.50 |

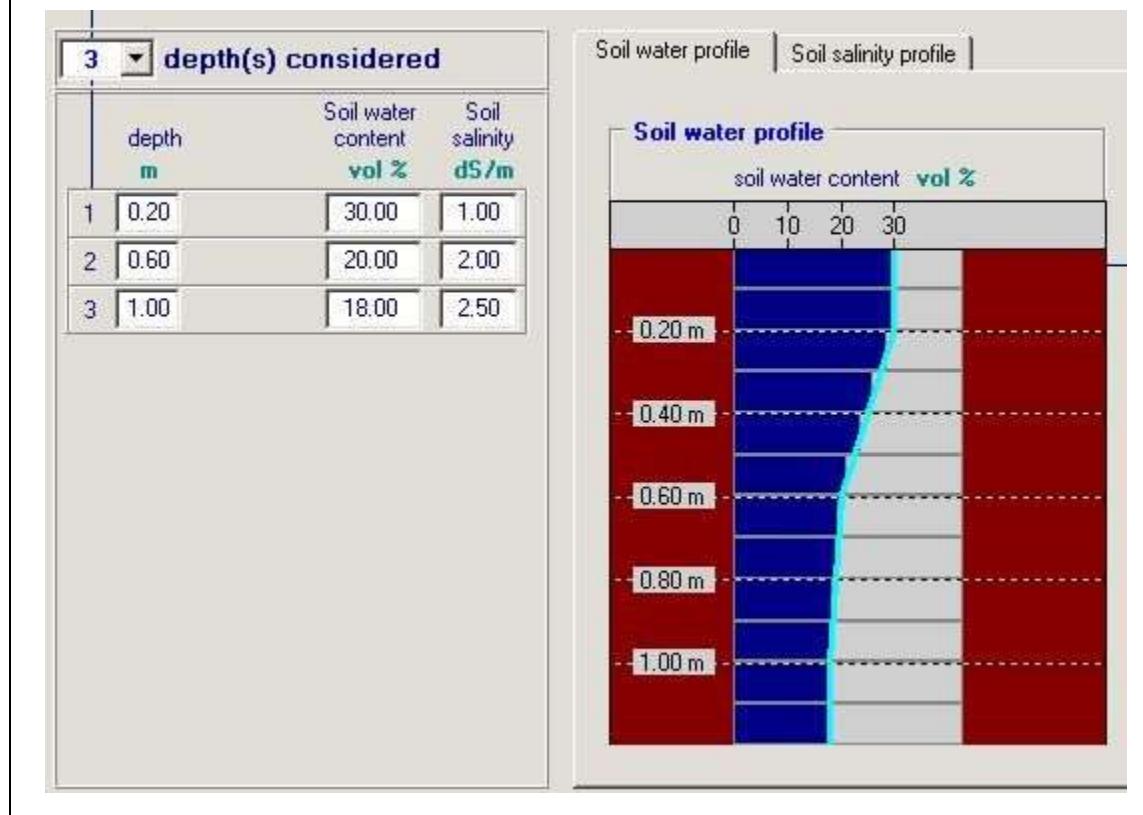


Table 2.23u – 5. – Example of initial conditions one month after planting, with indication of the observed soil water content at particular depths, the canopy cover and the biomass already produced at that day

| | | |
|--|----------------------|------------|
| initial conditions 1 month after planting | | |
| 5.0 : AquaCrop Version (October 2015) | | |
| 31.00 : initial canopy cover (%) at start of simulation period | | |
| 0.150 : biomass (ton/ha) produced before the start of the simulation period | | |
| -9.00 : initial effective rooting depth that can be reached without water stress will be used as default | | |
| 0.0 : water layer (mm) stored between soil bunds (if present) | | |
| 0.00 : electrical conductivity (dS/m) of water layer stored between soil bunds (if present) | | |
| 1 : soil water content specified at particular depths | | |
| 6 : number of soil depths considered | | |
| Soil depth (m) | Water content (vol%) | ECe (dS/m) |
| 0.10 | 10.00 | 0.00 |
| 0.40 | 15.00 | 0.00 |
| 0.60 | 30.00 | 0.00 |
| 0.80 | 30.00 | 0.00 |
| 1.00 | 33.00 | 0.00 |
| 1.20 | 25.00 | 0.00 |

| Description | Initial soil water and salinity content | Initial crop development and production |
|--|---|---|
| Initial crop development and production | | |
| | | |
| Growing cycle From: 22 March - To: 24 July | | |
| Simulation period | | |
| Start: after germination 22 April | | |
| at start simulation period | Default (no stress) | Specified |
| Initial Canopy Cover (CC) | <input type="radio"/> 53.07 % | <input checked="" type="radio"/> 31.00 % |
| Biomass produced (B) before start simulation period | <input type="radio"/> 0.000 ton/ha | <input checked="" type="radio"/> 0.150 ton/ha |
| Initial rooting depth (Z) | <input checked="" type="radio"/> 0.56 m | <input type="radio"/> 0.56 m |

2.23.10 File with off-season conditions (*.OFF)

A file with off-season conditions (Tab. 2.23v - 1 and 2.23v - 4) contains field management (the presence of mulches) and irrigation management conditions (irrigation events and the quality of the irrigation water) in the off-season (i.e. before and after the growing cycle).

In the absence of a file with off-season conditions, no mulches and irrigation events are considered before and after the growing cycle.

Table 2.23v – 1. – Structure of the file with off-season conditions

| Line | Description | Format |
|-------------|--|--|
| 1 | First line is a description of the file content | String of characters |
| 2 | Version number of AquaCrop | Real (1 digit) |
| 3 | Percentage (%) of ground surface covered by mulches before the growing period | Integer |
| 4 | Percentage (%) of ground surface covered by mulches after the growing period | Integer |
| 5 | Effect (%) of mulches on the reduction of soil evaporation, which depends on the type of mulches (see Table 2.23v - 2) | Integer |
| 6 | Number of irrigation events before the growing period (Maximum = 5) | Integer |
| 7 | The Electrical Conductivity (dS/m) of the irrigation water before the growing period | Real (1 digit) |
| 8 | Number of irrigation events after the growing period (Maximum = 5) | Integer |
| 9 | The Electrical Conductivity (dS/m) of the irrigation water after the growing period | Real (1 digit) |
| 10 | Percentage of soil surface wetted by irrigation in the off-season. This percentage is generally closely linked with the irrigation method. Indicative values for the percentage of soil surface wetted for various irrigation methods are presented in Table 2.23v – 3. Default = 100 | Integer |
| 11 | Empty line | - |
| 12 | Title ('Day Depth(mm) When') | String of characters |
| 13 | Dotted line ('=====') | String of characters |
| 14 and next | For the 1 st irrigation event (if any) before the growing period: - The number of days after the start of the simulation period - The net irrigation application depth (mm) - String of characters stating that the event occurred before the growing period Repeat for each successive irrigation event before the growing period (if any) | Integer Integer String of characters |

| | | |
|--|---|---|
| | <p>For the 1st irrigation event (if any) after the growing period:</p> <ul style="list-style-type: none"> - The number of days after the end of the growing period - The net irrigation application depth (mm) - String of characters stating that the event occurred after the growing period <p>Repeat for each successive irrigation event after the growing period (if any)</p> <p>The net irrigation application depth refers to the net irrigation amount. Extra water applied to the field to account for conveyance losses or the uneven distribution of irrigation water on the field should not be added.</p> | <p>Integer</p> <p>Integer</p> <p>String of characters</p> |
|--|---|---|

Table 2.23v – 2. – Effect of mulches on the reduction of soil evaporation

| Type of mulches | Effect on reduction of soil evaporation |
|--|---|
| Synthetic plastic mulches (completely reducing the evaporation of water from the soil surface) | 100 % |
| Organic mulches, which consists of unincorporated plant residues or foreign material imported to the field such as a straw | 50 % |
| User specified mulches | 10 ... 100 % |

Table 2.23v – 3. – Indicative values for soil surface wetted for various irrigation methods

| Irrigation method | Soil surface wetted (%) |
|--|-------------------------|
| Sprinkler irrigation | 100 |
| Basin irrigation | 100 |
| Border irrigation | 100 |
| Furrow irrigation (every furrow), narrow bed | 60 – 100 |
| Furrow irrigation (every furrow), wide bed | 40 – 60 |
| Furrow irrigation (alternated furrows) | 30 – 50 |
| Trickle/Drip - Micro irrigation | 15 – 40 |
| Subsurface drip irrigation | 0 |

Table 2.23v – 4. – Example of a file with off-season conditions

| Irrigation and field management conditions in the off-season | | | |
|--|------------|---|--|
| 5.0 | : | AquaCrop Version (October 2015) | |
| 0 | : | percentage (%) of ground surface covered by mulches BEFORE growing period | |
| 70 | : | percentage (%) of ground surface covered by mulches AFTER growing period | |
| 50 | : | effect (%) of mulches on reduction of soil evaporation | |
| 1 | : | number of irrigation events BEFORE growing period | |
| 1.5 | : | quality of irrigation water BEFORE growing period (dS/m) | |
| 0 | : | number of irrigation events AFTER growing period | |
| 4.0 | : | quality of irrigation water AFTER growing period (dS/m) | |
| 100 | : | percentage (%) of soil surface wetted by off-season irrigation | |
| Day | Depth (mm) | When | |
| 10 | 40 | before season | |

| Total Reduction in Soil evaporation | |
|-------------------------------------|---|
| 0 % | |
| Before growing cycle | |
| Soil Cover (mulch) | |
| 0 | % |

| Total Reduction in Soil evaporation | |
|-------------------------------------|---|
| 35 % | |
| After growing cycle | |
| Soil Cover (mulch) | |
| 70 | % |

| Irrigation events | |
|-----------------------|----------|
| When? | Depth? |
| Day No. 1 = 12 March | |
| Event | Date |
| 1 | 21 March |
| 2 | |
| 3 | |
| 4 | |
| 5 | |
| Day No. 10 = 21 March | |
| Clear All Events | |

| Irrigation water quality | |
|--------------------------|------|
| Electrical conductivity | |
| 1.5 | dS/m |
| Class - moderate | |

| growing cycle | |
|---------------|--|
| From 22 March | |
| To 24 July | |

2.23.11 Single and Multiple run Project files (*.PRO and *.PRM)

A project file is a file which contains all the required information for a simulation run. Distinction is made between projects containing the required information for a single simulation run (with 'PRO' as the filename extension) and projects consisting of a set of successive runs (for simulations in successive years), the so called multiple run projects (with 'PRM' as the filename extension).

A project file contains (Table 2.23w - 1):

- the period(s) of the growing cycle (from day 1 after sowing/transplanting to crop maturity);
- the simulation period(s): the first and last day of the simulation period which need not to coincide with the growing cycle;
- the file names (with their directory) containing the characteristics of the selected environment (climate, crop, irrigation management, field management, soil profile and groundwater table file);
- the file names (with their directory) containing the initial and off-season conditions; and
- the specific program settings for the run(s).

Table 2.23w – 1. – Structure and example of a project file

| <i>Title (Line 1) and Version number (Line 2)</i> | |
|---|--|
| winter wheat on sandy loam soil in Tunis for 22 successive years | |
| 6.0 : AquaCrop Version (March 2017) | |
| <i>The simulation period (Line 3 and 4) and the period of the growing cycle (Line 5 and 6) for the (first) simulation run – See Table 2.23w - 5 for calculation of day numbers</i> | |
| 28702 : First day of simulation period - 1 August 1979 28977 : Last day of simulation period - 2 May 1980 28791 : First day of cropping period - 29 October 1979 28977 : Last day of cropping period - 2 May 1980 | |
| <i>Setting of the program parameters (Line 7 to 27)</i> | |
| 4 : Evaporation decline factor for stage II 1.10 : Ke(x) Soil evaporation coefficient for fully wet and non-shaded soil surface 5 : Threshold for green CC below which HI can no longer increase (% cover) 70 : Starting depth of root zone expansion curve (% of Zmin) 5.00 : Maximum allowable root zone expansion (fixed at 5 cm/day) -6 : Shape factor for effect water stress on root zone expansion 20 : Required soil water content in top soil for germination (% TAW) 1.0 : Adjustment factor for FAO-adjustment soil water depletion (p) by ETo 3 : Number of days after which deficient aeration is fully effective 1.00 : Exponent of senescence factor adjusting drop in photosynthetic activity 12 : Decrease of p(sen) once early canopy senescence is triggered (% of p(sen)) 10 : Thickness top soil (cm) in which soil water depletion has to be determined 30 : Depth [cm] of soil profile affected by water extraction by soil evaporation 0.30 : Considered depth (m) of soil profile for calculation of mean θ for CN adjust. 1 : CN is adjusted to Antecedent Moisture Class 20 : salt diffusion factor (capacity for salt diffusion in micro pores) [%] 100 : salt solubility [g/liter] 16 : shape factor for effect of soil water content gradient on capillary rise 12.0 : Default minimum temperature (°C) if no temperature file is specified 28.0 : Default maximum temperature (°C) if no temperature file is specified 3 : Default method for the calculation of growing degree days | |

Table 2.23w – 1. – Structure and example of project file ... continued

| |
|---|
| <i>The file names with their directory (path) containing the characteristics of the selected climatic conditions (Line 28 to 42) for the (first) simulation run</i> |
| -- 1. Climate (CLI) file Tunis.CLI C:\FAO\AquaCrop\DATA\ 1.1 Temperature (TMP) file Tunis.TMP C:\FAO\AquaCrop\DATA\ 1.2 Reference ET (ETO) file Tunis.ETO C:\FAO\AquaCrop\DATA\ 1.3 Rain (PLU) file Tunis.PLU C:\FAO\AquaCrop\DATA\ 1.4 Atmospheric CO ₂ (CO ₂) file MaunaLoa.CO ₂ C:\FAO\AquaCrop\SIMUL\ |
| <i>The file name with its directory (path) containing the characteristics of the selected crop (Line 43 to 45) for the (first) simulation run</i> |
| -- 2. Crop (CRO) file WheatGDD.CRO C:\FAO\AquaCrop\DATA\ |
| <i>The file name with its directory (path) containing the characteristics of the selected irrigation management (Line 46 to 48) for the (first) simulation run</i> |
| -- 3. Irrigation (IRR) file (None) (None) |
| <i>The file name with its directory (path) containing the characteristics of the selected field management (Line 49 to 51) for the (first) simulation run</i> |
| -- 4. Management (MAN) file SF80B.MAN C:\FAO\AquaCrop\DATA\ |
| <i>The file name with its directory (path) containing the characteristics of the selected soil profile (Line 52 to 54) for the (first) simulation run</i> |
| -- 5. Soil profile (SOL) file SANDYLOAM.SOL C:\FAO\AquaCrop\DATA\ |
| <i>The file name with its directory (path) containing the characteristics of the selected groundwater table (Line 55 to 57) for the (first) simulation run</i> |
| -- 6. Groundwater (GWT) file (None) (None) |
| <i>The file names with its directory (path) containing the initial conditions (Line 58 to 60) for the (first) simulation run</i> |
| -- 7. Initial conditions (SW0) file SLiniTun.SW0 C:\FAO\AquaCrop\DATA\ |
| <i>The file name with its directory (path) containing the off-season conditions (Line 61 to 63) for the (first) simulation run</i> |
| -- 8. Off-season conditions (OFF) file (None) (None) |
| <i>In case of multiple projects: the simulation period, the crop growth cycle, file names containing the characteristics of the selected environment, file names containing the initial and off-season conditions for each of the successive run(s) are given in the next lines (Line 64 to ...)</i> |

In the absence of climate, irrigation management, field management, groundwater, initial and off-season conditions files, the default settings are assumed when running the simulation (Tab. 2.23w - 2).

Table 2.23w – 2. – Default settings assumed at the start of a simulation in the absence of climate, irrigation management, field management, groundwater, initial and/or off-season conditions file

| Environment | File | Remarks |
|-----------------------|--------|---|
| Climate | (None) | A default minimum and maximum air temperature (see Climate), an ETo of 5 mm/day, no rainfall and an average atmospheric CO ₂ concentration of 369.47 ppm are assumed throughout the growing cycle. When running a simulation without a climate file, the user has still the option to specify other than the default ETo and rainfall data. This climatic data can be specified for each day of the simulation period in the Input panel of the Simulation run menu |
| Irrigation management | (None) | Rainfed cropping is assumed. When running a simulation in this mode, irrigation can still be scheduled. The quality of the irrigation water and the irrigation application amount can be specified for each day of the simulation period in the Input panel of the Simulation run menu |
| Field management | (None) | No specific field management conditions are considered. It is assumed that soil fertility is unlimited, and that field surface practices do not affect soil evaporation or surface run-off |
| Groundwater | (None) | Absence of a shallow groundwater table |
| Simulation | File | Remarks |
| Initial conditions | (None) | At the start of the simulation it is assumed that in the soil profile (i) the soil water content is at field capacity and (ii) salts are absent |
| Off-season conditions | (None) | No specific field management conditions are considered outside the growing period. When running a simulation there are no irrigation events and mulches do not cover the field surface in the off-season |

An example of a single project (WheatTunis.PRO) and a multiple project file (TunisWheat.PRM) are given in Table 2.23w - 3 and Table 2.23w - 4.

Table 2.23w – 3. – Example of a single Project file (files with extension ‘PRO’)**File: WheatTunis.PRO**

```

1 year project for wheat (22 November 1979 - 23 May 1980), Tunis region, sandy loam soil
 6.0      : AquaCrop Version (March 2017)
28716     : First day of simulation period - 15 August 1979
28998     : Last day of simulation period - 23 May 1980
28815     : First day of cropping period - 22 November 1979
28998     : Last day of cropping period - 23 May 1980
  4       : Evaporation decline factor for stage II
 1.10     : Ke(x) Soil evaporation coefficient for fully wet and non-shaded soil surface
   5       : Threshold for green CC below which HI can no longer increase (% cover)
  70      : Starting depth of root zone expansion curve (% of Zmin)
 5.00     : Maximum allowable root zone expansion (fixed at 5 cm/day)
 -6      : Shape factor for effect water stress on root zone expansion
 20      : Required soil water content in top soil for germination (% TAW)
 1.0      : Adjustment factor for FAO-adjustment soil water depletion (p) by ETo
   3      : Number of days after which deficient aeration is fully effective
 1.00     : Exponent of senescence factor adjusting drop in photosynthetic activity of dying crop
 12      : Decrease of p(sen) once early canopy senescence is triggered (% of p(sen))
 10      : Thickness top soil (cm) for determination of soil water depletion
 30      : Depth [cm] of soil profile affected by water extraction by soil evaporation
 0.30     : Considered depth (m) of soil profile for calculation of mean soil water content for CN adjustment
   1      : CN is adjusted to Antecedent Moisture Class
  20     : salt diffusion factor (capacity for salt diffusion in micro pores) [%]
100      : salt solubility [g/liter]
 16      : shape factor for effect of soil water content gradient on capillary rise
12.0     : Default minimum temperature (°C) if no temperature file is specified
28.0     : Default maximum temperature (°C) if no temperature file is specified
   3      : Default method for the calculation of growing degree days
-- 1. Climate (CLI) file
Tunis.CLI
C:\FAO\AquaCrop\DATA\
1.1 Temperature (Tnx or TMP) file
Tunis.TMP
C:\FAO\AquaCrop\DATA\
1.2 Reference ET (ETo) file
Tunis.ETo
C:\FAO\AquaCrop\DATA\
1.3 Rain (PLU) file
Tunis.Plu
C:\FAO\AquaCrop\DATA\
1.4 Atmospheric CO2 concentration (CO2) file
MaunaLoa.CO2
C:\FAO\AquaCrop\SIMUL\
-- 2. Crop (CRO) file
WheatGDD.CRO
C:\FAO\AquaCrop\DATA\
-- 3. Irrigation management (IRR) file
(None)
(None)
-- 4. Field management (MAN) file
(None)
(None)
-- 5. Soil profile (SOL) file
SandyLoam.SOL
C:\FAO\AquaCrop\DATA\
-- 6. Groundwater table (GWT) file
(None)
(None)
-- 7. Initial conditions (SW0) file
DryWet.SW0
C:\FAO\AquaCrop\DATA\
-- 8. Off-season conditions (OFF) file
(None)
(None)

```

Table 2.23w – 4. – Example of a multiple Project file (files with extension ‘PRM’) with generated planting date and KEEP option for initial conditions.

```

22 year project for wheat cultivated in Tunis on sandy loam - KEEP initial conditions
 6.0      : AquaCrop Version (March 2017)
28716    : First day of simulation period - 15 August 1979
28977    : Last day of simulation period - 2 May 1980
28791    : First day of cropping period - 29 October 1979
28977    : Last day of cropping period - 2 May 1980
  4       : Evaporation decline factor for stage II
 1.10     : Ke(x) Soil evaporation coefficient for fully wet and non-shaded soil surface
   5       : Threshold for green CC below which HI can no longer increase (% cover)
  70      : Starting depth of root zone expansion curve (% of Zmin)
 5.00     : Maximum allowable root zone expansion (fixed at 5 cm/day)
 -6      : Shape factor for effect water stress on root zone expansion
 20      : Required soil water content in top soil for germination (% TAW)
 1.0      : Adjustment factor for FAO-adjustment soil water depletion (p) by ETo
   3       : Number of days after which deficient aeration is fully effective
 1.00     : Exponent of senescence factor adjusting drop in photosynthetic activity of dying crop
 12      : Decrease of p(sen) once early canopy senescence is triggered (% of p(sen))
 10      : Thickness top soil (cm) for determination of soil water depletion
 30      : Depth [cm] of soil profile affected by water extraction by soil evaporation
 0.30     : Considered depth (m) of soil profile for calculation of mean soil water content for CN adjustment
   1       : CN is adjusted to Antecedent Moisture Class
  20      : salt diffusion factor (capacity for salt diffusion in micro pores) [%]
100      : salt solubility [g/liter]
  16      : shape factor for effect of soil water content gradient on capillary rise
12.0     : Default minimum temperature (°C) if no temperature file is specified
28.0     : Default maximum temperature (°C) if no temperature file is specified
   3       : Default method for the calculation of growing degree days
-- 1. Climate (CLI) file
Tunis.CLI
C:\FAO\AquaCrop\DATA\
1.1 Temperature (Tnx or TMP) file
Tunis.TMP
C:\FAO\AquaCrop\DATA\
1.2 Reference ET (ETo) file
Tunis.ETo
C:\FAO\AquaCrop\DATA\
1.3 Rain (PLU) file
Tunis.Plu
C:\FAO\AquaCrop\DATA\
1.4 Atmospheric CO2 concentration (CO2) file
MaunaLoa.CO2
C:\FAO\AquaCrop\SIMUL\
-- 2. Crop (CRO) file
WheatGDD.CRO
C:\FAO\AquaCrop\DATA\
-- 3. Irrigation management (IRR) file
(None)
(None)
-- 4. Field management (MAN) file
(None)
(None)
-- 5. Soil profile (SOL) file
SandyLoam.SOL
C:\FAO\AquaCrop\DATA\
-- 6. Groundwater table (GWT) file
(None)
(None)
-- 7. Initial conditions (SW0) file
DryWet.SW0
C:\FAO\AquaCrop\DATA\
-- 8. Off-season conditions (OFF) file
(None)
(None)

```

Table 2.23w – 4. – Example of a multiple Project file ... continued

| | |
|--|---|
| 28978 | : First day of simulation period - 3 May 1980 |
| 29378 | : Last day of simulation period - 7 June 1981 |
| 29209 | : First day of cropping period - 20 December 1980 |
| 29378 | : Last day of cropping period - 7 June 1981 |
| -- 1. Climate (CLI) file | |
| Tunis.CLI | |
| C:\FAO\AquaCrop\DATA\ | |
| 1.1 Temperature (TMP) file | |
| Tunis.TMP | |
| C:\FAO\AquaCrop\DATA\ | |
| 1.2 Reference ET (ETo) file | |
| Tunis.ETo | |
| C:\FAO\AquaCrop\DATA\ | |
| 1.3 Rain (PLU) file | |
| Tunis.Plu | |
| C:\FAO\AquaCrop\DATA\ | |
| 1.4 Atmospheric CO ₂ (CO2) file | |
| MaunaLoa.CO2 | |
| C:\FAO\AquaCrop\SIMUL\ | |
| -- 2. Crop (CRO) file | |
| WheatGDD.CRO | |
| C:\FAO\AquaCrop\DATA\ | |
| -- 3. Irrigation (IRR) file | |
| (None) | |
| (None) | |
| -- 4. Management (MAN) file | |
| (None) | |
| (None) | |
| -- 5. Soil profile (SOL) file | |
| SandyLoam.SOL | |
| C:\FAO\AquaCrop\DATA\ | |
| -- 6. Groundwater (GWT) file | |
| (None) | |
| (None) | |
| -- 7. Initial conditions (SW0) file | |
| KeepSWC | |
| Keep soil water profile of previous run | |
| -- 8. Off-season conditions (OFF) file | |
| (None) | |
| (None) | |
| 29379 | : First day of simulation period - 8 June 1981 |
| 29747 | : Last day of simulation period - 11 June 1982 |
| 29585 | : First day of cropping period - 31 December 1981 |
| 29747 | : Last day of cropping period - 11 June 1982 |
| -- 1. Climate (CLI) file... | |
| ... | |

The figure is a screenshot of the AquaCrop software's timeline interface. It features a top navigation bar with a 'year' dropdown set to '1979' and a month dropdown set to 'JAN'. Below this is a horizontal timeline for five years: 1979, 1980, 1981, 1982, and 1983. Each year is represented by a blue bar at the bottom and a green bar above it. The green bars represent the 'crop growing cycle', which starts in January and ends in June or July. The blue bars represent the 'simulation period', which covers the entire year from January to December. A legend at the bottom identifies the colors: green for 'crop growing cycle' and blue for 'simulation period'.

AquaCrop uses day numbers to specify the start and end of the simulation period and of the growing cycle. The day number refers to the days elapsed since 0th January 1901 at 0 am. The calculation procedure is given in Table 2.23w - 5 and the code in Table 2.23w - 6.

Table 2.23w – 5. – Number of days elapsed since 0th January 1901, 0 am

| | |
|---|-----------------------------|
| Validity: The method is valid from 1901 to 2099 only (time range in AquaCrop) | |
| Rules | |
| 6. Subtract 1901 from the year | |
| 7. Multiply by 365.25 | |
| 8. According to the month add: | |
| <ul style="list-style-type: none"> - January : 0 - February : 31 - March : 59.25 - April : 90.25 - May : 120.25 - June : 151.25 - July : 181.25 - August : 212.25 - September : 243.25 - October : 273.25 - November : 304.25 - December : 334.25 | |
| 9. Add the number of the day within the month | |
| 10. Take the integer | |
| Example | |
| For 24 August 1982 | |
| 1. Subtract 1901 from the year | 1982 – 1901 = 81 |
| 2. Multiply by 365.25 | 81 x 365.25 = 29585.25 |
| 3. Add 212.25 for August | 29585.25 + 212.25 = 29797.5 |
| 4. Add the number of the day | 29797.5 + 24 = 29821.5 |
| 5. Take the integer | 29821 |

Table 2.23w – 6. – Calculation code to derive a day-number from a given date (day/month/year)

```

CONST ElapsedDays :
ARRAY [1..12] of double = (0, 31, 59.25, 90.25, 120.25, 151.25, 181.25,
212.25, 243.25, 273.25, 304.25, 334.25);

INPUT: Dayi : DD (Integer); Monthi : MM (Integer); Yeari : YYYY (Integer);
OUTPUT: DayNr (LongInt);

PROCEDURE DetermineDayNr (Dayi, Monthi, Yeari : INTEGER;
                           VAR DayNr : Longint);

BEGIN
DayNr := TRUNC((Yeari - 1901)*365.25 + ElapsedDays[Monthi] + Dayi + 0.05);
END; (* DetermineDayNr *)

```

2.23.12 File with field data (*.OBS)

A file with field data (Tab. 2.23x - 1 and 2.23x - 2) contains observed field data which consists of observed green canopy cover (CC), dry above ground biomass (B) and/or soil water content (SWC) collected at a number of specific days. The mean value together with its standard deviation can be specified if various observations were made during the sampling at a specific day. The soil water content is the total water content in a well-defined zone (e.g. root zone). Therefore the soil depth, for which soil water contents were calculated, has to be specified.

Table 2.23x – 1. – Structure of a file with field data

| Line | Description | Format |
|-------------------|--|--|
| 1 | First line is a description of the file content | String of characters |
| 2 | Version number of AquaCrop | Real (1 digit) |
| 3 | The depth (m) of the sampled profile (for soil water content) | Real (2 digits) |
| 4 | First day of field data | Integer |
| 5 | First month of field data | Integer |
| 6 | First year of record (1901 if not linked to a specific year) | Integer |
| 7 | Empty line | - |
| 8 | Title ('Day Canopy Cover ...') | String of characters |
| 9 | Title ('Mean Std ...') | String of characters |
| 10 | Dotted line ('=====') | String of characters |
| 11 and next | For the first day of observation specify <ul style="list-style-type: none"> - The day number at which the observation was made (with reference to the date specified in line 4 (DD), 5 (MM) and 6 (YYYY)); - The mean value of sampled green Canopy Cover (%) on that day (-9.0 if no field data was collected) - The standard deviation (%) for the various CC observations made during the sampling on that day (-9.0 if not available or non-applicable) - The mean value of sampled dry above ground biomass (ton/ha) on that day (-9.0 if no field data was collected) - The standard deviation for the various B observations made during the sampling on that day (-9.0 if not available or non-applicable) - The mean value of sampled total soil water content (mm) in the well-defined zone on that day (-9.0 if no field data was collected) - The standard deviation for the various SWC observations made during the sampling on that day (-9.0 if not available or non-applicable) Repeat for each successive day with observations | Integer Real (1 digit) Real (1 digit) Real (3 digits) Real (1 digit) Real (1 digit) Real (1 digit) Real (1 digit) |

Table 2.23x – 2. – Example of a file with field data.

| measurements of CC, B and SWC at particular days | | | | | | | |
|--|---|------|----------------------|------|-------------------------|------|--|
| | 5.0 : AquaCrop Version (October 2015) | | | | | | |
| | 1.00 : depth of sampled soil profile | | | | | | |
| | 22 : first day of observations | | | | | | |
| | 3 : first month of observations | | | | | | |
| | 1901 : first year of observations (1901 if not linked to a specific year) | | | | | | |
| Day | Canopy cover (%) | | dry Biomass (ton/ha) | | Soil water content (mm) | | |
| | Mean | Std | Mean | Std | Mean | Std | |
| 11 | 5.0 | 3.0 | -9.000 | -9.0 | 300.0 | 20.0 | |
| 30 | 30.0 | 5.0 | 1.000 | 0.3 | -9.0 | -9.0 | |
| 40 | 50.0 | -9.0 | -9.000 | -9.0 | 250.0 | 25.0 | |
| 50 | 60.0 | 5.0 | -9.000 | -9.0 | -9.0 | -9.0 | |
| 72 | -9.0 | -9.0 | 4.000 | 0.2 | 150.0 | 30.0 | |
| 90 | -9.0 | -9.0 | 4.400 | 0.3 | -9.0 | -9.0 | |
| 110 | 45.0 | 6.0 | 5.000 | 0.5 | 100.0 | 10.0 | |
| 120 | -9.0 | -9.0 | 5.500 | 0.5 | 100.0 | 10.0 | |

2.23.13 Text files with climatic data (*.TXT)

The text file is a file with extension ‘txt’ (as created by Notepad) or ‘CXT’ (as used in the ETo calculator), in which climatic data for a specific time range is saved in columns (Table 2.23y - 1). The climatic parameters, with their units, recognized by AquaCrop for import are listed in Table 2.23y – 2.

The text file is typically a copy from a spreadsheet but contains only the numerical values (no headings, line numbers, or dates). The file may contain daily, 10-daily or monthly climatic data. The text file consists of climatic data recorded in a specific time range (ranging from a few days up to several years) or of calculated averages for a number of years. The text file has lines and columns:

- Lines: There are as many lines (rows) as day’s, 10-day’s or months in the imported time range. Each line contains the climatic data (or average) for only one day, 10-day or month of the time range, and this in successive order;
- Columns: The text file can contain up to 10 columns. Each column contains the data of one of the climatic parameters listed in Table 2.23y - 1.

Table 2.23y – 1. – Example of a text file containing climatic data. It consists of a small part of the ‘LosBanos1997_2014.txt’ file with daily data for Los Baños (Philippines) at 14.17 °N and 170 m.a.s.l.: Solar radiation (MJ/m².day), Maximum and Minimum temperature (°C), wind speed at 10 m above ground level (m/sec), dewpoint temperature (°C), mean relative humidity (%) and rainfall.

| | | | | | | |
|------|------|------|-----|------|------|-----|
| 12.9 | 25.7 | 21.5 | 5.1 | 20.1 | 82.7 | 0.1 |
| 11.3 | 26.9 | 20.5 | 5.2 | 19.5 | 82.1 | 0 |
| 13 | 27.6 | 20.7 | 4.3 | 19.6 | 78.1 | 0 |
| 15.1 | 28.1 | 19.4 | 3.9 | 19.4 | 75.7 | 0.4 |
| 17.7 | 27 | 20.6 | 3.1 | 19.4 | 77.6 | 5 |
| 17 | 27.4 | 19.9 | 3.2 | 18.6 | 74.7 | 0.1 |
| 15.6 | 29.3 | 19.1 | 3.5 | 19.7 | 78 | 2.5 |
| 18.1 | 28.4 | 21.1 | 4.1 | 19.9 | 72.6 | 0 |
| 18.6 | 28.6 | 21.7 | 3.2 | 20 | 74.6 | 1.1 |
| 15.6 | 28.3 | 21.4 | 3.4 | 19.7 | 73.7 | 0.6 |

Table 2.23y - 2. – Climatic parameters, with their units, recognized by AquaCrop for import

| Climatic parameter (Description and Symbol) | Units |
|--|--|
| Air temperature data | |
| Maximum air temperature (Tmax) | °C or °F |
| Mean air temperature (Tmean) | °C or °F |
| Minimum air temperature (Tmin) | °C or °F |
| Air Humidity data | |
| Maximum Relative Humidity (RHmax) | % |
| Mean Relative Humidity (RHmean) | % |
| Minimum Relative Humidity (RHmin) | % |
| Dewpoint temperature (Tdew) | °C or °F |
| Actual vapour pressure: e(act) | kPa, mbar, psi, atm or mmHG |
| Temperature of dry bulb (Tdry) | °C or °F |
| Temperature of wet bulb (Twet) | °C or °F |
| Wind speed data | |
| Wind speed at x m above soil surface: u(x) | m/sec, km/day, knot or ft/sec |
| Radiation and sunshine data | |
| Actual duration of sunshine in a day (n) | hour |
| Relative sunshine duration (n/N) | - |
| Solar or shortwave radiation (Rs) | MJ/m ² .day, W/m ² , J/cm ² .day, mm/day, cal/cm ² .day |
| Net radiation (Rn) | MJ/m ² .day, W/m ² , J/cm ² .day, mm/day, cal/cm ² .day |
| ETo, Reference crop evapotranspiration | |
| Direct import of reference crop evapotranspiration (ETo) | mm/day |
| Rainfall data | |
| Rainfall (Rain) | mm or inch |

2.24 Files with program settings

2.25 Output files

Simulation results are stored in a set of output files. By default the output files are stored in the OUTP subdirectory of the AquaCrop folder. Distinction is made between output files containing daily data, seasonal results and evaluation of simulation results. The output files with daily data contain information on the:

- Climate input variables
- Crop development and production;
- Soil water content at various depths of the soil profile;
- Soil salinity at various depths of the soil profile;
- Soil water content in the soil profile and root zone;
- Soil salinity in the soil profile and root zone;
- Various variables of the soil water balance;
- Net irrigation water requirement.

The variables listed in the output files are given in sections 2.25.1 to 2.25.8.

The variables listed in the seasonal output file are given in section 2.25.9.

The evaluation of the simulation results are recorded in 2 output files (section 2.25.10):

- Data output file (simulated and the observed field data, with their standard deviation);
- Statistics output file: statics of the evaluation of the simulation results.

The data in the files can be retrieved in spread sheet programs for further processing and analysis.

2.25.1 Climate input variables

Default file name: ProjectCLIM.OUT

| Nr | Symbol | Description | Unit |
|----|--------|---|------|
| 1 | Day | | - |
| 2 | Month | | - |
| 3 | Year | | - |
| 4 | DAP | Days after planting/sowing | - |
| 5 | Stage | Crop growth stage: 0: before or after cropping; 1: between sowing and germination or transplant recovering; 2: vegetative development; 3: flowering; 4: yield formation and ripening -9: no crop as a result of early canopy senescence | - |
| 6 | Rain | Rainfall | mm |
| 7 | ETo | Reference evapotranspiration | mm |
| 8 | Tmin | Minimum air temperature | °C |
| 9 | Tavg | Average air temperature | °C |
| 10 | Tmax | Maximum air temperature | °C |
| 11 | CO2 | Atmospheric CO2 concentration | ppm |

2.25.2 Crop development and production

Default file name: ProjectCROP.OUT

| Nr | Symbol | Description | Unit |
|----|------------|---|-------------------|
| 1 | Day | | - |
| 2 | Month | | - |
| 3 | Year | | - |
| 4 | DAP | Days after planting/sowing | - |
| 5 | Stage | Crop growth stage: 0: before or after cropping; 1: between sowing and germination or transplant recovering; 2: vegetative development; 3: flowering; 4: yield formation and ripening -9: no crop as a result of early canopy senescence | - |
| 6 | GD | Growing degrees | °C-day |
| 7 | Z | Effective rooting depth | m |
| 8 | StExp | Percent water stress reducing leaf expansion | % |
| 9 | StSto | Percent water stress inducing stomatal closure | % |
| 10 | StSen | Percent water stress triggering early canopy senescence | % |
| 11 | StSalt | Percent salinity stress | % |
| 12 | StWeed | Relative cover of weeds | % |
| 13 | CC | Total green Canopy Cover of crop and weeds | % |
| 14 | CCw | Crop green Canopy Cover in weed infested field | % |
| 15 | StTr | Percent temperature stress affecting crop transpiration | % |
| 16 | Kc(Tr) | Crop coefficient for transpiration | - |
| 17 | Trx | Maximum crop transpiration of crop and weeds | mm |
| 18 | Tr | Total transpiration of crop and weeds | mm |
| 19 | TrW | Crop transpiration in weed infested field | mm |
| 20 | Tr/Trx | Relative total transpiration of crop and weeds (100 Tr/Trx) | % |
| 21 | WP | Crop water productivity adjusted for CO2, soil fertility and products synthesized | g/m ² |
| 22 | Biomass | Cumulative crop biomass | ton/ha |
| 23 | HI | Harvest Index adjusted for failure of pollination, inadequate photosynthesis and water stress | % |
| 24 | Yield Part | Crop yield (HI x Biomass) | ton/ha |
| 25 | Brelative | Relative biomass (Reference: no water, no soil fertility, no soil salinity stress, no weed infestation) | % |
| 26 | WPet | ET Water productivity for yield part (kg yield produced per m ³ water evapotranspired) | kg/m ³ |

2.25.3 Soil water balance

Default file name: ProjectWABAL.OUT

| Nr | Symbol | Description | Unit |
|----|--------|---|------|
| 1 | Day | | - |
| 2 | Month | | - |
| 3 | Year | | - |
| 4 | DAP | Days after planting/sowing | - |
| 5 | Stage | Crop growth stage: 0: before or after cropping; 1: between sowing and germination or transplant recovering; 2: vegetative development; 3: flowering; 4: yield formation and ripening -9: no crop as a result of early canopy senescence | - |
| 6 | WCTot | Water content in total soil profile | mm |
| 7 | Rain | Rainfall | mm |
| 8 | Irri | Water applied by irrigation | mm |
| 9 | Surf | Stored water on soil surface between bunds | mm |
| 10 | Infilt | Infiltrated water in soil profile | mm |
| 11 | RO | Surface runoff | mm |
| 12 | Drain | Water drained out of the soil profile | mm |
| 13 | CR | Water moved upward by capillary rise | mm |
| 14 | Zgwt | Depth of the groundwater table (-9.90 if absent) | m |
| 15 | Ex | Maximum soil evaporation | mm |
| 16 | E | Actual soil evaporation | mm |
| 17 | E/E | Relative evaporation (100 E/EX) | % |
| 18 | Trx | Maximum crop transpiration | mm |
| 19 | Tr | Total transpiration of crop and weeds | mm |
| 20 | Tr/Trx | Relative transpiration (100 Tr/Trx) | % |
| 21 | ETx | Maximum evapotranspiration | mm |
| 22 | ET | Actual evapotranspiration | mm |
| 23 | ET/ETx | Relative evapotranspiration (100 ET/ETx) | % |

2.25.4 Soil water content (profile and root zone)

Default file name: ProjectProf.OUT

| Nr | Symbol | Description | Unit |
|----|---------|---|------|
| 1 | Day | | - |
| 2 | Month | | - |
| 3 | Year | | - |
| 4 | DAP | Days after planting/sowing | - |
| 5 | Stage | Crop growth stage: 0: before or after cropping; 1: between sowing and germination or transplant recovering; 2: vegetative development; 3: flowering; 4: yield formation and ripening -9: no crop as a result of early canopy senescence | - |
| 6 | WCTot | Water content total soil profile | mm |
| 7 | Wr(Zx) | Water content in maximum effective root zone | mm |
| 8 | Z | Effective rooting depth | m |
| 9 | Wr | Water content in effective root zone | mm |
| 10 | Wr(SAT) | Water content in effective root zone if saturated | mm |
| 11 | Wr(FC) | Water content in effective root zone at field capacity | mm |
| 12 | Wr(exp) | Water content in effective root zone at upper threshold for leaf expansion | mm |
| 13 | Wr(sto) | Water content in effective root zone at upper threshold for stomatal closure | mm |
| 14 | Wr(sen) | Water content in effective root zone at upper threshold for early canopy senescence | mm |
| 15 | Wr(PWP) | Water content in effective root zone at permanent wilting point | mm |

2.25.5 Soil salinity (profile and root zone)

Default file name: ProjectSalt.OUT

| Nr | Symbol | Description | Unit |
|----|---------|---|--------|
| 1 | Day | | - |
| 2 | Month | | - |
| 3 | Year | | - |
| 4 | DAP | Days after planting/sowing | - |
| 5 | Stage | Crop growth stage: 0: before or after cropping; 1: between sowing and germination or transplant recovering; 2: vegetative development; 3: flowering; 4: yield formation and ripening -9: no crop as a result of early canopy senescence | - |
| 6 | SaltIn | Salt infiltrated in the soil profile | ton/ha |
| 7 | SaltOut | Salt drained out of the soil profile | ton/ha |
| 8 | SaltUp | Salt moved upward from the groundwater table | ton/ha |
| 9 | SaltTot | Salt content in the total soil profile | ton/ha |
| 10 | SaltZ | Salt content in the effective root zone | ton/ha |
| 11 | Z | Effective rooting depth | m |
| 12 | ECe | Electrical conductivity of the saturated soil-paste extract from the root zone | dS/m |
| 13 | ECsw | Electrical conductivity of the soil water in the root zone | dS/m |
| 14 | StSalt | Salinity stress | % |
| 15 | Zgwt | Depth of the groundwater table (-9.90 if absent) | m |
| 16 | ECgw | Electrical conductivity of the groundwater | dS/m |

2.25.6 Soil water content (compartments)

Default file name: ProjectCompWC.OUT

| Nr | Symbol | Description | Unit |
|----|--------|---|------|
| 1 | Day | | - |
| 2 | Month | | - |
| 3 | Year | | - |
| 4 | DAP | Days after planting/sowing | - |
| 5 | Stage | Crop growth stage: 0: before or after cropping; 1: between sowing and germination or transplant recovering; 2: vegetative development; 3: flowering; 4: yield formation and ripening -9: no crop as a result of early canopy senescence | - |
| 6 | WC1 | soil water content compartment 1 * | vol% |
| 7 | WC2 | soil water content compartment 2 | vol% |
| 8 | WC3 | soil water content compartment 3 | vol% |
| 9 | WC4 | soil water content compartment 4 | vol% |
| 10 | WC5 | soil water content compartment 5 | vol% |
| 11 | WC6 | soil water content compartment 6 | vol% |
| 12 | WC7 | soil water content compartment 7 | vol% |
| 13 | WC8 | soil water content compartment 8 | vol% |
| 14 | WC9 | soil water content compartment 9 | vol% |
| 15 | WC10 | soil water content compartment 10 | vol% |
| 16 | WC11 | soil water content compartment 11 | vol% |
| 17 | WC12 | soil water content compartment 12 | vol% |

* The soil depth (corresponding at the centre of the compartment) is specified for each compartment in the file

2.25.7 Soil salinity (compartments)

Default file name: ProjectCompEC.OUT

| Nr | Symbol | Description | Unit |
|----|--------|---|------|
| 1 | Day | | - |
| 2 | Month | | - |
| 3 | Year | | - |
| 4 | DAP | Days after planting/sowing | - |
| 5 | Stage | Crop growth stage: 0: before or after cropping; 1: between sowing and germination or transplant recovering; 2: vegetative development; 3: flowering; 4: yield formation and ripening -9: no crop as a result of early canopy senescence | - |
| 6 | EC1 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 1 * | dS/m |
| 7 | EC2 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 2 | dS/m |
| 8 | EC3 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 3 | dS/m |
| 9 | EC4 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 4 | dS/m |
| 10 | EC5 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 5 | dS/m |
| 11 | EC6 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 6 | dS/m |
| 12 | EC7 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 7 | dS/m |
| 13 | EC8 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 8 | dS/m |
| 14 | EC9 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 9 | dS/m |
| 15 | EC10 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 10 | dS/m |
| 16 | EC11 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 11 | dS/m |
| 17 | EC12 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 12 | dS/m |

* The soil depth (corresponding at the centre of the compartment) is specified for each compartment in the file

2.25.8 Net irrigation requirement

Default file name: ProjectInet.OUT

| Nr | Symbol | Description | Unit |
|----|--------|---|------|
| 1 | Day | | - |
| 2 | Month | | - |
| 3 | Year | | - |
| 4 | DAP | Days after planting/sowing | - |
| 5 | Stage | Crop growth stage: 0: before or after cropping; 1: between sowing and germination or transplant recovering; 2: vegetative development; 3: flowering; 4: yield formation and ripening -9: no crop as a result of early canopy senescence | - |
| 6 | E | Actual soil evaporation | mm |
| 7 | Trx | Maximum crop transpiration | mm |
| 8 | ET | Evapotranspiration: Sum of E and Trx | mm |
| 9 | Rain | Rainfall | mm |
| 10 | Inet | Net irrigation requirement | mm |

2.25.9 Seasonal output

Default file name: ProjectRun.OUT

| Nr | Symbol | Description | Unit |
|----|-----------|---|-------------------|
| 1 | RunNr | Number simulation run | - |
| 2 | Day1 | Start day of simulation run | - |
| 3 | Month1 | Start month of simulation run | - |
| 4 | Year1 | Start year of simulation run | - |
| 5 | Rain | Rainfall | mm |
| 6 | ETo | Reference evapotranspiration | mm |
| 7 | GD | Growing degrees | °C.day |
| 8 | CO2 | Atmospheric CO2 concentration | ppm |
| 9 | Irri | Water applied by irrigation OR net irrigation requirement | mm |
| 10 | Infilt | Infiltrated water in soil profile | mm |
| 11 | Runoff | Water lost by surface runoff | mm |
| 12 | Drain | Water drained out of the soil profile | mm |
| 13 | Upflow | Water moved upward by capillary rise | mm |
| 14 | E | Soil evaporation | mm |
| 15 | E/Ex | Relative soil evaporation (100 E/Ex) | % |
| 16 | Tr | Total transpiration of crop and weeds | mm |
| 17 | Trw | Crop transpiration in weed infested field | mm |
| 18 | Tr/Trx | Relative crop transpiration (100 Tr/Trx) | % |
| 19 | SaltIn | Salt infiltrated in the soil profile | ton/ha |
| 20 | SaltOut | Salt drained out of the soil profile | ton/ha |
| 21 | SaltUp | Salt moved upward by capillary rise from groundwater table | ton/ha |
| 22 | SaltProf | Salt stored in the soil profile | ton/ha |
| 23 | Cycle | Length of crop cycle: from germination to maturity (or early senescence) | days |
| 24 | SaltStr | Average soil salinity stress | % |
| 25 | FertStr | Average soil fertility stress | % |
| 26 | WeedStr | Average relative cover of weeds | % |
| 27 | TempStr | Average temperature stress (affecting transpiration) | % |
| 28 | ExpStr | Average leaf expansion stress | % |
| 29 | StoStr | Average stomatal stress | % |
| 30 | Biomass | Cumulative biomass produced | ton/ha |
| 31 | Brelative | Relative biomass (Reference: no water, no soil fertility, no soil salinity stress, no weed infestation) | % |
| 32 | HI | Harvest Index adjusted for failure of pollination, inadequate photosynthesis and water stress | % |
| 33 | Yield | Yield (HI x Biomass) | ton/ha |
| 34 | WPet | ET Water Productivity for yield part (kg yield produced per m ³ water evapotranspired) | kg/m ³ |
| 35 | DayN | End day of simulation run | - |
| 36 | MonthN | End month of simulation run | - |
| 37 | YearN | End year of simulation run | - |

2.25.10 Evaluation of simulation results

The evaluation of the simulation results are recorded in 2 output files:

- Data output file: which contain for each day of the simulation period the simulated green canopy cover (CC), biomass (B) and soil water content (SWC), and the observed field data (with their standard deviation);
- Statistics output file: which contain the statics of the evaluation of the simulation results for Canopy Cover, biomass and soil water content (see 2.21.5 ‘Evaluation of simulation results).

▪ Data output file

Default file name: ProjectEvalData.OUT

| Nr | Symbol | Description | Unit |
|----|--------|---|--------|
| 1 | Day | | - |
| 2 | Month | | - |
| 3 | Year | | - |
| 4 | DAP | Days after planting/sowing | - |
| 5 | Stage | Crop growth stage: 0: before or after cropping; 1: between sowing and germination or transplant recovering; 2: vegetative development; 3: flowering; 4: yield formation and ripening -9: no crop as a result of early canopy senescence | - |
| 6 | CCsim | simulated Green Canopy Cover | % |
| 7 | CCobs | observed Green Canopy Cover (-9.0 = no field data) | % |
| 8 | CCstd | standard deviation of observed Green Canopy Cover | % |
| 9 | Bsim | simulated Cumulative biomass produced | ton/ha |
| 10 | Bobs | observed Cumulative biomass produced (-9.000 = no field data) | ton/ha |
| 11 | Bstd | standard deviation of observed Cumulative biomass produced | ton/ha |
| 12 | SWCsim | simulated Soil Water Content for specified soil depth * | mm |
| 13 | SWCobs | observed Soil Water Content for specified soil depth (-9.0 = no field data) | mm |
| 14 | SWCstd | standard deviation of observed Soil Water Content for specified soil depth | mm |

* The soil depth is specified in meter

- **Statistics output file**

Default file name: ProjectEvalStat.OUT

Text file with

- at the dates of observations: the observed (with standard deviation) and simulated Canopy Cover, Biomass production and Soil water content;
- the number of valid observations/simulations sets and the average of observed and simulated Canopy Cover, Biomass production and Soil water content;
- Statistical indicators for Canopy Cover, Biomass production and Soil water content: Pearson Correlation Coefficient (r); Root mean square error (RMSE); Normalized root mean square error CV(RMSE); Nash-Sutcliffe model efficiency coefficient (EF); and Willmott's index of agreement (d).

An example is presented in Table 2.25a.

Table 2.25a – Example of ProjectEvalStat.OUT

AquaCrop 6.0 (March 2017) - Output created on (date) : 24/03/2017 at (time) : 10:42:13
Evaluation of simulation results - Statistics

| ASSESSMENT OF CANOPY COVER ----- | | | | |
|----------------------------------|------------------------|------------|-----------|----------|
| Nr | Canopy Cover (%) ----- | | | |
| | Observed | +/- St Dev | Simulated | Date |
| 1 | 5.0 | 3.0 | 3.0 | 1 April |
| 2 | 30.0 | 5.0 | 44.0 | 20 April |
| 3 | 50.0 | -9.0 | 57.0 | 30 April |
| 4 | 60.0 | 5.0 | 57.0 | 10 May |
| 5 | 45.0 | 6.0 | 35.5 | 9 July |

| | | |
|---|---|----------|
| Valid observations/simulations sets (n) | : | 5 |
| Average of observed Canopy Cover | : | 38.0 % |
| Average of simulated Canopy Cover | : | 39.3 % |
| <hr/> | | |
| Pearson Correlation Coefficient (r) | : | 0.91 |
| Root mean square error (RMSE) | : | 8.3 % CC |
| Normalized root mean square error CV(RMSE) | : | 22.0 % |
| Nash-Sutcliffe model efficiency coefficient (EF): | | 0.81 |
| Willmott's index of agreement (d) | : | 0.95 |
| <hr/> | | |

| ASSESSMENT OF BIOMASS PRODUCTION ----- | | | | |
|--|------------------------|------------|-----------|----------|
| Nr | Biomass (ton/ha) ----- | | | |
| | Observed | +/- St Dev | Simulated | Date |
| 1 | 1.000 | 0.300 | 0.940 | 20 April |
| 2 | 4.000 | 0.200 | 3.961 | 1 June |
| 3 | 4.400 | 0.300 | 4.613 | 19 June |
| 4 | 5.000 | 0.500 | 5.084 | 9 July |
| 5 | 5.500 | 0.500 | 5.103 | 19 July |

| | | |
|---|---|--------------|
| Valid observations/simulations sets (n) | : | 5 |
| Average of observed Biomass production | : | 3.980 ton/ha |
| Average of simulated Biomass production | : | 3.940 ton/ha |
| <hr/> | | |
| Pearson Correlation Coefficient (r) | : | 0.99 |

| | | | |
|---|---|-------|--------|
| Root mean square error (RMSE) | : | 0.207 | ton/ha |
| Normalized root mean square error CV(RMSE).... | : | 5.2 | % |
| Nash-Sutcliffe model efficiency coefficient (EF): | : | 0.98 | |
| Willmott's index of agreement (d) | : | 1.00 | |

ASSESSMENT OF SOIL WATER CONTENT -----

| ----- Soil water content (mm) ----- | | | | |
|-------------------------------------|----------|------------|-----------|----------|
| Nr | Observed | +/- St Dev | Simulated | Date |
| 1 | 300.0 | 20.0 | 280.8 | 1 April |
| 2 | 250.0 | 25.0 | 215.9 | 30 April |
| 3 | 150.0 | 30.0 | 159.6 | 1 June |
| 4 | 100.0 | 10.0 | 125.9 | 9 July |
| 5 | 100.0 | 10.0 | 125.0 | 19 July |

| | | |
|---|---|----------|
| Valid observations/simulations sets (n) | : | 5 |
| Average of observed Soil water content | : | 180.0 mm |
| Average of simulated Soil water content | : | 181.4 mm |

| | | |
|---|---|---------|
| Pearson Correlation Coefficient (r) | : | 0.99 |
| Root mean square error (RMSE) | : | 24.2 mm |
| Normalized root mean square error CV(RMSE).... | : | 13.4 % |
| Nash-Sutcliffe model efficiency coefficient (EF): | : | 0.91 |
| Willmott's index of agreement (d) | : | 0.97 |
