Food and Agriculture Organization of the United Nations

Chapter 2
Users guide

AquaCrop
Version 7.1

Reference manual

August 2023

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Food and Agriculture Organization of the United Nations
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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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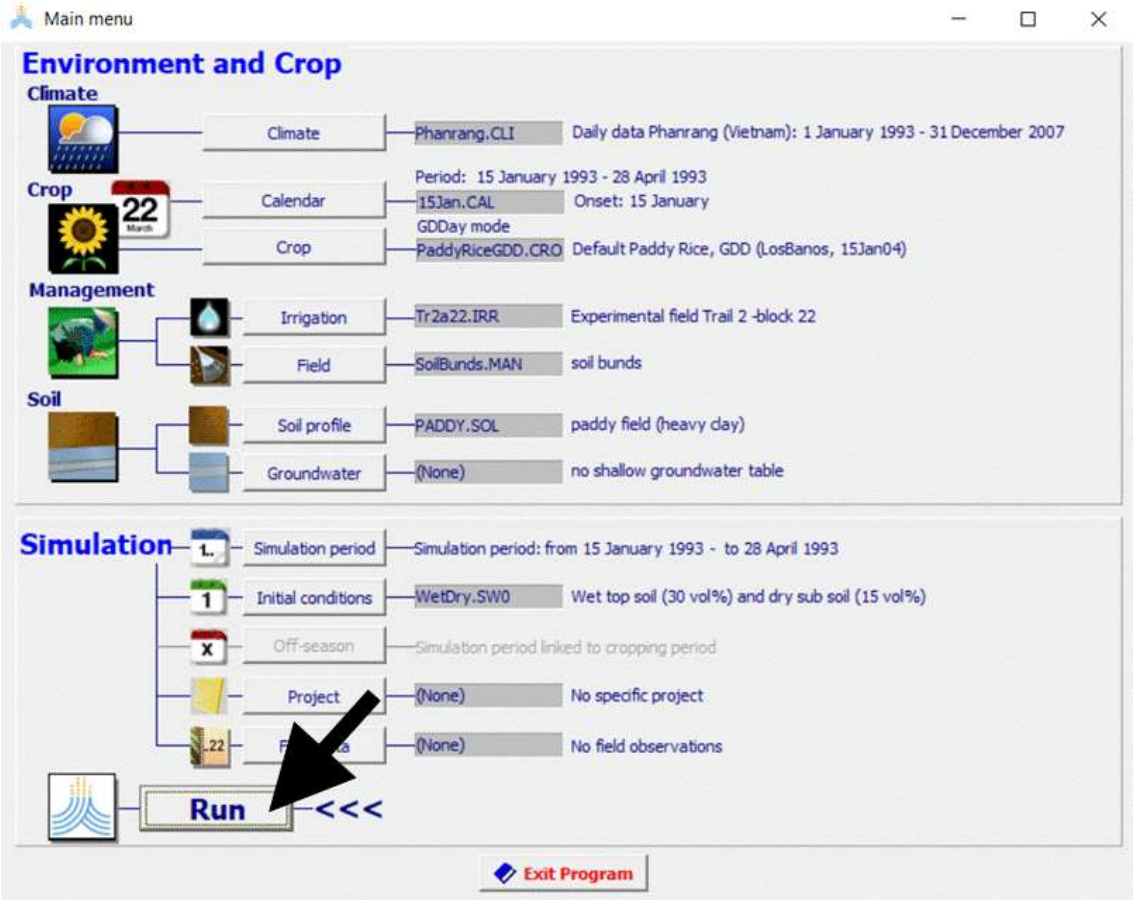
Chapter 2.
Users guide

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

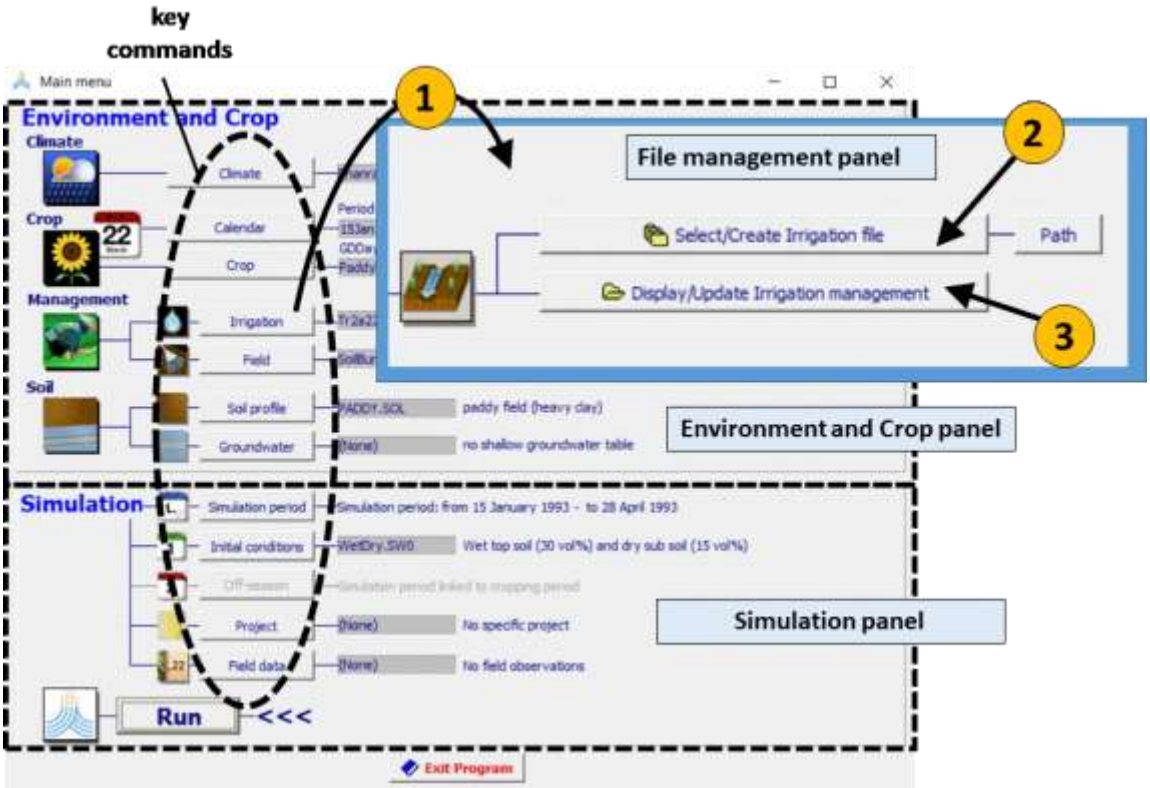


Figure 2.2 – *Main menu* of AquaCrop. By selecting (1) one of the key commands, the user gets access to the file management panel from which (2) files can be selected or created and (3) the input characteristics can be displayed and updated.

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**, **Calendar,** **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.

When a perennial crop file is loaded, AquaCrop adjusts automatically the start and end of the growing period by considering the rules specified in the internal crop calendar and the climatic data for the simulation year. For a seeding/planting year the start of the growing period is either given by a Calendar file or specified as input (see 2.11 'Start of the growing cycle').

In the ***Main menu***, the user specifies the year number of the lifetime of the perennial crop (Fig. 2.2/b). Year 1, is the seeding/planting year.

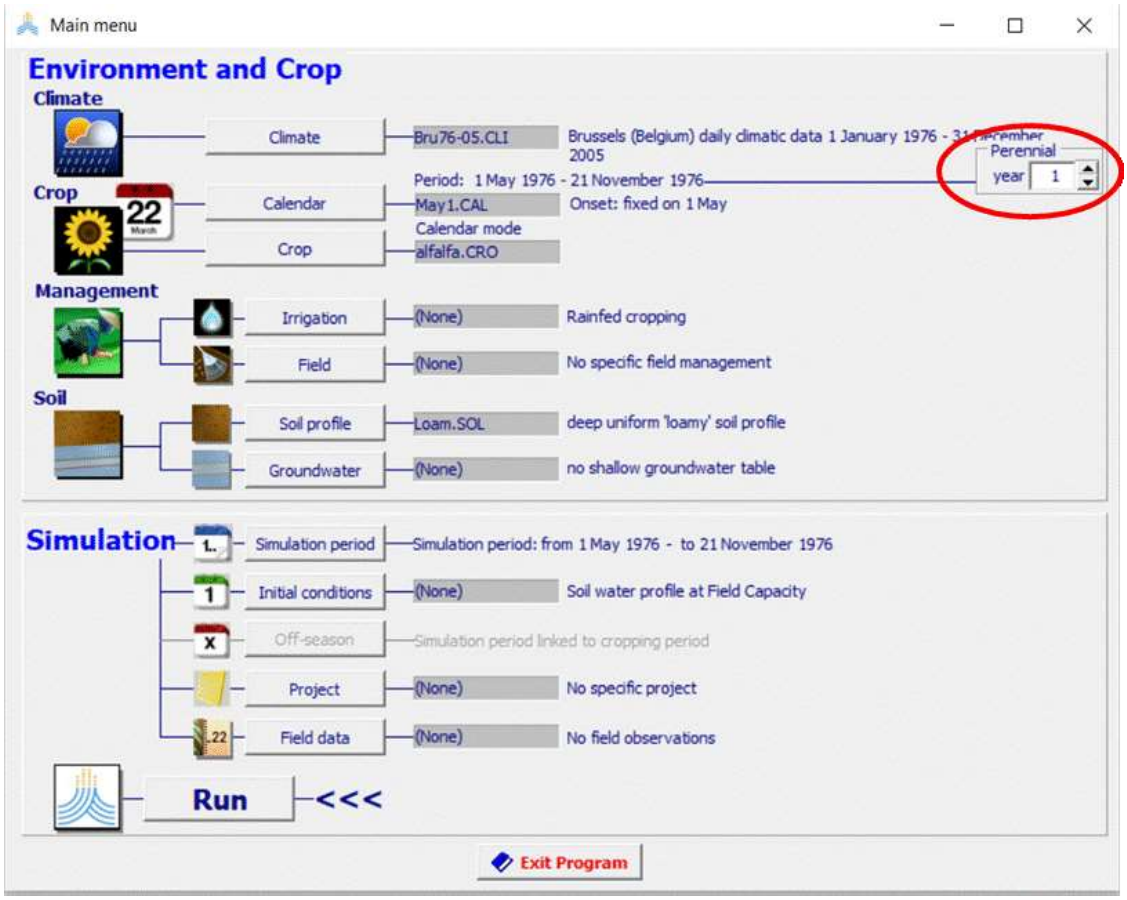


Figure 2.2/b – Specification of the year number of the lifetime of the perennial crop in the *Main menu*.

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, crop calendar, irrigation management, field management, groundwater, initial and off-season conditions, and field data files, the default settings are assumed (Tab. 2.3).

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).

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
Calendar	(None)	The onset of the growing period is specified by the user
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)	

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.

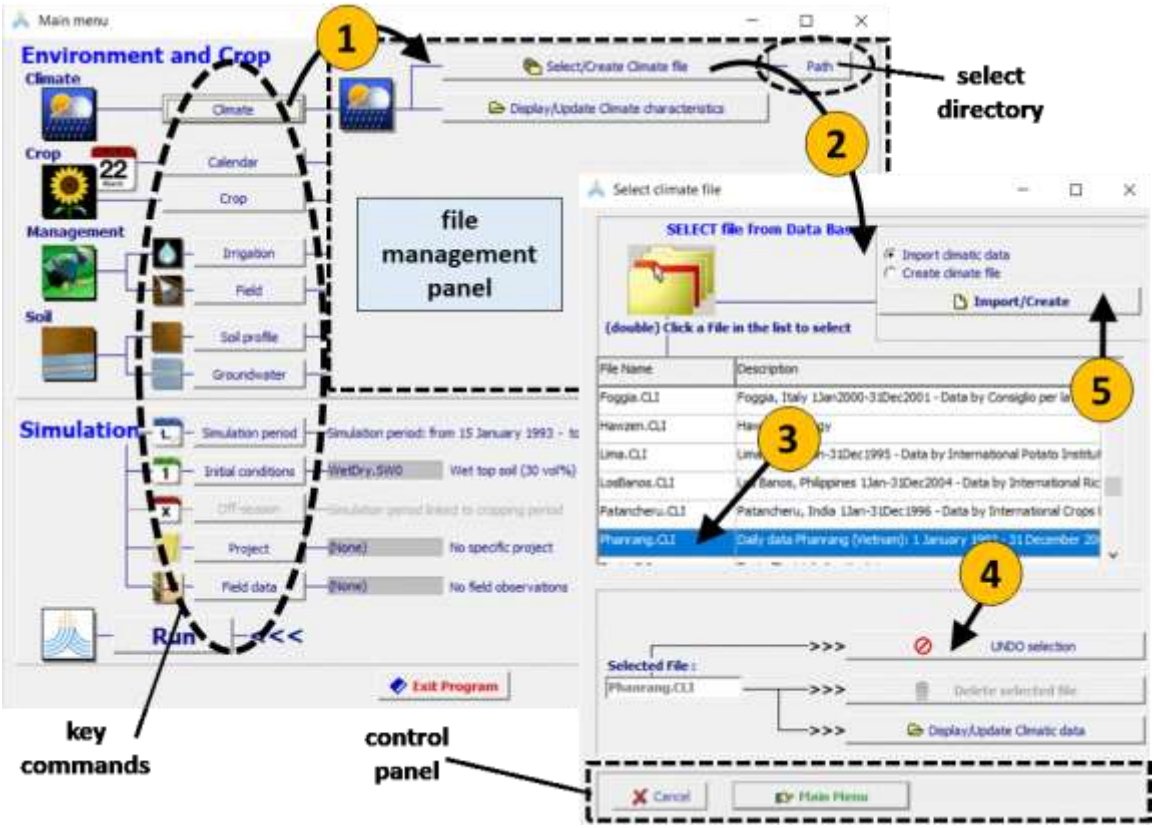


Figure 2.4 – By selecting (1) one of the key commands and subsequently (2) the corresponding <Select/Create> command in the file management panel in the *Main menu*, the user gets access to the *Select file* menus in which (3) one of the available files can be selected, (4) the selection can be undone,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

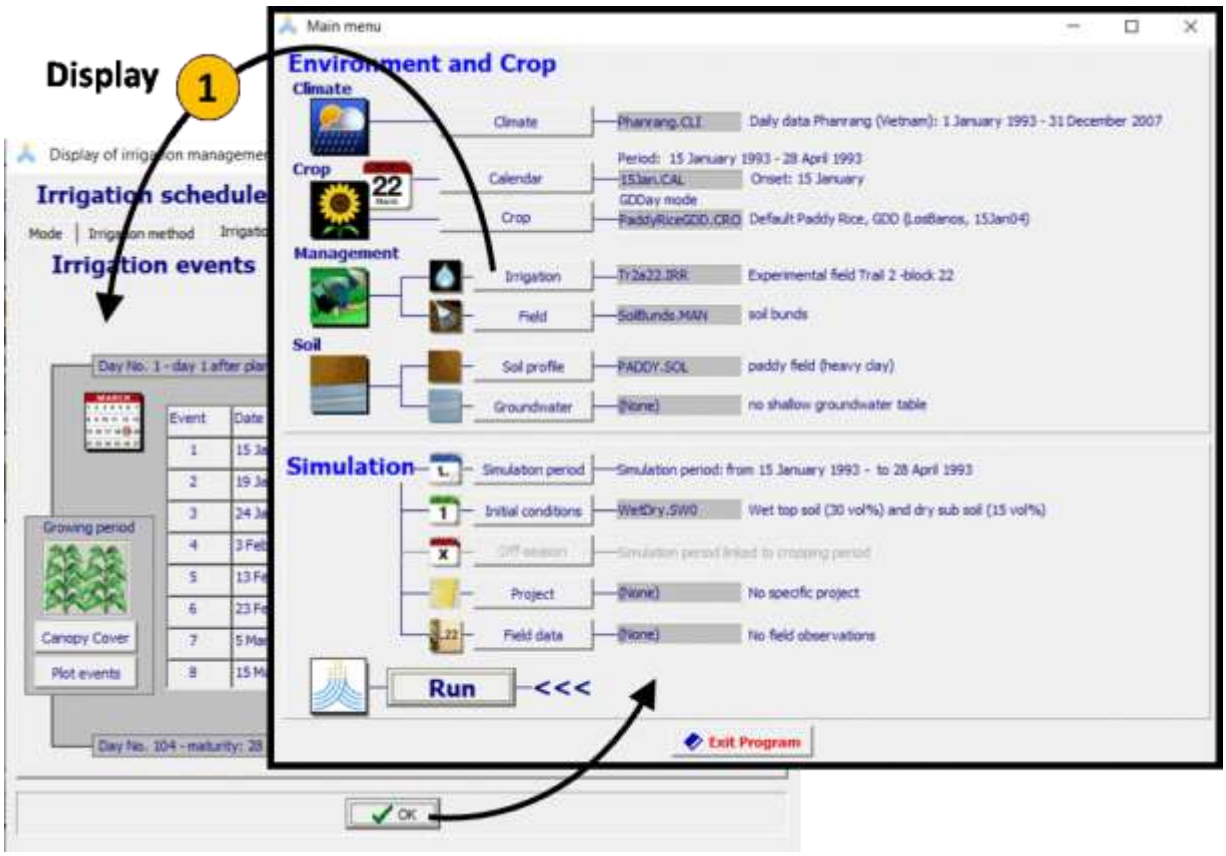


Figure 2.5a - By clicking on the Icons (or file names) in the *Main menu* the specified input data is displayed in a set of *Display* menus

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).

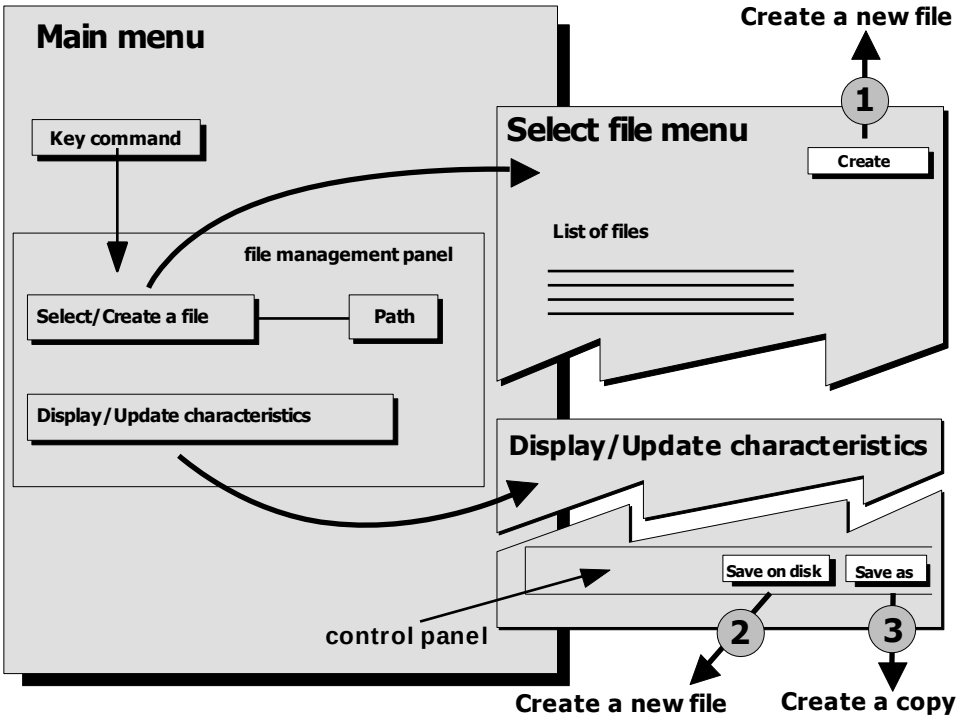


Figure 2.6a – Options to create a new file by selecting (1) the <Create> command at the top of the *Select file* menu, and (2) the <Save on disk> command (if the characteristics were not retrieved from a file) or (3) the <Save as> command (if the characteristics were retrieved from a file), in the control 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 CO_2 file (Fig. 2.6b)

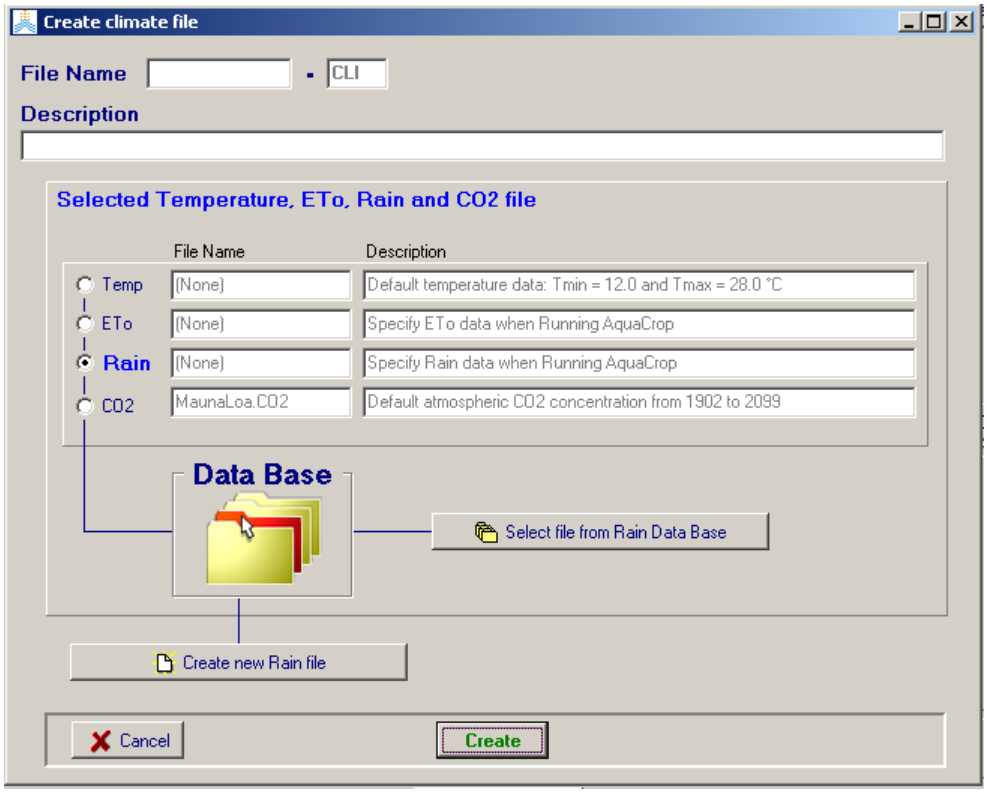


Figure 2.6b – *Create climate file* menu

- **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 (herbaceous forage crops):
  - winter dormant period
  - non dormant (Winter active) cultivar

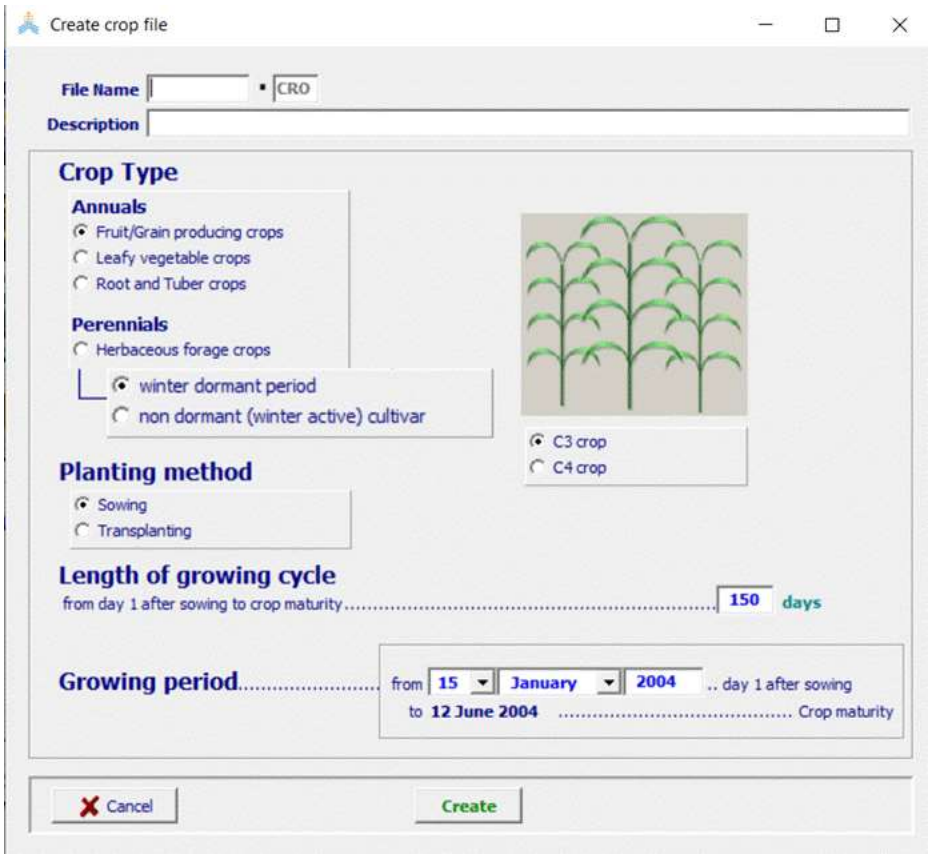


Figure 2.6c – *Create crop file* menu

- **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.

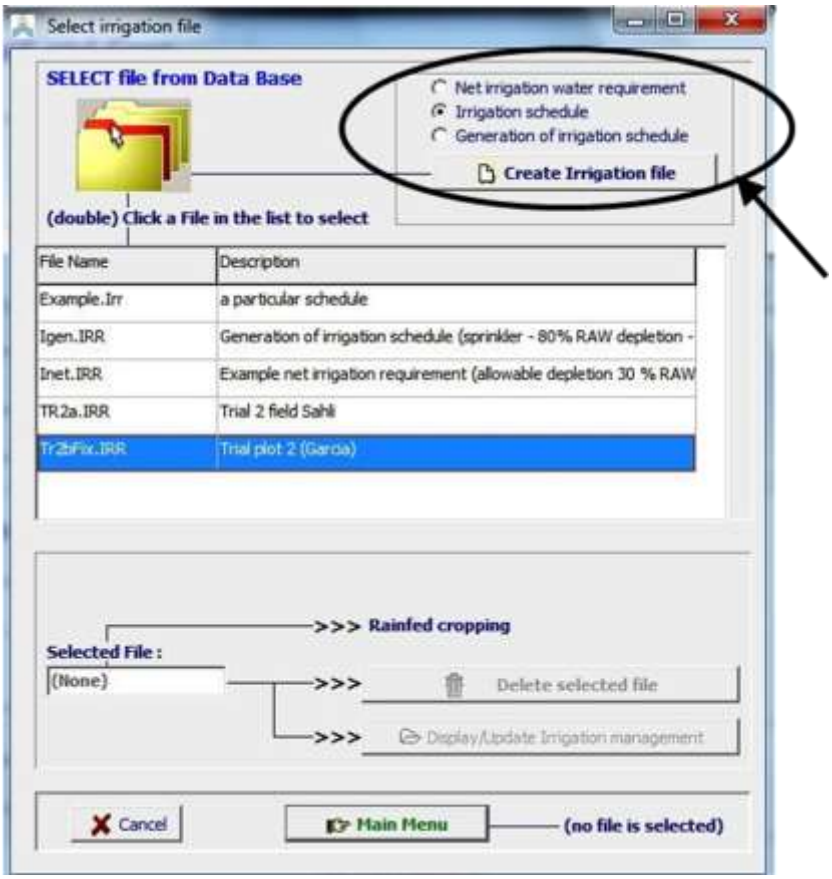


Figure 2.6d – Selection of the type of irrigation file that needs to be created

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).

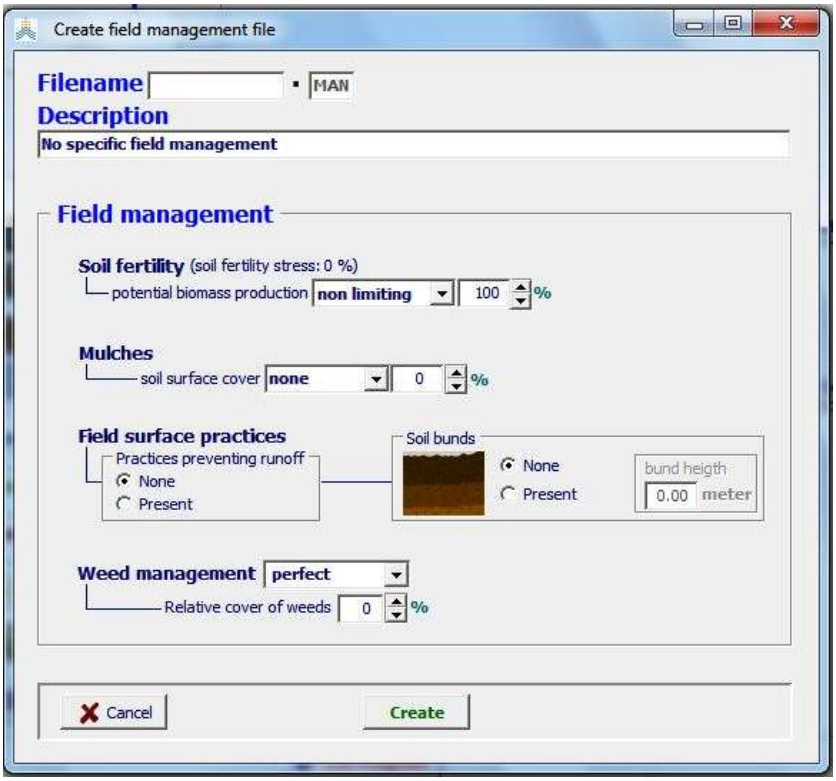


Figure 2.6e – *Create field management* menu

- **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).

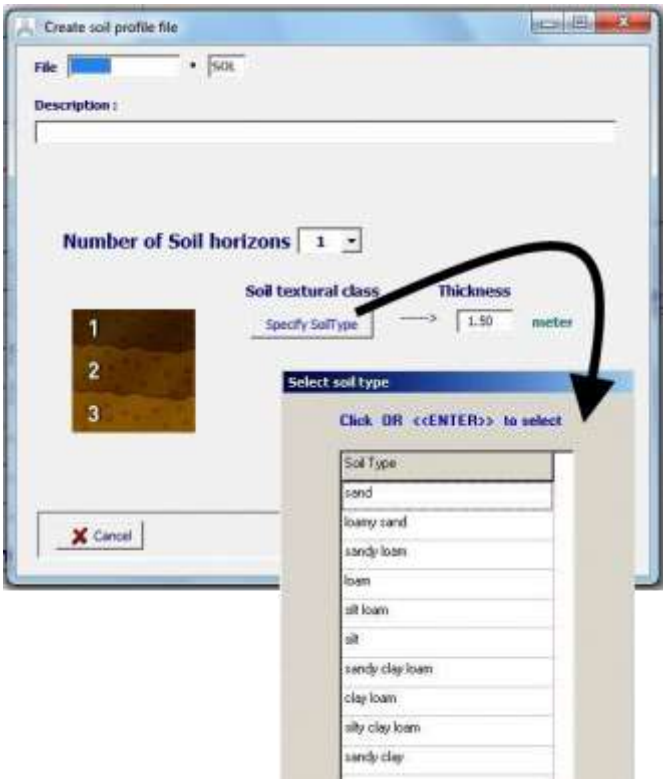


Figure 2.6f – *Create soil profile file* menu

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 crop calendar file**

When creating a crop calendar file, the user specifies if the start of the growing cycle is fixed or is generated by a rainfall or air temperature criterion. The parameters are displayed and the values can be adjusted in the ***Crop calendar characteristics*** menu (see 2.11 Crop calendar characteristics).

- **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.

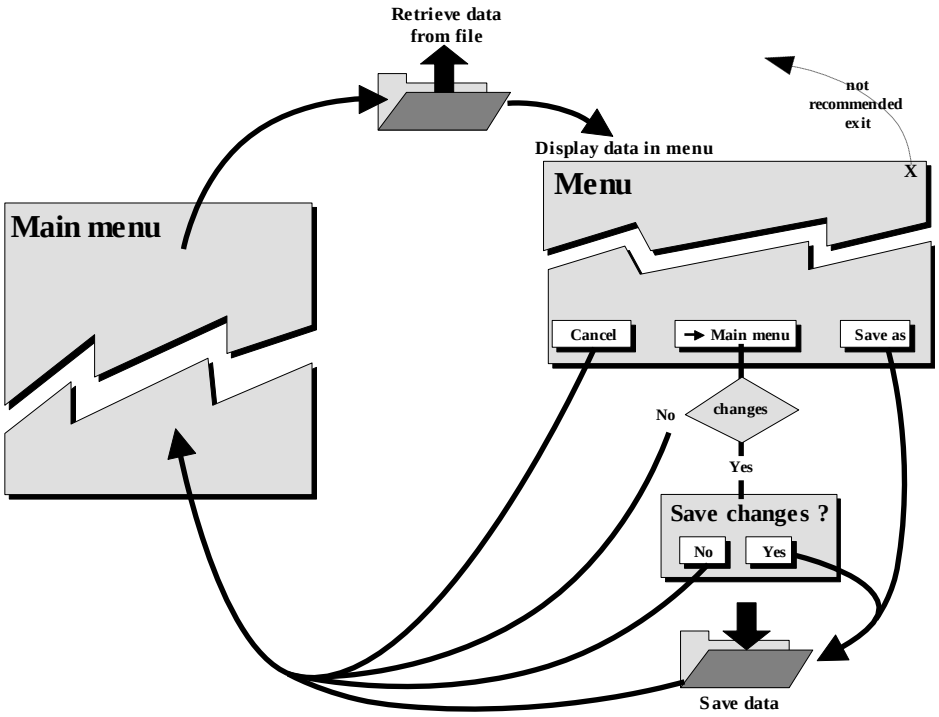


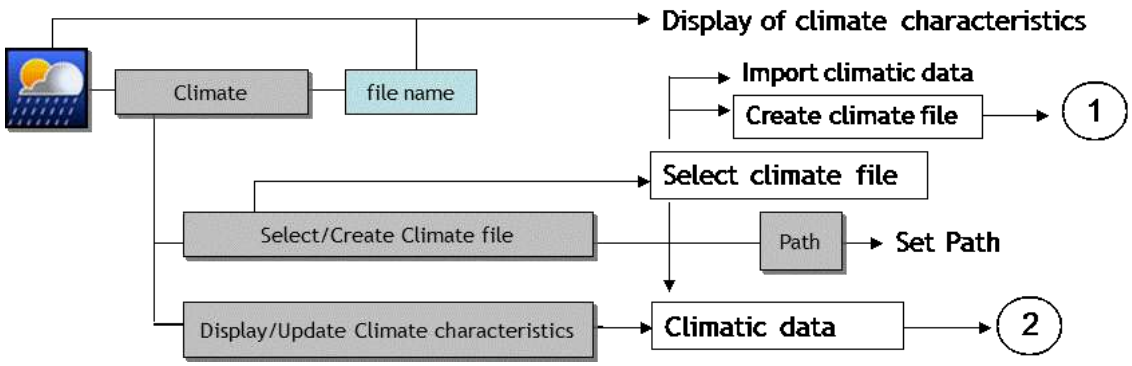
Figure 2.7 – Options to exit and close a menu

Menu reference

2.8 Hierarchical structure of the menus

2.8.1 Environment and Crop panel (Main menu)

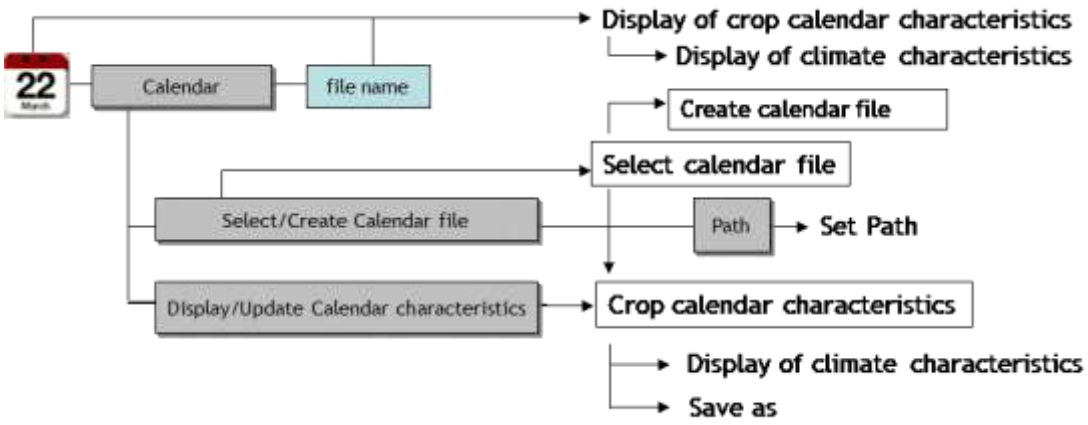
- **Climate**



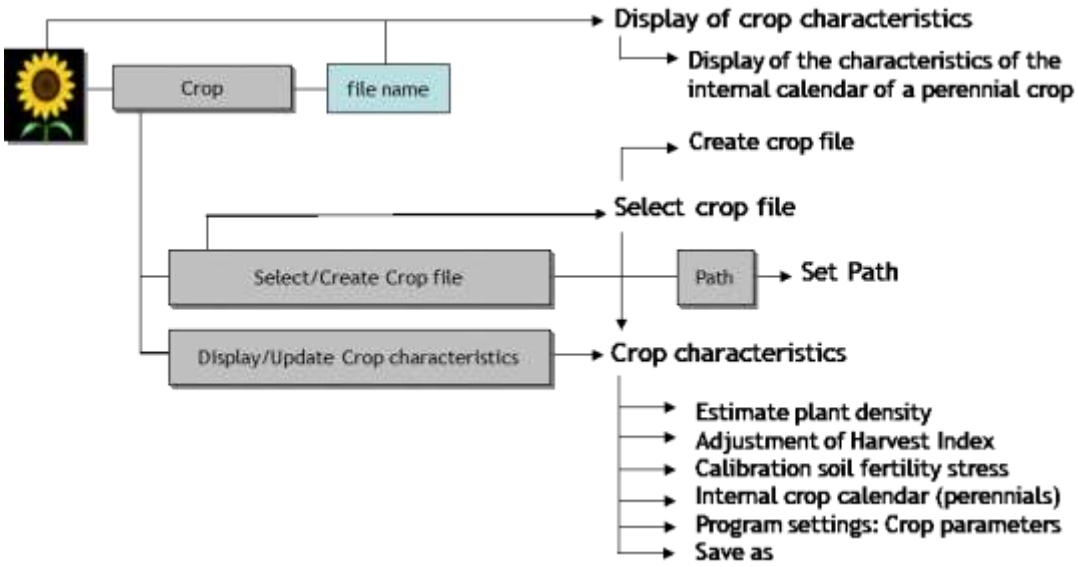
1) from the ***Create climate file*** menu the user gets access to:
   - ***Select temperature file*** menu
   - ***Create temperature file*** menu
   - ***Select ETo file*** menu
   - ***Create ETo file*** menu
   - ***Select rain file*** menu
   - ***Create rain file*** menu
   - ***Select CO2 file*** menu

2) from the C***limatic 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

- **Calendar**

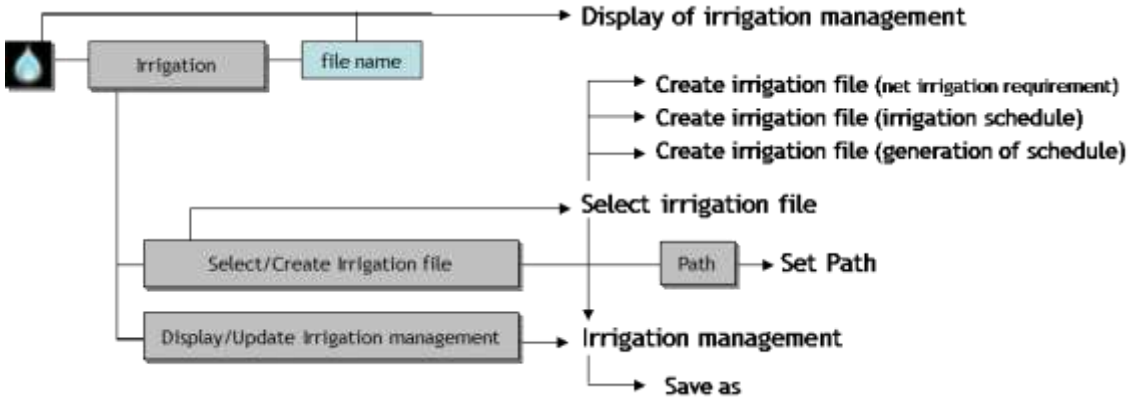


- **Crop**

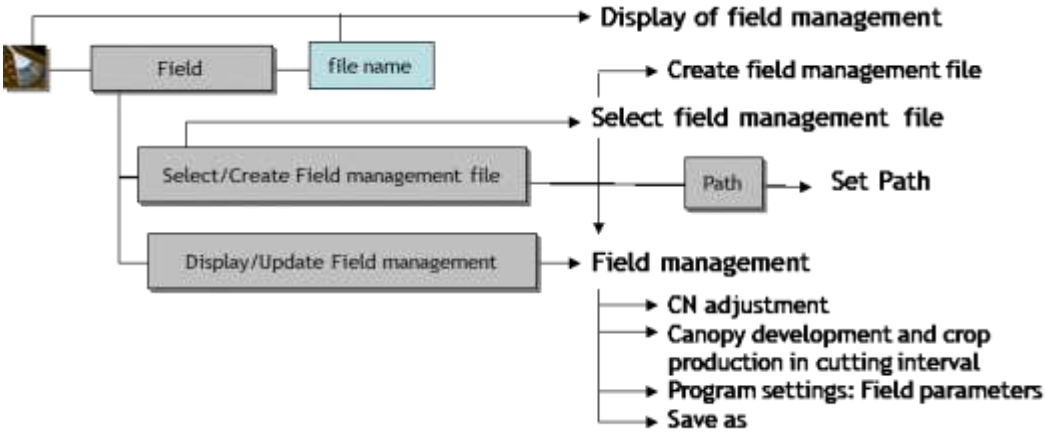


- **Management**

- irrigation management

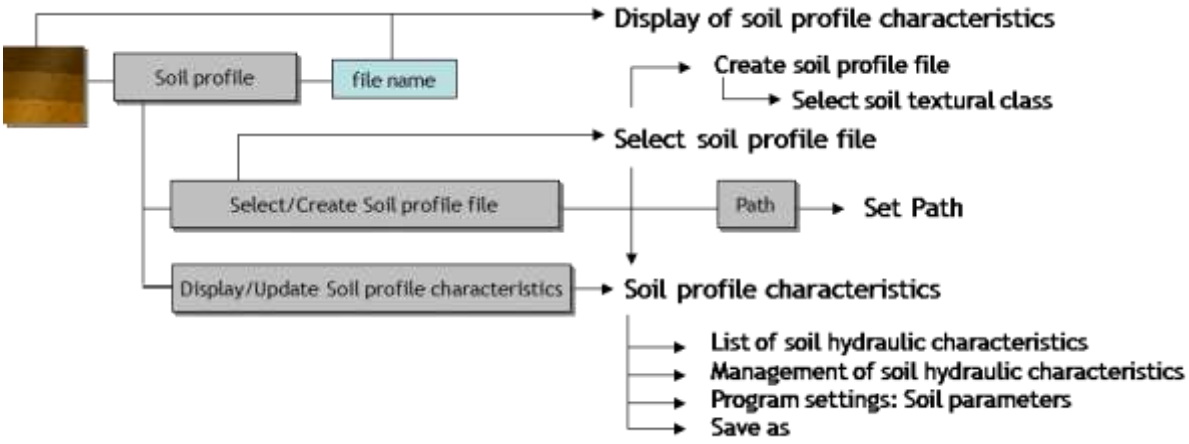


- field management

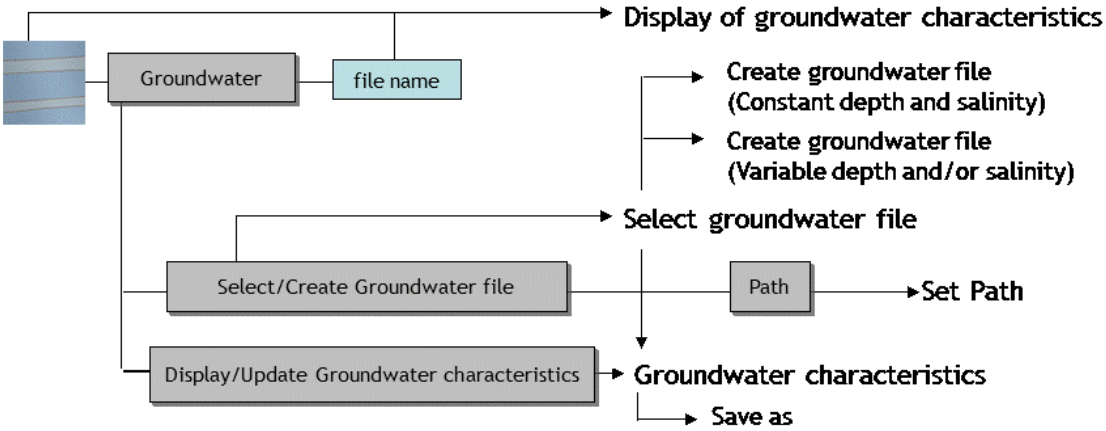


- **Soil**

- soil profile

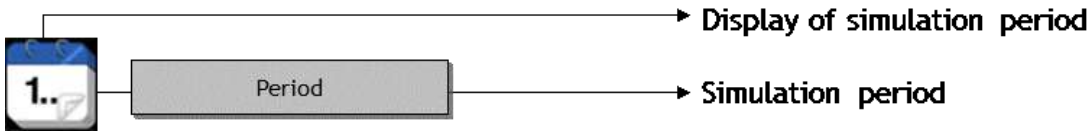


- groundwater

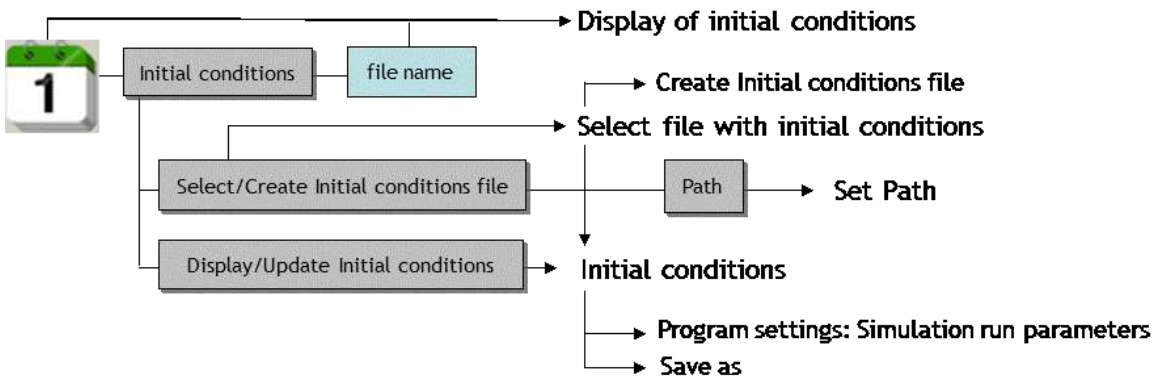


2.8.2 Simulation panel (Main menu)

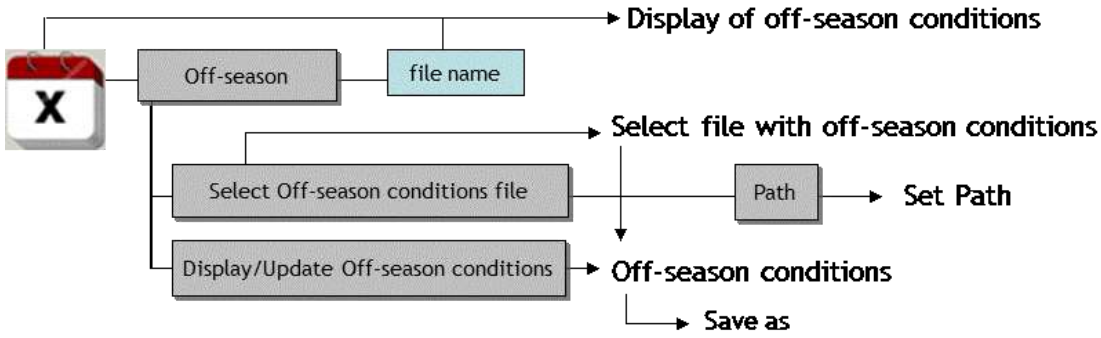
- **Simulation period**



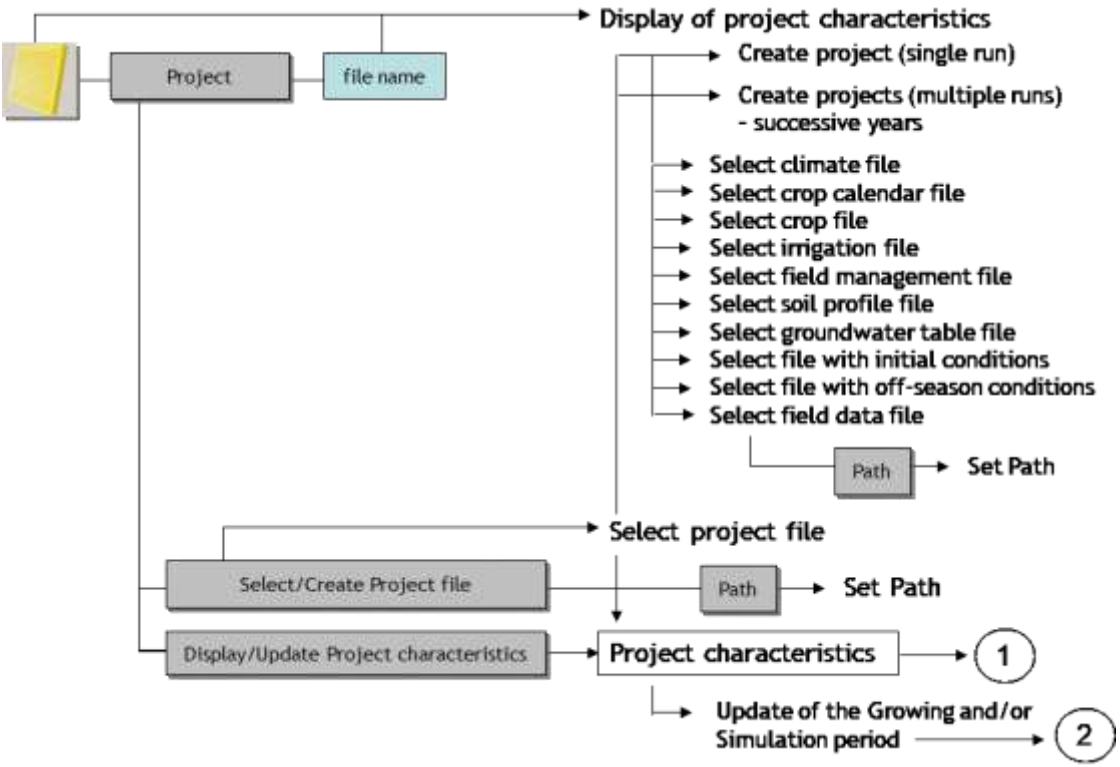
- **Initial conditions**



- **Off-season conditions**



- **Project**

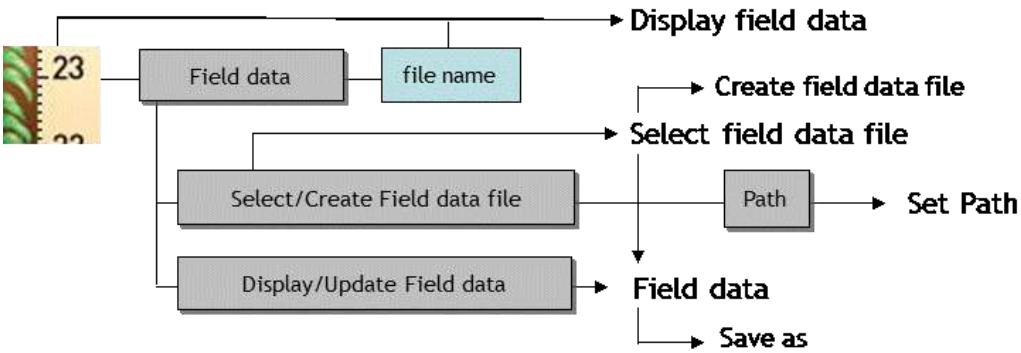


1) from the ***Project characteristics*** menu the user gets access to:
   - ***Display of climate characteristics*** menu
   - ***Display of crop calendar characteristics*** menu
   - ***Display of crop characteristics*** menu
   - ***Display of irrigation characteristics*** menu
   - ***Select irrigation file*** menu
   - ***Display of field characteristics*** menu
   - ***Select field management file*** menu
   - ***Display of soil profile characteristics*** menu
   - ***Select soil profile file*** menu
   - ***Display of groundwater table characteristics*** menu
   - ***Select groundwater table 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
   - ***Display of field data characteristics*** menu
   - ***Select field data file*** menu
   - ***Program settings: Crop parameters*** menu
   - ***Program settings: Field parameters*** menu

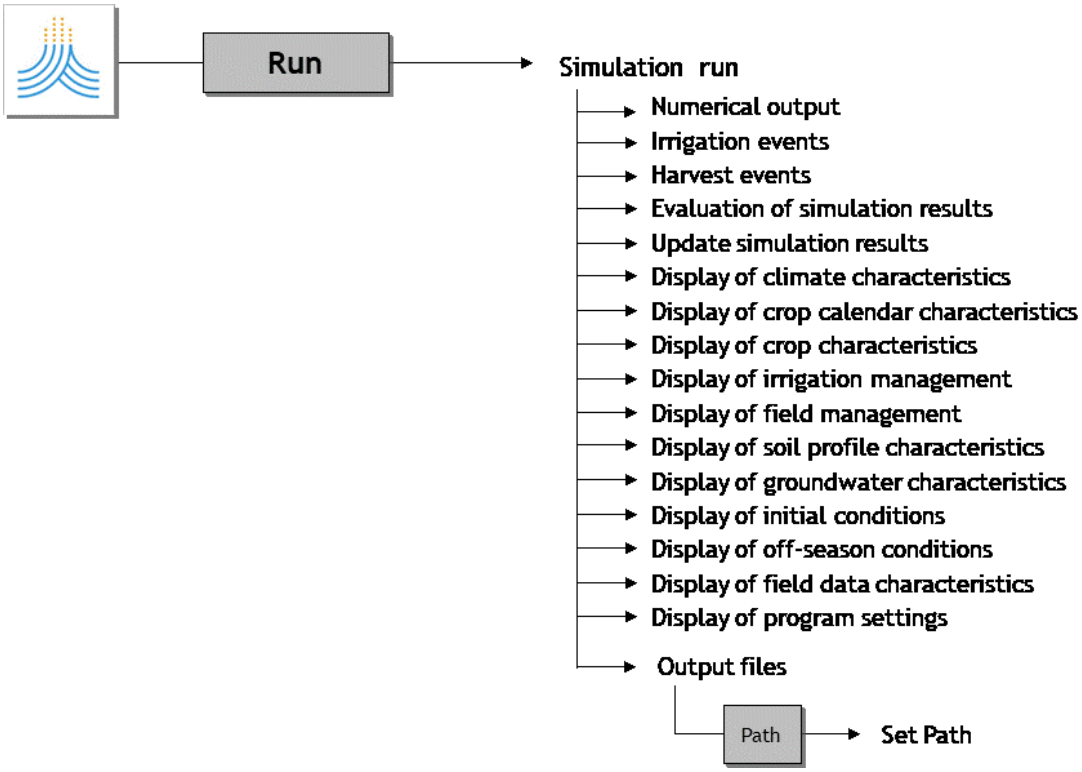
- ***Program settings: Soil parameters*** menu
- ***Program settings: Temperature parameters*** menu
- ***Program settings: 10-day or monthly rainfall***
- ***Update of the Growing and/or Simulation period*** menu
- ***Save as*** menu

2) From the ***Update of the Growing and/or Simulation period*** menu the user get access to:
   - ***Select climate file*** menu
   - ***Select crop calendar file*** menu
   - ***Select crop file*** menu

- **Field data**



- **Run**


Run
Simulation run
Numerical output
Irrigation events
Harvest events
Evaluation of simulation results
Update simulation results
Display of climate characteristics
Display of crop calendar characteristics
Display of crop characteristics
Display of irrigation management
Display of field management
Display of soil profile characteristics
Display of groundwater characteristics
Display of initial conditions
Display of off-season conditions
Display of field data characteristics
Display of program settings
Output files
Path
Set Path

2.9 Climatic data

2.9.1 Climatic data required by AquaCrop

For each day of the simulation period, AquaCrop requires:
- the minimum (Tn) and maximum (Tx) 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 ET_o 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 CO_2 concentration for the year 2000 measured at Mauna Loa Observatory in Hawaii. Other CO_2 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 CO_2 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).

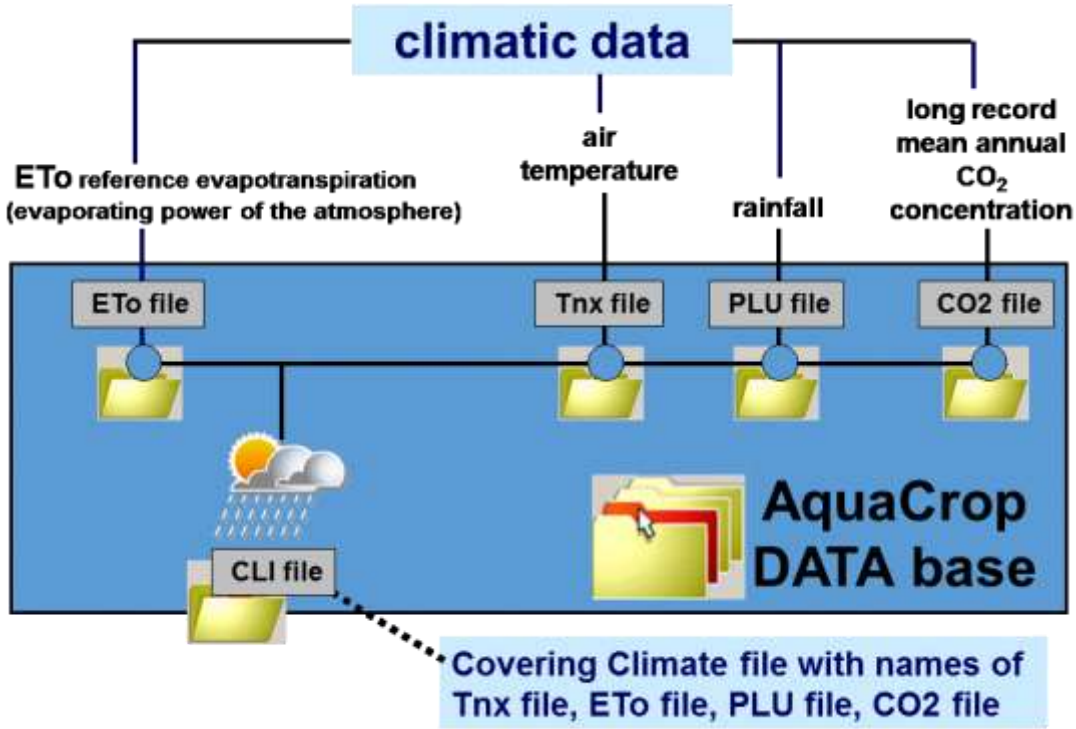


Figure 2.9a – Climate files (*.CLI) and files with climatic data (*.ETo, *.Tnx, *.PLU, *.CO2) available in AquaCrop data base

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).

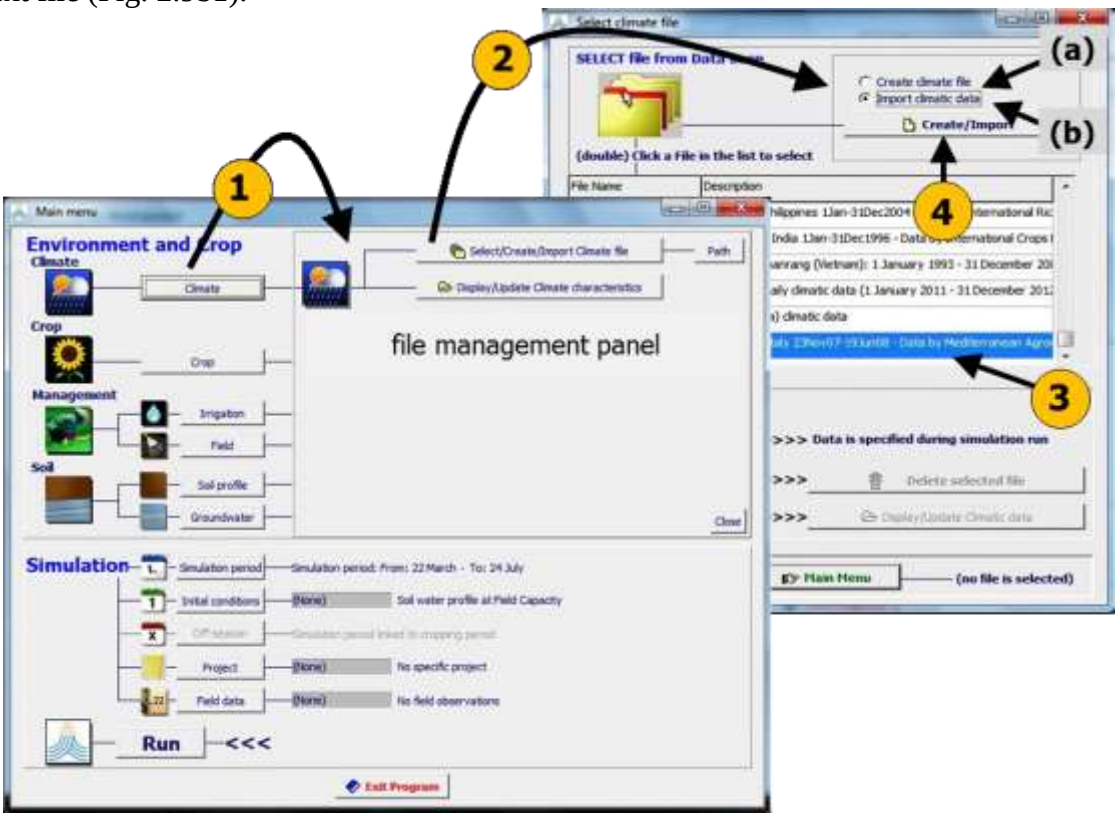


Figure 2.9b1 – By selecting (1) the <Climate> command and subsequently (2) the <Select/Create Climate file> command in the file management panel in the *Main menu*, the user gets access to the *Select climatic file* menu, in which (3) one of the available CLI files, or (4) the command (a) to <Create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

<u>Type of data</u>

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.

<u>Free format text files with climatic data (files with extension '.txt')</u>

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
ETo, Reference crop evapotranspiration	
Direct import of reference crop evapotranspiration (ETo)	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);

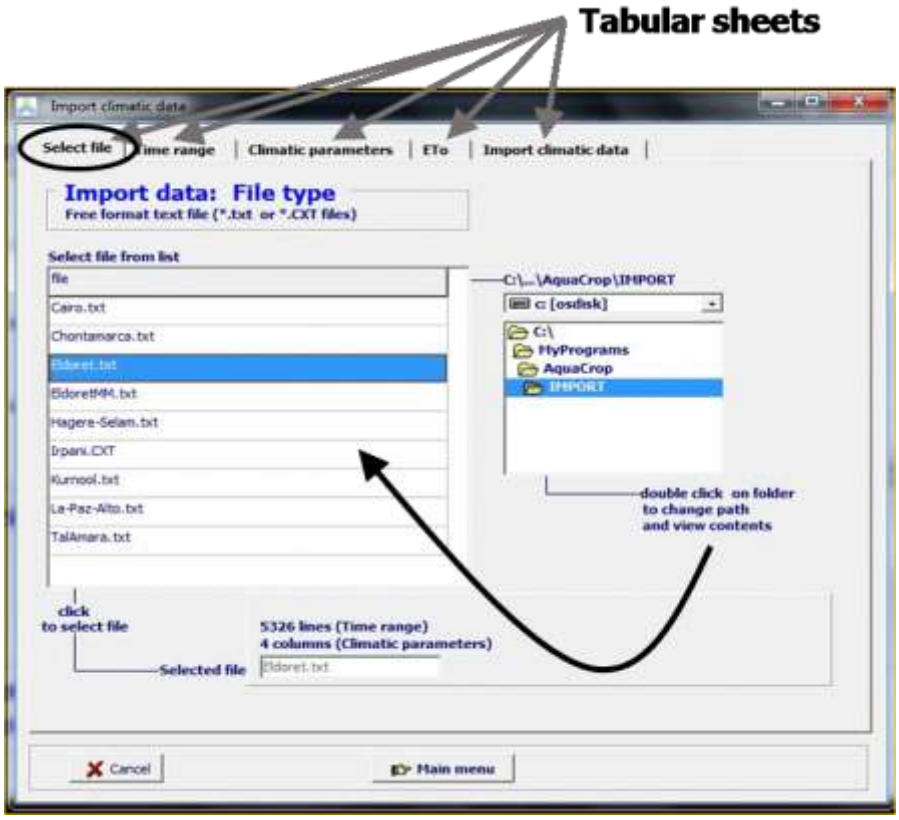


Figure 2.9b2 – *Import climatic data* menu with its tabular sheets: 'Select file' (displayed), 'Time range', 'Climatic parameters', 'ETo', and 'Import climatic data'

- **'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.

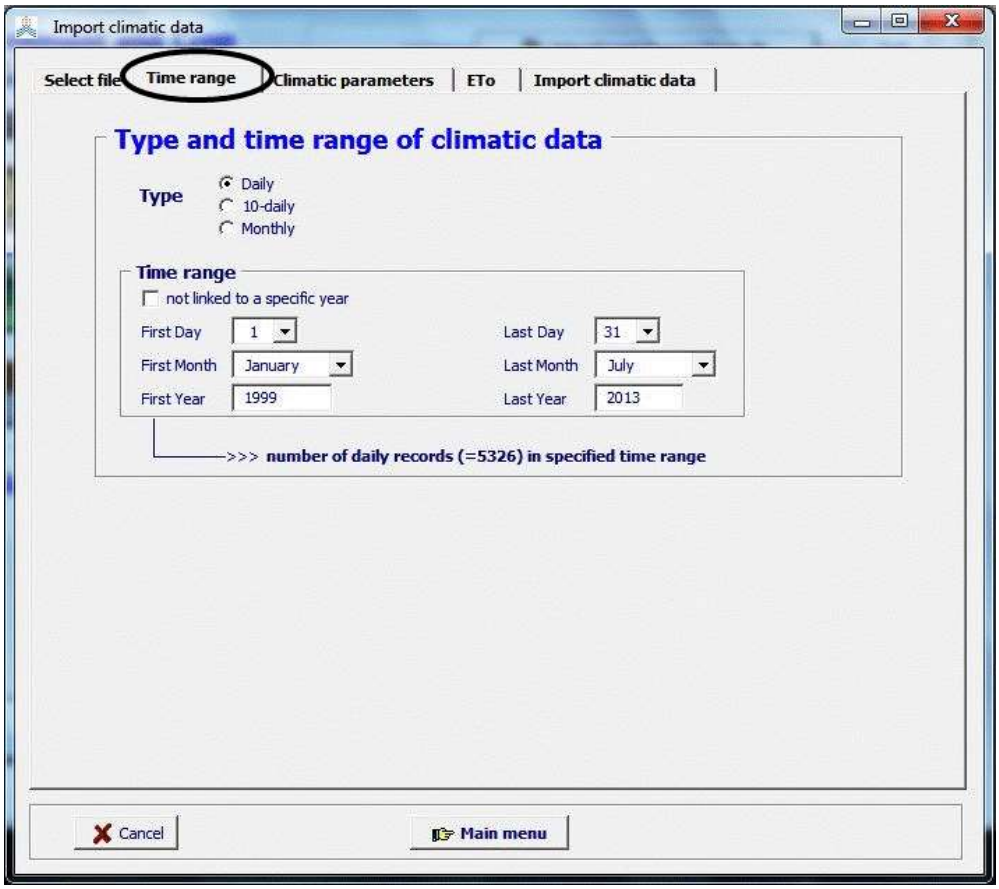


Figure 2.9b3 – The 'Time range' tabular sheet of the *Import climatic data* menu: for 'Eldoret.txt' (containing a long record of daily temperature and rainfall data)

<u>Tabular sheet: 'Climatic parameters'</u>

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 in the 'Climatic parameters' tabular sheet.

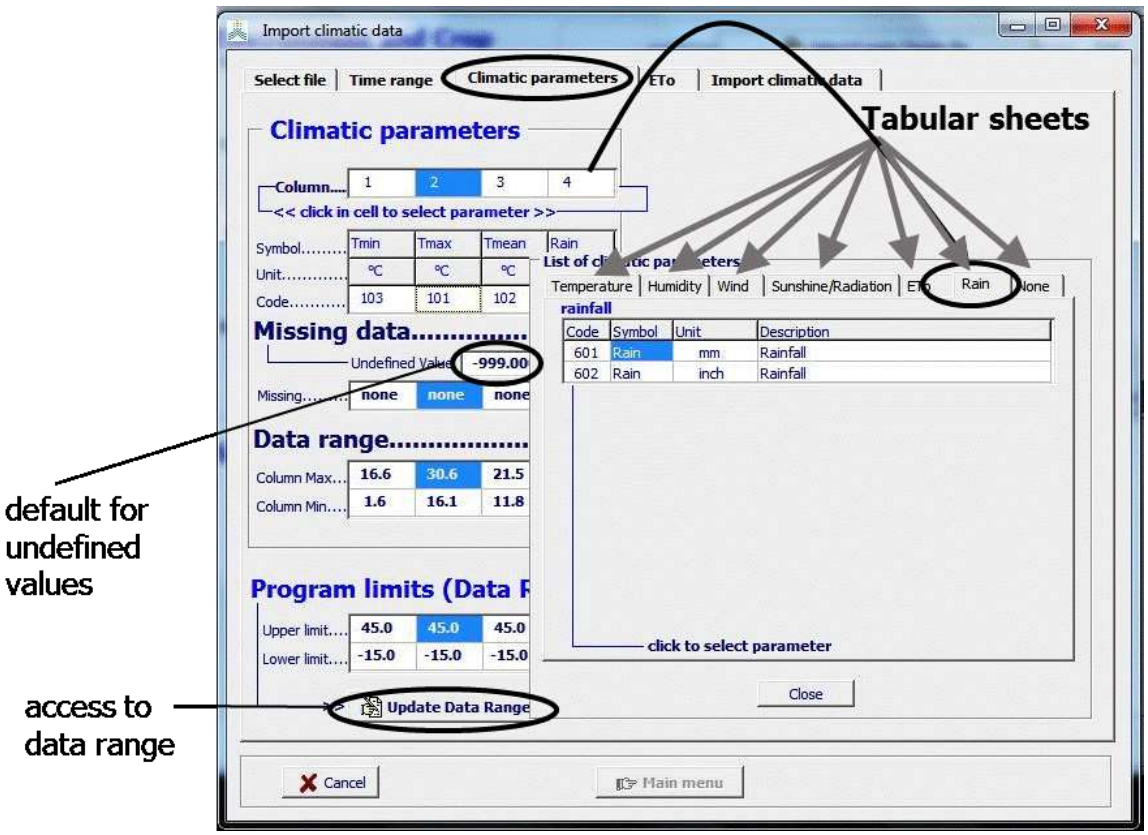


Figure 2.9b4 – The 'Climatic parameters' tabular sheet of the *Import climatic data* menu for 'Eldoret.txt' (containing a long record of daily temperature (minimum, maximum and average) and rainfall data)

<u>Tabular sheet: 'ETo'</u>

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 (Tdew) 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 Tdew ≈ 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, Tdew 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).

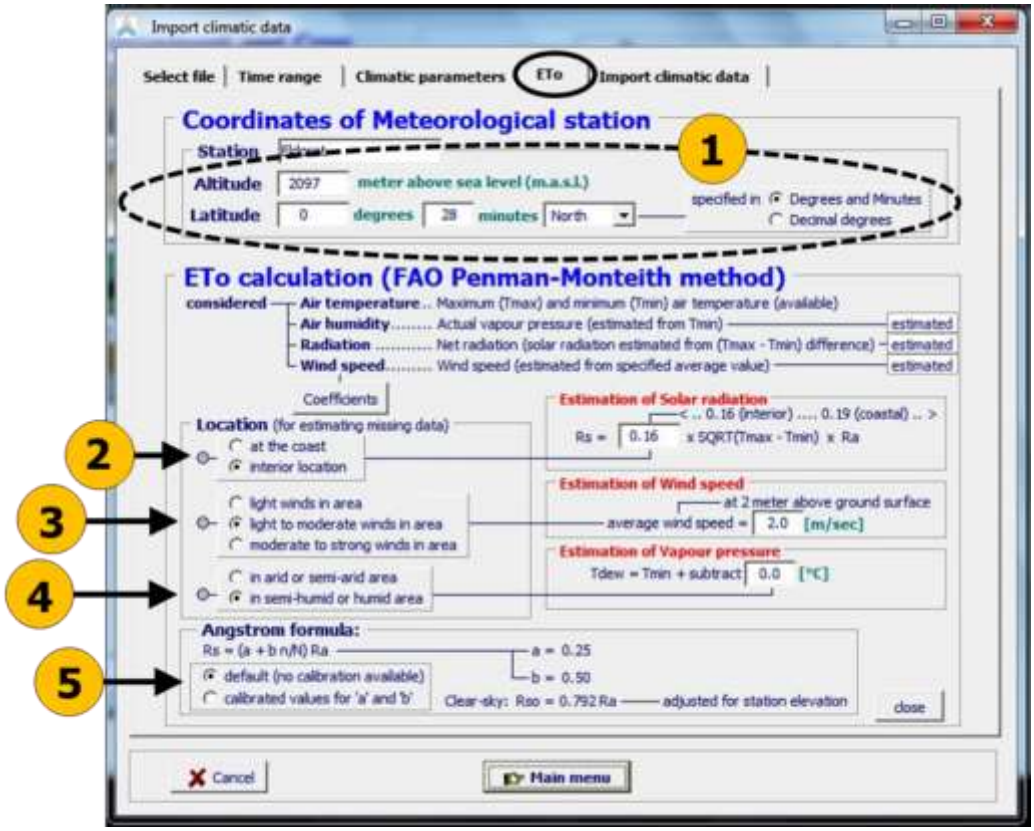


Figure 2.9b5 – The 'ETo' tabular sheet of the *Import climatic data* menu for 'Eldoret.txt' (containing a long record of daily temperature and rainfall data), with (1) specification of the coordinates; choices made for estimating missing (2) solar radiation, (3) wind speed, and (4) vapour pressure; and (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 m/sec u_2 = 2.0 m/sec u_2 = 4.0 m/sec	
Vapour pressure: dewpoint temperature	- in arid or semi-arid area - in semi-humid or humid area	Tdew ≈ Tmin – 2°C Tdew ≈ Tmin	

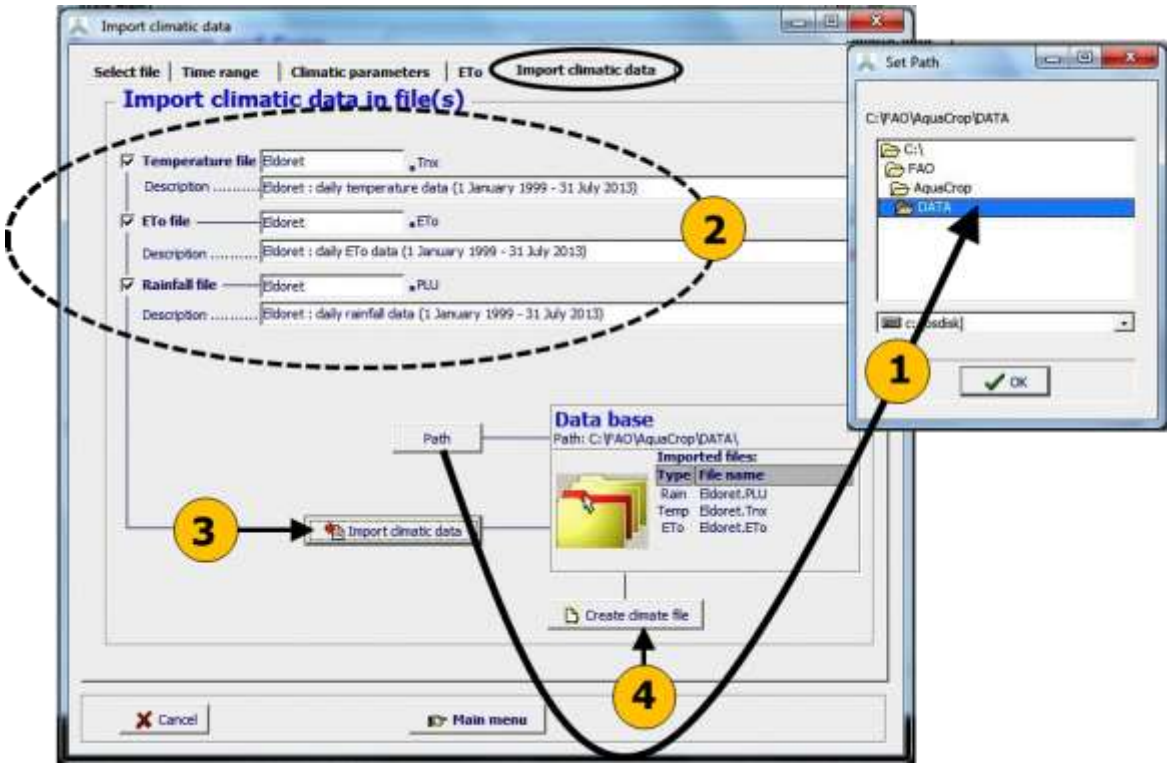


Figure 2.9b6 – The 'Import climatic data' tabular sheet of the *Import climatic data* menu for 'Eldoret.txt' (containing a long record of daily temperature and rainfall data), with specification of (1) folder, and (2) names and description of files with climatic data. By selecting (3) the <Import climatic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

<u>Tabular sheet: 'Import climatic data'</u>

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

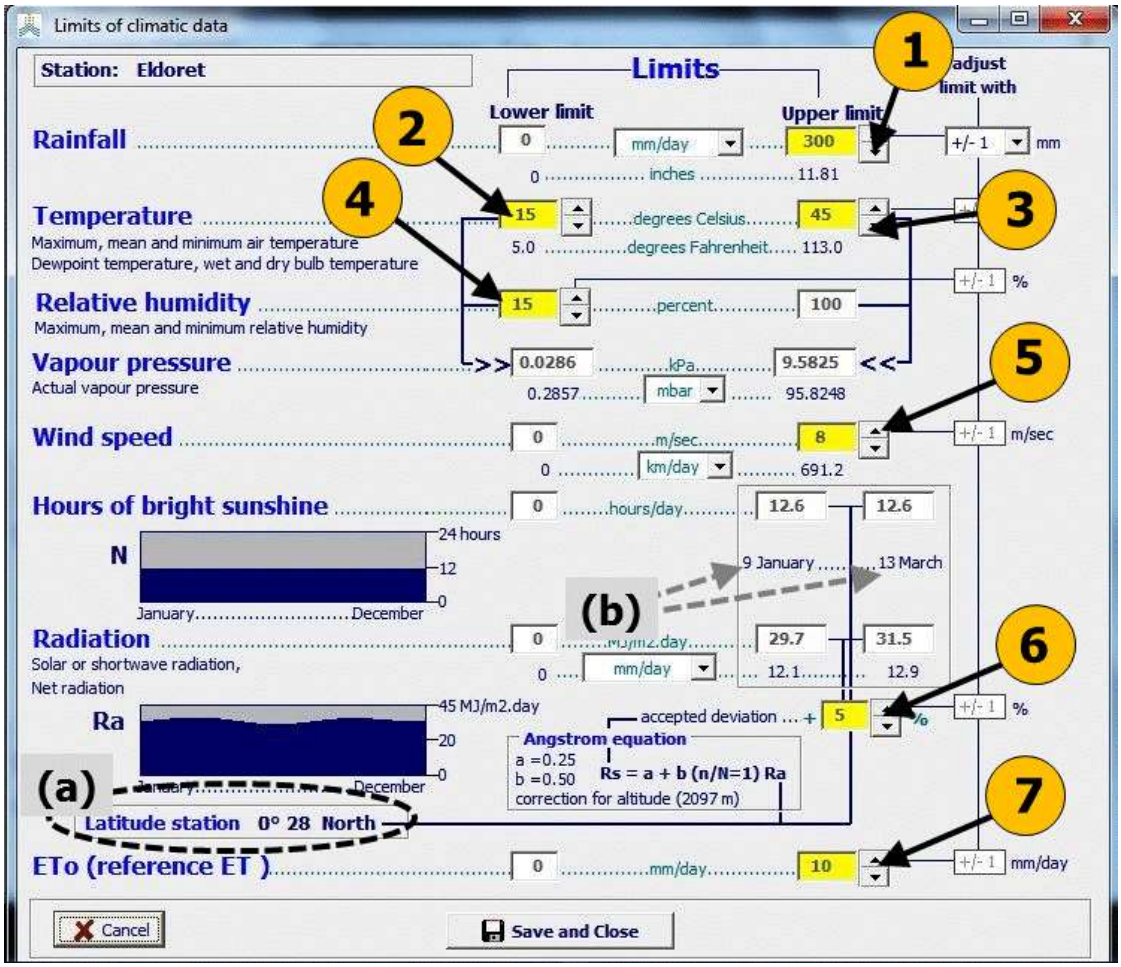


Figure 2.9b7 – The *Limits of climatic data* menu in which upper and/or lower limits can be adjusted for (1) total rainfall, (2) and (3) air temperature, (4) relative humidity, (5) daily wind speed, (6) deviation from maximum possible daily radiation (given by (a) latitude and (b) time of the year),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

2.9.3 CO2 files

Mean annual atmospheric CO_2 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 year), 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 CO_2 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 four different RCP's ('RCP2-6.CO2', RCP4-5.CO2', 'RCP6-0.CO2' and 'RCP8-5.CO2') are available in the DATA subdirectory of AquaCrop. 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;
- In 2021, IPCC released a new set of climate scenarios with respect to the sixth IPCC report. CO2 files for the five "Shared Socioeconomic Pathways" (SSPs) are added to the DATA subdirectory ('SSP1-1.9.CO2', 'SSP1-2.6.CO2', 'SSP2-4.5.CO2', 'SSP3-7.0.CO2' and 'SSP5-8.5.CO2') The represent different socio-economic developments as well as different pathways of atmospheric greenhouse gas concentrations. Compared to the previous used RCPs, the new SSPs scenarios have been improved in a variety of ways (IPCC, 2021). In Figure 2.9c, the CO_2 concentrations of the new set of SSPs are plotted next to the RCPs.
- The user can also create:
  - CO2 file containing (observed and/or projected) annual atmospheric CO_2 concentrations for a number of years;
  - CO2 file containing only one specific annual atmospheric CO_2 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').

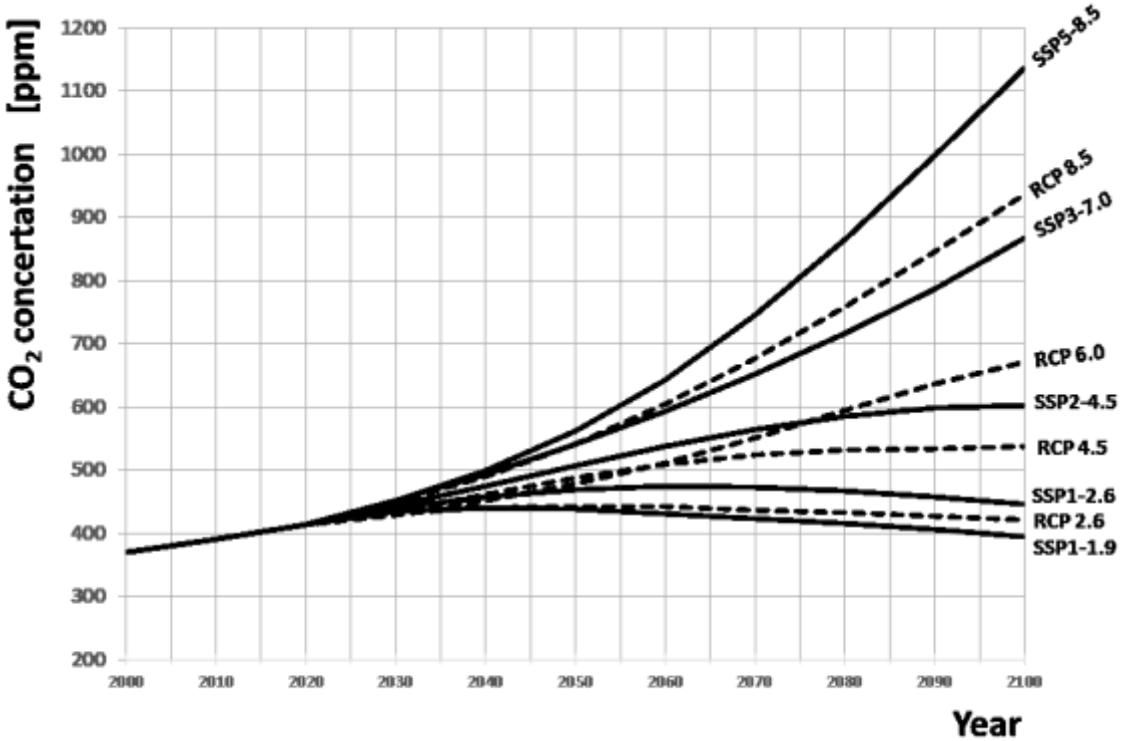


Figure 2.9c – Projected CO_2 concentrations for 5 SSPs (solid line) and 4 RCPs (dotted lines), available in the database of AquaCrop.

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).

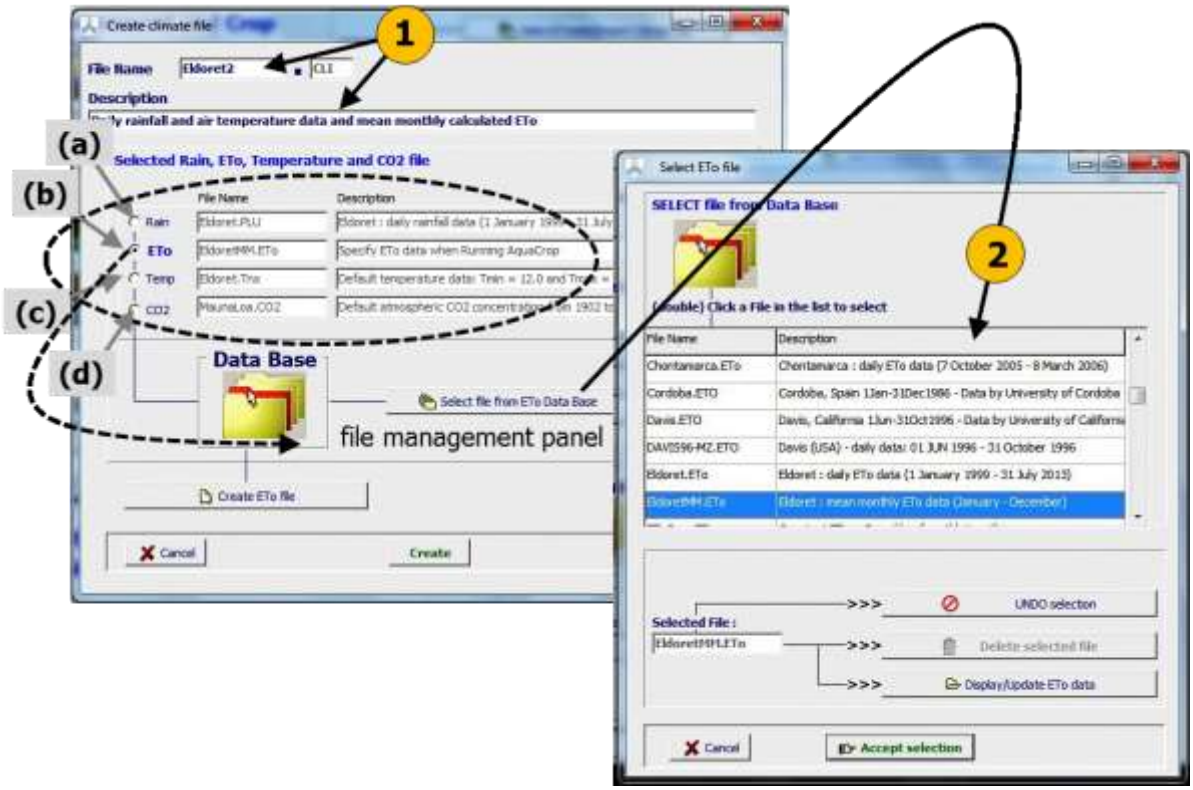
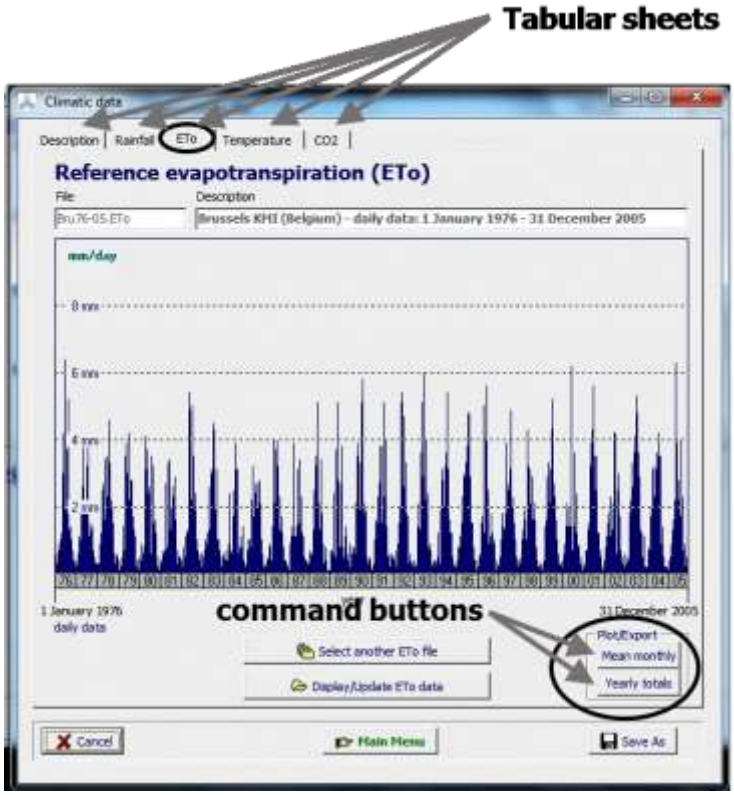


Figure 2.9d – *Create climate file* menu in which the user composes the covering climate file (1) by specifying its name and description, and (2) by selecting a (a) rainfall, (b) ETo, (c) air temperature and (d) CO2 file from the Data Base.

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	– Mean monthly (with the option to display rainfall with or without mean ETo) – Yearly totals	Plot of • 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	– Mean monthly (with the option to display as 'mm/day' or 'mm/month') – Yearly totals	Plot of • mean monthly ETo (mm/day), • mean monthly ETo (mm/month), • total yearly ETo within the period of available climatic data
Temperature	– Mean monthly (with the option to display as growing degree-days) – Yearly values (with the option to display as growing degree days)	Plot of • mean monthly air temperatures, • monthly growing degree-days (2.9e4), • mean yearly air temperatures, • total yearly growing degree-days within the period of available climatic data. When the data is displayed as growing degree-days, the base and upper temperatures for crop development for the selected crop are considered

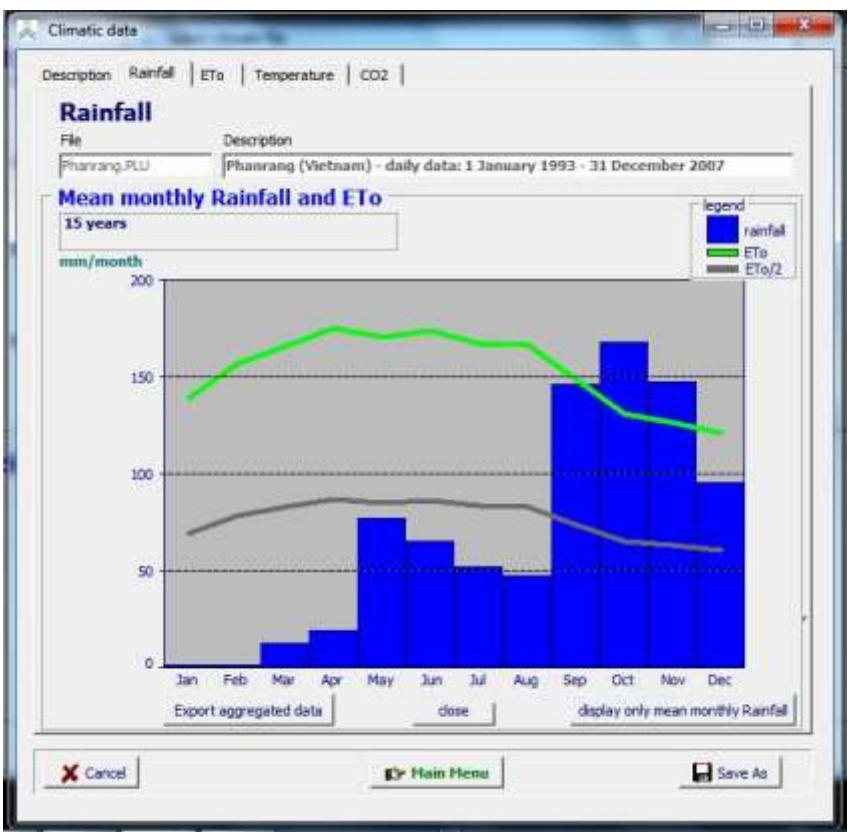


Figure 2.9e2 – Mean monthly Rainfall and ETo in Phanrang (Vietnam) for the 1993 – 2007 period in the 'Rainfall' tabular sheet of the *Climatic data* menu

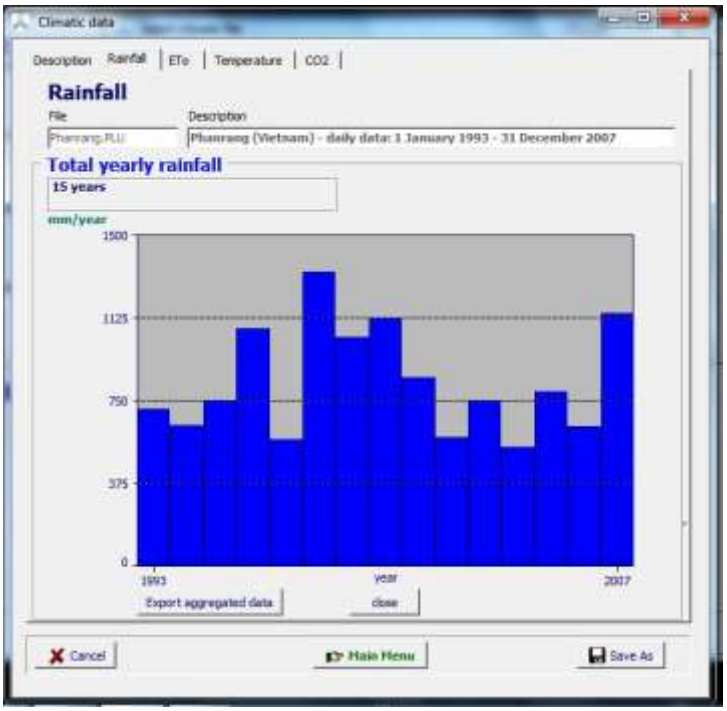


Figure 2.9e3 – Total yearly rainfall in Phanrang (Vietnam) for the 1993 – 2007 period in the 'Rainfall' tabular sheet of the *Climatic data* menu

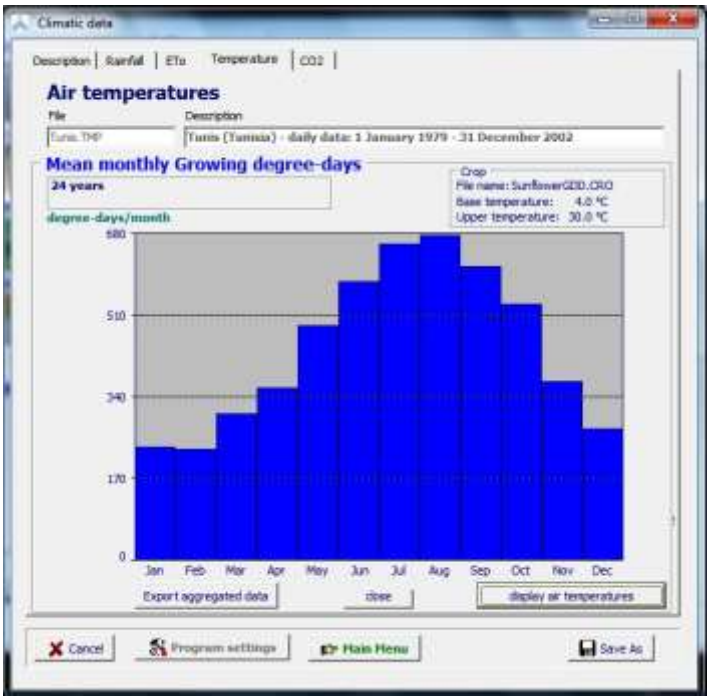


Figure 2.9e4 – Mean monthly Growing degree-days for a crop with a base temperature for crop development of 4 °C and an upper temperature of 30 °C, in Tunis (Tunisia) for the 1979 – 2002 period in the 'Temperature' tabular sheet of the *Climatic data* menu

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.

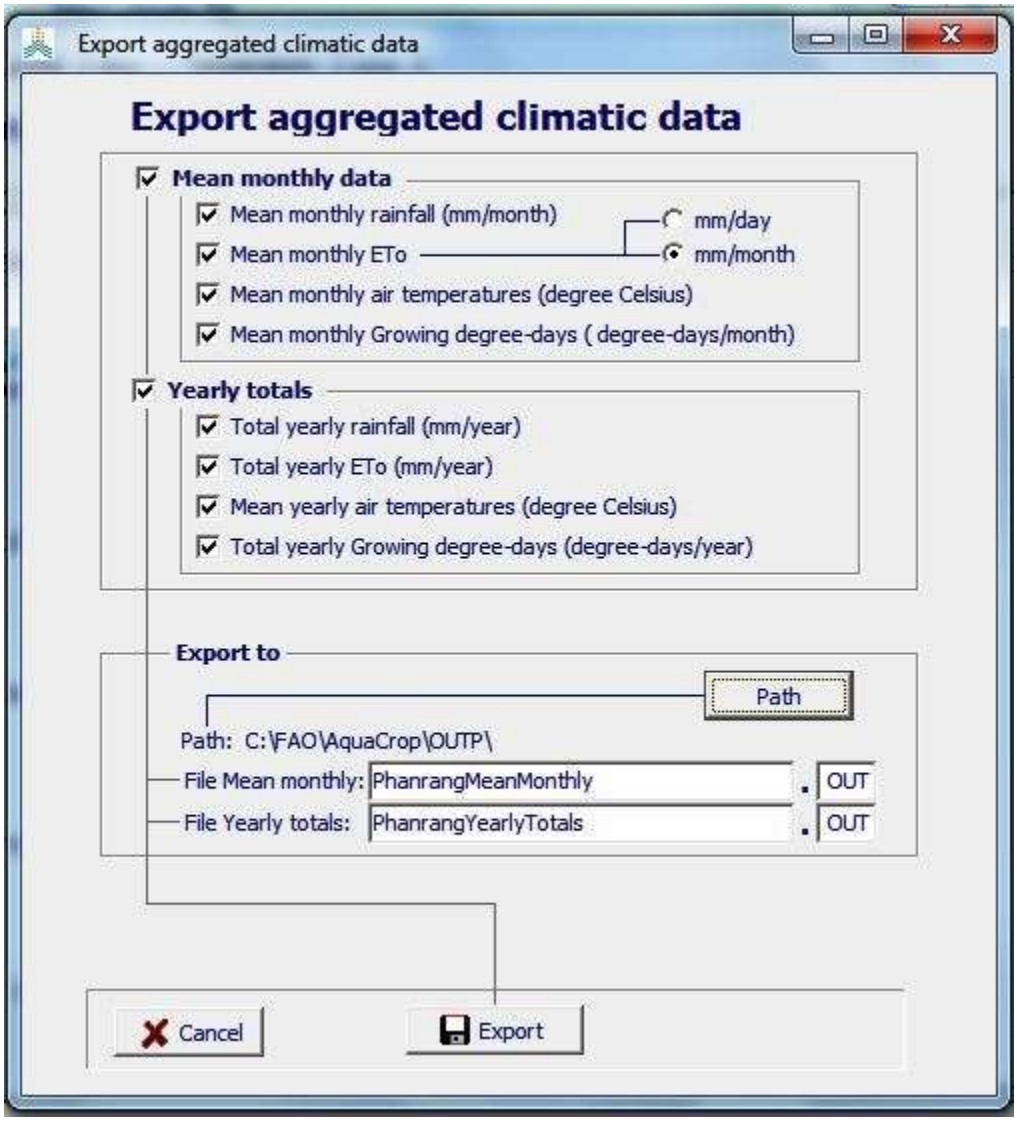


Figure 2.9e5 – The *Export aggregated climatic data* menu

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
	Temperature parameters ▪ 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 °C T_x = 28 °C
	10-day or monthly rainfall Procedures to estimate effective rainfall, surface runoff and soil evaporation when rainfall data consists of 10-day or monthly totals (see Chapter 3) ▪ 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);
– Perennials (herbaceous forage crops) for climates with a winter dormant period or a non dormant (Winter active) cultivar: crop characteristics change between the 1st year of cultivation (planting/sowing year) and the successive years of cultivation (with regrowth).

- **Calibrated crops**

The data base of AquaCrop contains calibrated and validated crop parameters (described in Annex 1. Crop parameters) for the following crops: Alfalfa, Barley, Cassava, Cotton, Dry beans, 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) Conservative generally applicable, (2) Conservative for a given specie but can or may be cultivar specific, (3) Dependent on environment and/or management, and (4) Cultivar specific

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)
ccini	Canopy size of individual plant at regrowth at 1st day (cm^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)
	Number of years at which CCx declines to 90 % of its value due to self-thinning – only for Perennials	Management (3)
	Shape factor of the decline of CCx over the years due to self-thinning – only for Perennials	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)
	Time from sowing to maximum rooting depth (days or GD days)	Management (3)

Table 2.10a. continued.

2. Crop transpiration		
Symbol	Description	Type (1), (2), (3), (4)
$Kc_{Tr,x}$	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)
	Number of days at end of season during which assimilates are stored in root system – only for perennial forage crops	Management (3) Cultivar (4)
	Percentage of assimilates, transferred to root system at last day of season – only for perennial forage crops	Management (3) Cultivar (4)
	Percentage of stored assimilates, transferred to above ground parts in next season – only for perennial forage crops	Management (3) Cultivar (4)
3.2 Harvest Index		
HI_o	Reference harvest index (%)	Cultivar (4)
	Excess of potential fruits (%)	Conservative (2)
	Dry matter content (%) of fresh yield	Cultivar (4)
	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)

Table 2.10a. continued.

4. Stresses		
Symbol	Description	Type (1), (2), (3), (4)
4.1 Soil water stresses		
$p_{exp,lower}$	Soil water depletion threshold for canopy expansion - Upper threshold	Conservative (1)
$p_{exp,upper}$	Soil water depletion threshold for canopy expansion - Lower threshold	Conservative (1)
	Shape factor for Water stress coefficient for canopy expansion	Conservative (1)
p_{sto}	Soil water depletion threshold for stomatal control – Upper threshold	Conservative (1)
	Shape factor for Water stress coefficient for stomatal control	Conservative (1)
p_{sen}	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 dormant period to be exceeded before crop is permanently wilted	Cultivar (4) Environment (3)
p_{pol}	Soil water depletion threshold for failure of pollination – Upper threshold	Conservative (1)
	Vol% at anaerobiotic 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)

Table 2.10a. continued.

Symbol	Description	Type (1), (2), (3), (4)
4.4 Soil salinity stress		
ECe_n	Electrical conductivity of the saturated soil-paste extract: lower threshold (at which soil salinity stress starts to occur)	Conservative (1)
ECe_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 ECsw (Electrical conductivity of the soil water)	Management (3)
5. Internal crop calendar – ***only for perennial forage crops***		
Symbol	Description	Type (1), (2), (3), (4)
	For perennial crops, the start and end of growth is determined by crop characteristics and weather conditions for the selected year of simulation. The options are to specify the start and/or end by: - A pre-set calendar day - Generated by a temperature criterion (the start/end is adjusted to the thermal regime of the year)	Cultivar (4) Environment (3)

- **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).

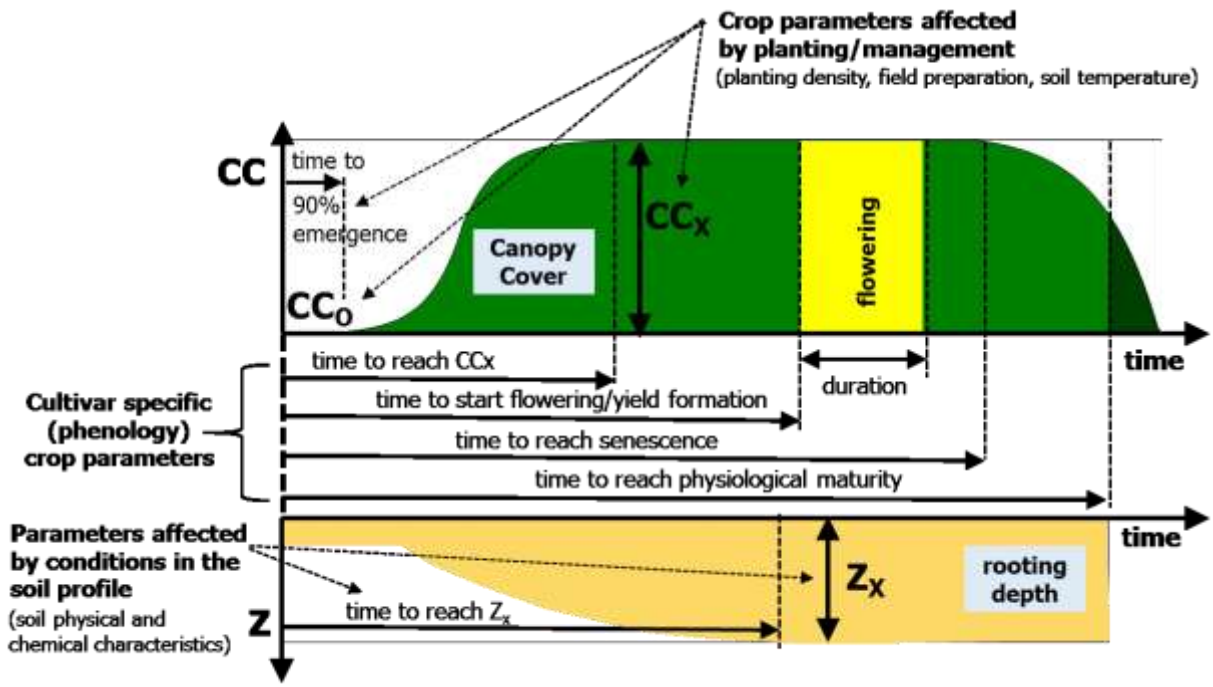


Figure 2.10b1 – Crop parameters to be tuned to the selected cultivar and the environmental conditions

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 specified by the user;
- **Plant density**, which will determine the initial (CC_o) canopy cover. The plant density is specified by (Fig. 2.10b2):
  1. the planting density;
  2. selecting one of the CC_o classes (ranging from very small to very high cover);
  3. specifying directly the percentage of CC_o (which might be useful for transplanted seedlings). The corresponding plant density will be derived from CC_o 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).

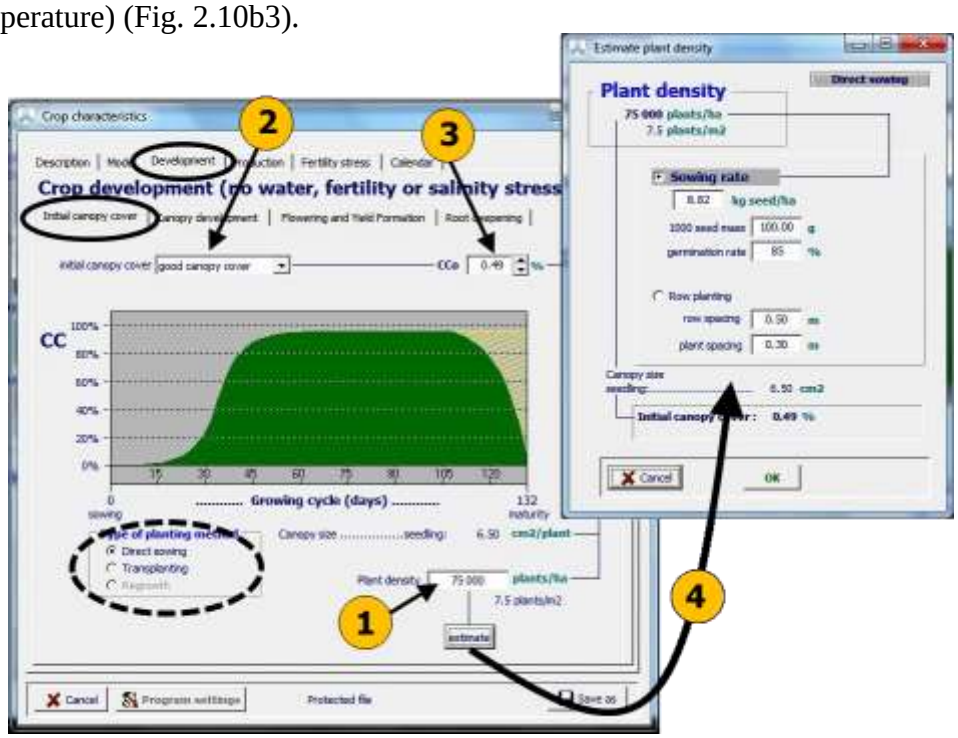


Figure 2.10b2 – The 'Initial canopy cover' tabular sheet of the 'Development' tabular sheet of the *Crop characteristics* menu in which the type of planting method (dotted oval) and the initial canopy cover (CC_o) is determined (1) by specifying plant density, (2) by selecting a predefined CC_o class, (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 necessary coincide with crop maturity;
- **Time to start flowering** (or the start of yield formation);
- **Duration of flowering**.

Reference Harvest Index (HIo): 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.

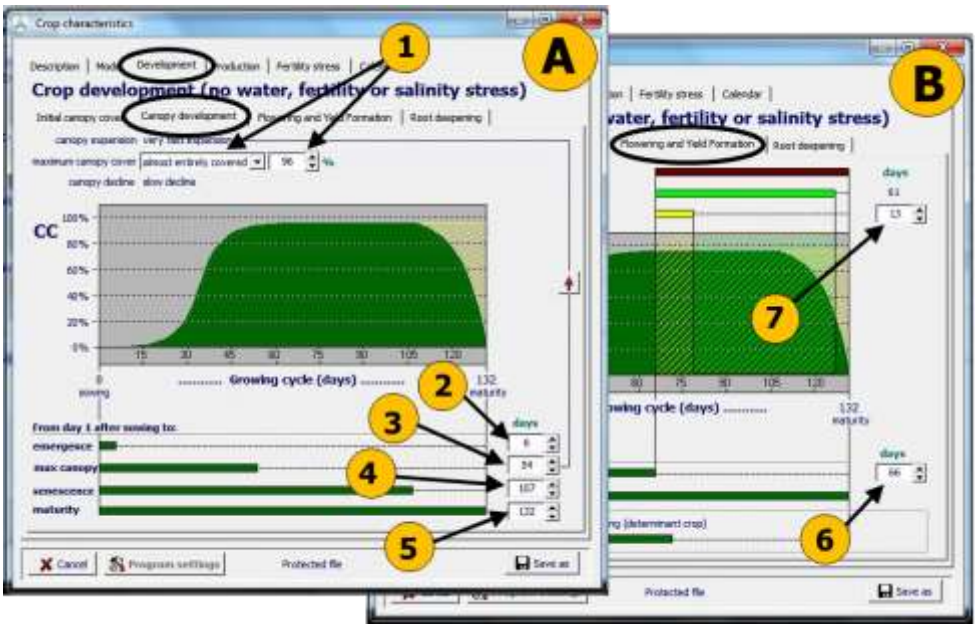


Figure 2.10b3 – The (A) 'Canopy development' and (B) 'Flowering and yield formation' tabular sheet of the 'Development' tabular sheet of the *Crop characteristics* menu including: (1) the maximum canopy cover (CC_x) by selecting a class or specifying the percentage, and the time to reach (2) 90% seedling 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).

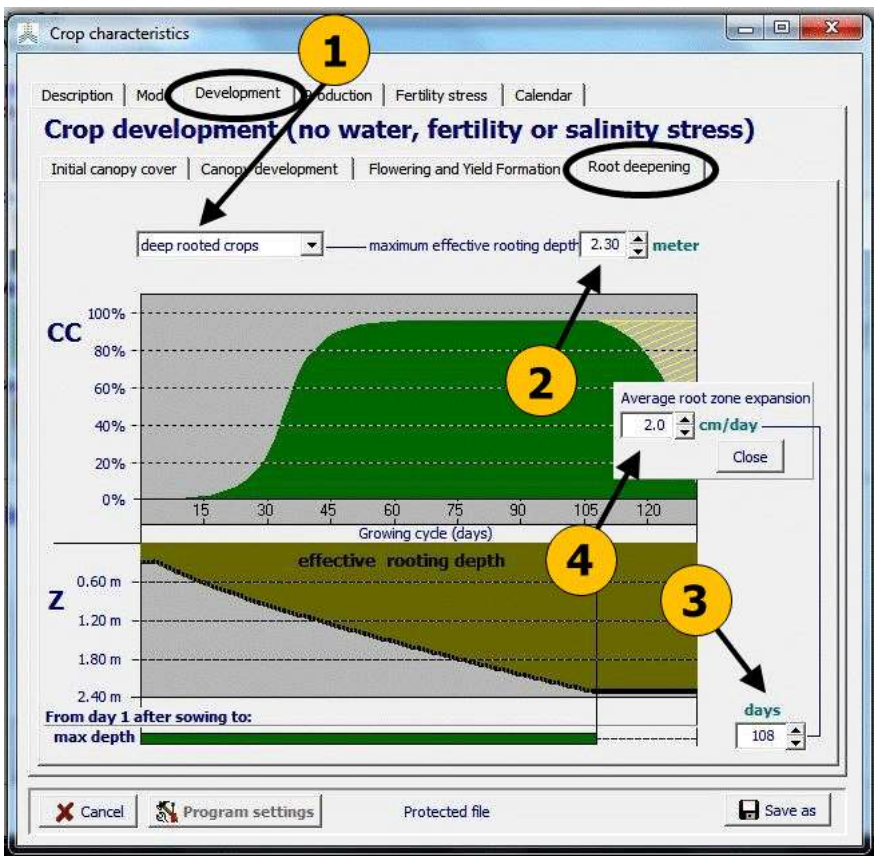


Figure 2.10b4 – The 'Root deepening' tabular sheet of the 'Development' tabular sheet of the *Crop characteristics* menu including: the maximum effective rooting depth (Zx), specified by (1) selecting a predefined class, or (2) by entering the value in meter, and the time to reach Z_x specified by (3)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

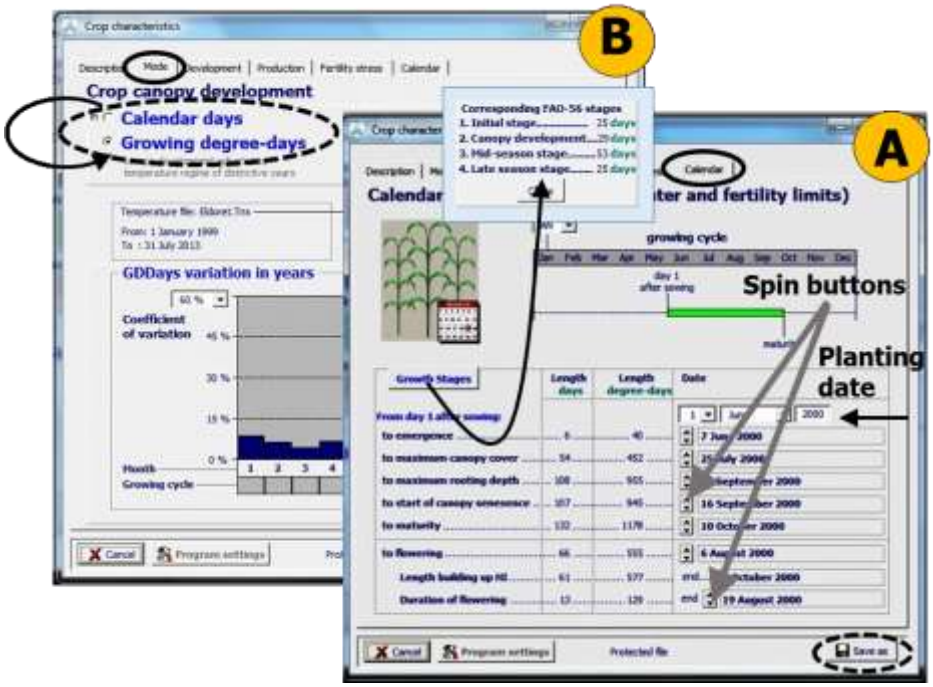


Figure 2.10b5 – (A) The 'Calendar' tabular sheet, to inspect or adjust the calendar of the growing period, and (B) The 'Mode' tabular sheet of the *Crop characteristics* menu to switch between calendar and thermal time. With the <Save as> command the fine-tuned crop characteristics can be saved in a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

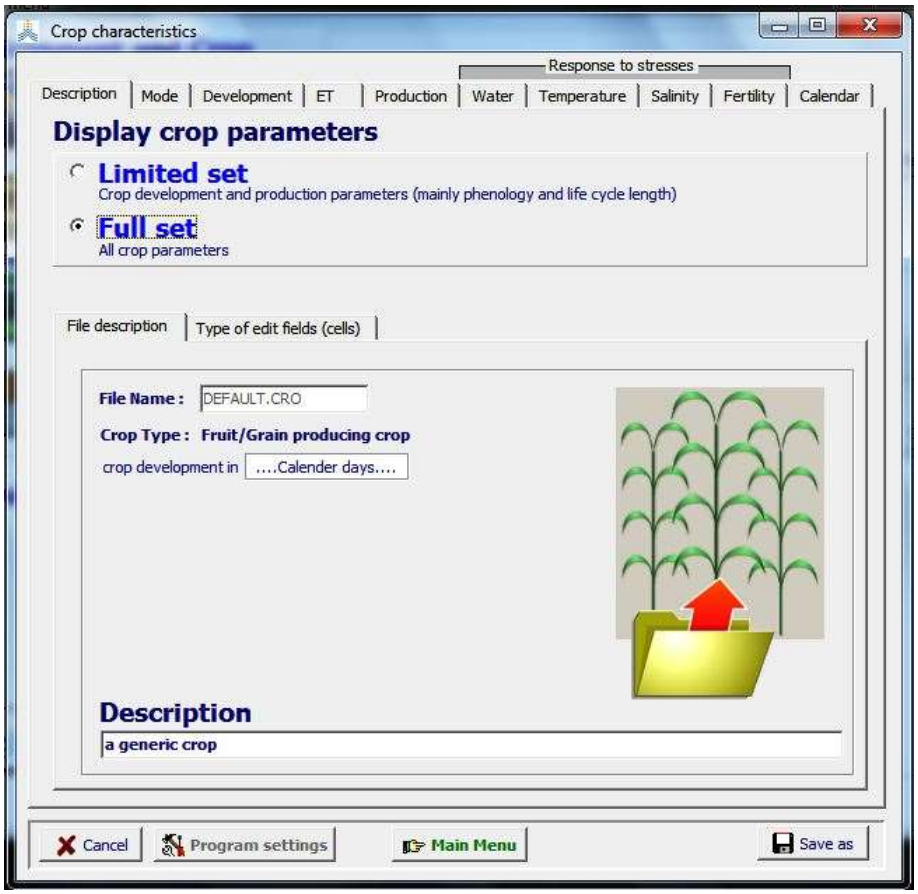


Figure 2.10c – The *Crop characteristics* menu with its 10 tabular sheets

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 - File description - Type of edit fields (cells) - Protected file (if applicable)	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 - Initial canopy cover	Crop development in the absence of water, soil fertility and/or soil salinity stress

- Canopy development - Flowering and yield formation or Root/Tuber formation; - Self-thinning (only for perennial herbaceous forage crops) - Root deepening	
ET - Coefficients - Water extraction pattern	Evapotranspiration in the absence of water, soil fertility and/or soil salinity stress
Production - Crop water productivity - Harvest Index - Water content - Yield potential - Transfer assimilates (only for perennial herbaceous forage crops)	Crop production in the absence of water, soil fertility and/or soil salinity stress

Water stress
- Canopy expansion
- Stomatal closure
- Early canopy senescence
- Aeration stress
- Harvest Index
  - Before flowering
  - During flowering
  - During yield formation
  - Overview
	Responses to water stress

Temperature stress - Crop development - Crop transpiration - Pollination	Responses to air temperature stress

Salinity stress
- Salt tolerance
- Crop response
  - Canopy Cover
  - Stomatal closure
	Responses to soil salinity stress

Fertility stress - Canopy - Water productivity - Transpiration - Biomass - Biomass – stress relationship	Responses to soil fertility stress

- Ks curves - Crop parameters	
Calendar With access to ***Internal crop calendar*** menu to specify restart and end of growth for perennial herbaceous forage crops	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).

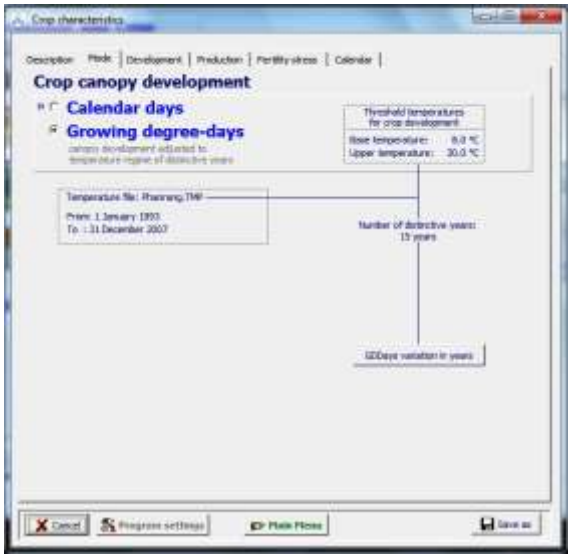
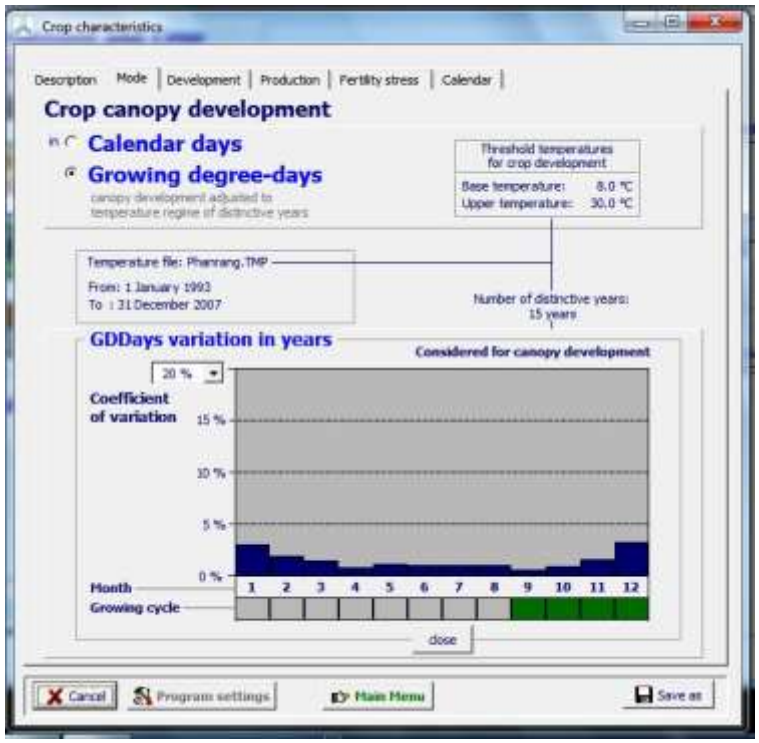


Figure 2.10e1 – The 'Mode' tabular sheet in the *Crop characteristics* menu



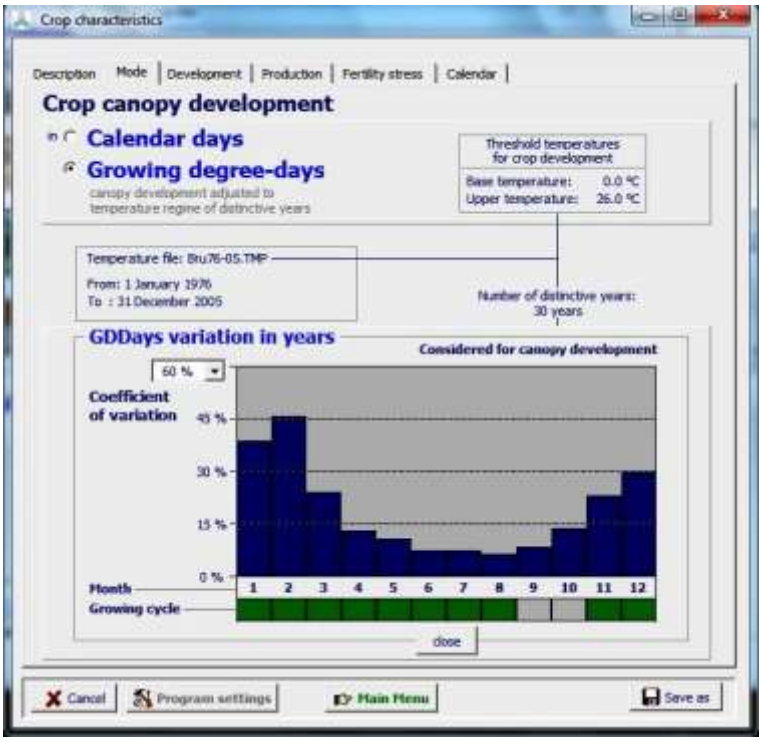


Figure 2.10e2– Display of the variations in growing degree-days in the distinctive months (top) of the 15 years of the Phanrang (Vietnam) temperature file, and (bottom) of the 30 years of the Brussels (Belgium) temperature file in the tabular sheet 'Mode'. The base an upper temperatures are those for 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);
- Self-thinning (only for perennial herbaceous forage crops)
- Root deepening.

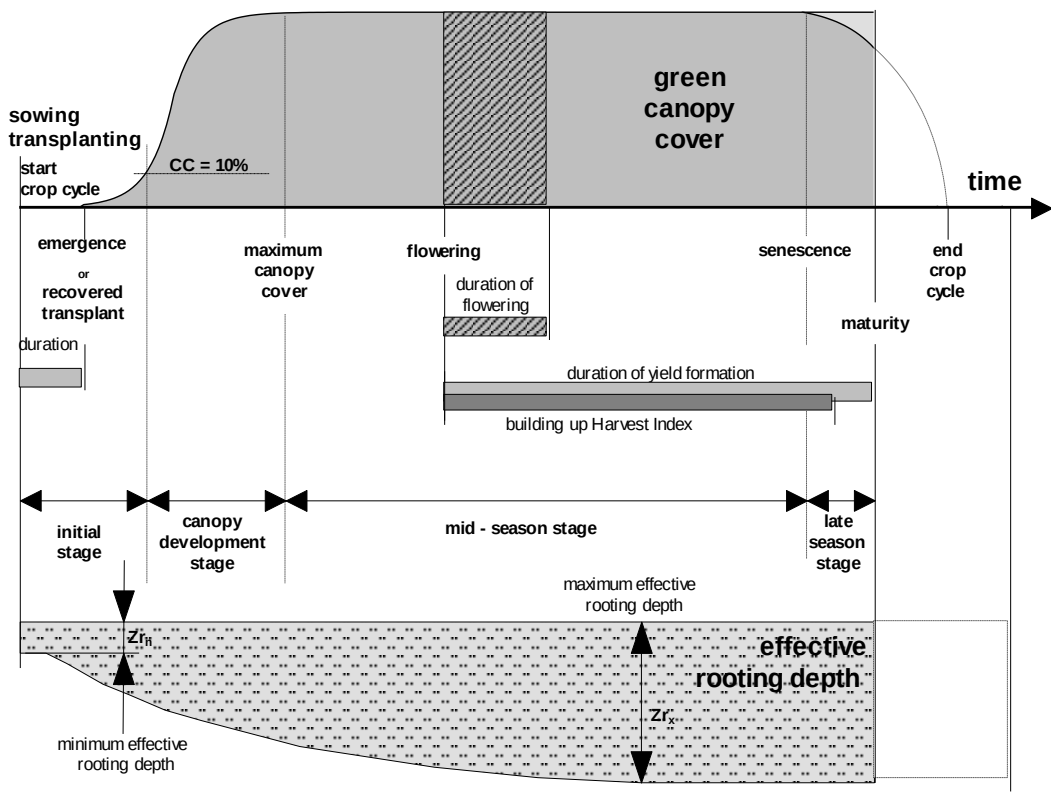


Figure 2.10f1 – Schematic representation of crop development for fruit/grain producing crops

- **Initial canopy cover for planting/sowing year**

The initial canopy cover (CC_o) 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_o).

Type of planting method for planting/sowing year

- Direct sowing: CCo 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_o);
- Transplanting: CCo refers to the initial canopy cover after transplanting and is obtained by multiplying plant density by the canopy size of the transplanted seedling (cc_o).

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).

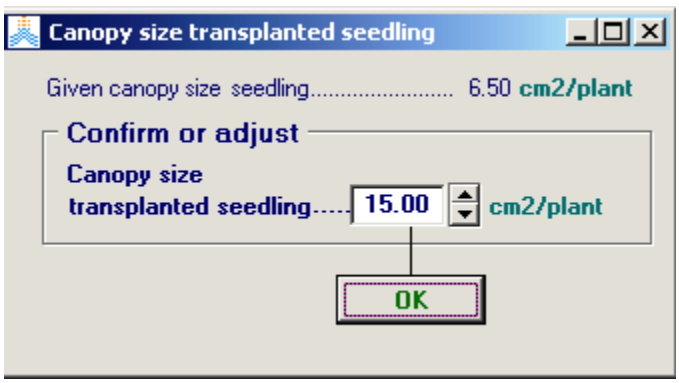


Figure 2.10f2 – Confirming the canopy size of the transplanted seedling when altering the planting method from direct sowing to transplanting in the *Canopy size transplanted seedling* menu

Specifying the initial canopy cover (CC_o)

CC_o 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.

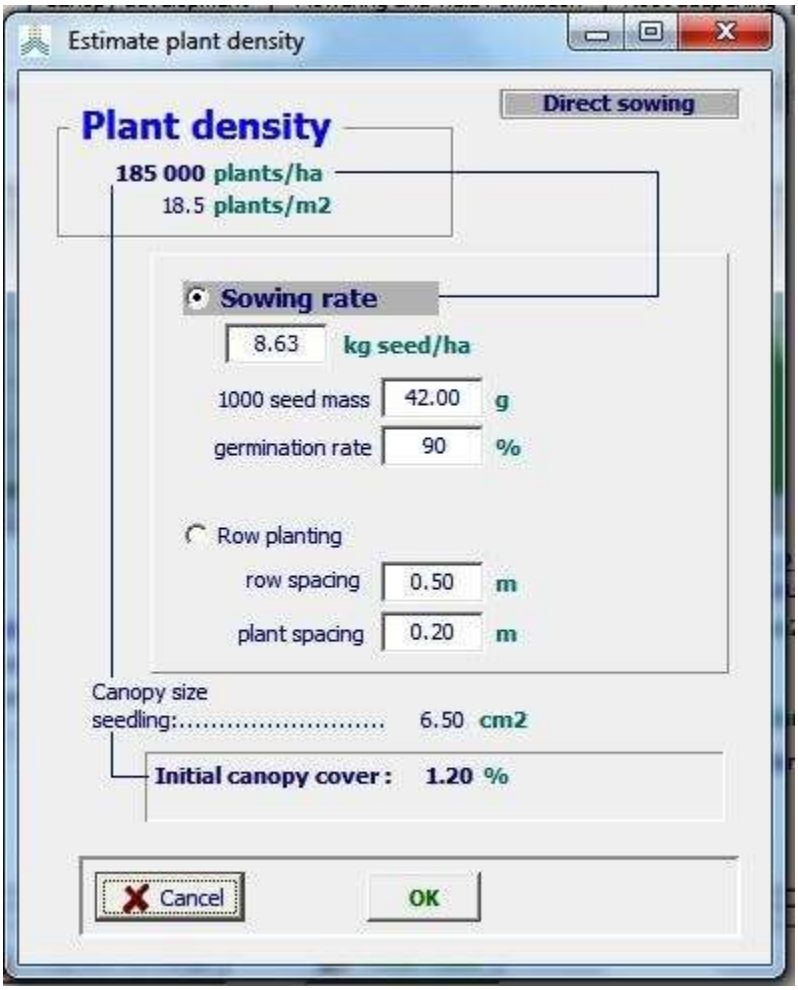


Figure 2.10f3 – Estimation of plant density from sowing rate or plant density in the *Estimate plant density* menu

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 %

- **Initial canopy cover for non-planting/sowing year (only for perennial crops)**

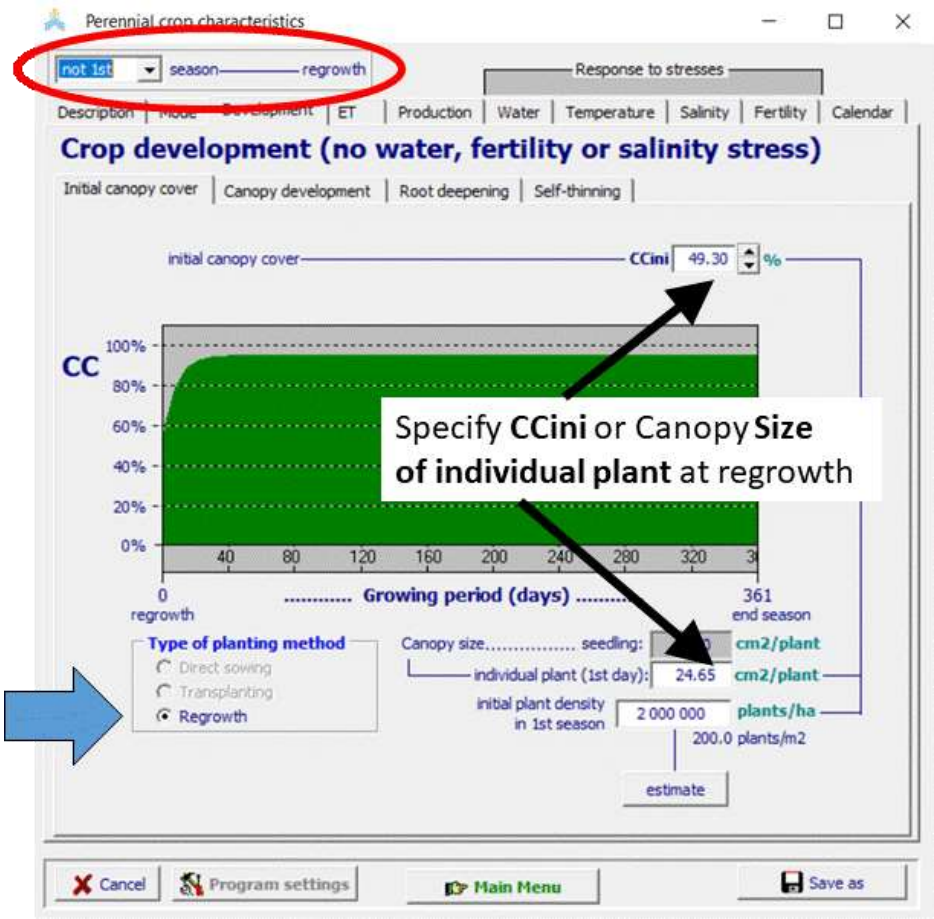


Figure 2.10f3/b – The initial canopy cover at regrowth is given by specifying (i) CCini directly or (ii) the canopy size of an individual plant at the start of regrowth in a non-planting/sowing year in the *Perennial Crop characteristics* menu.

In figure 2.10f3/b the crop development for non-limiting conditions is plotted for perennial herbaceous forage crops. By switching between '1st season' and 'not 1st season', AquaCrop displays the corresponding development of the canopy cover and root deepening (Fig 2.10f3/c).

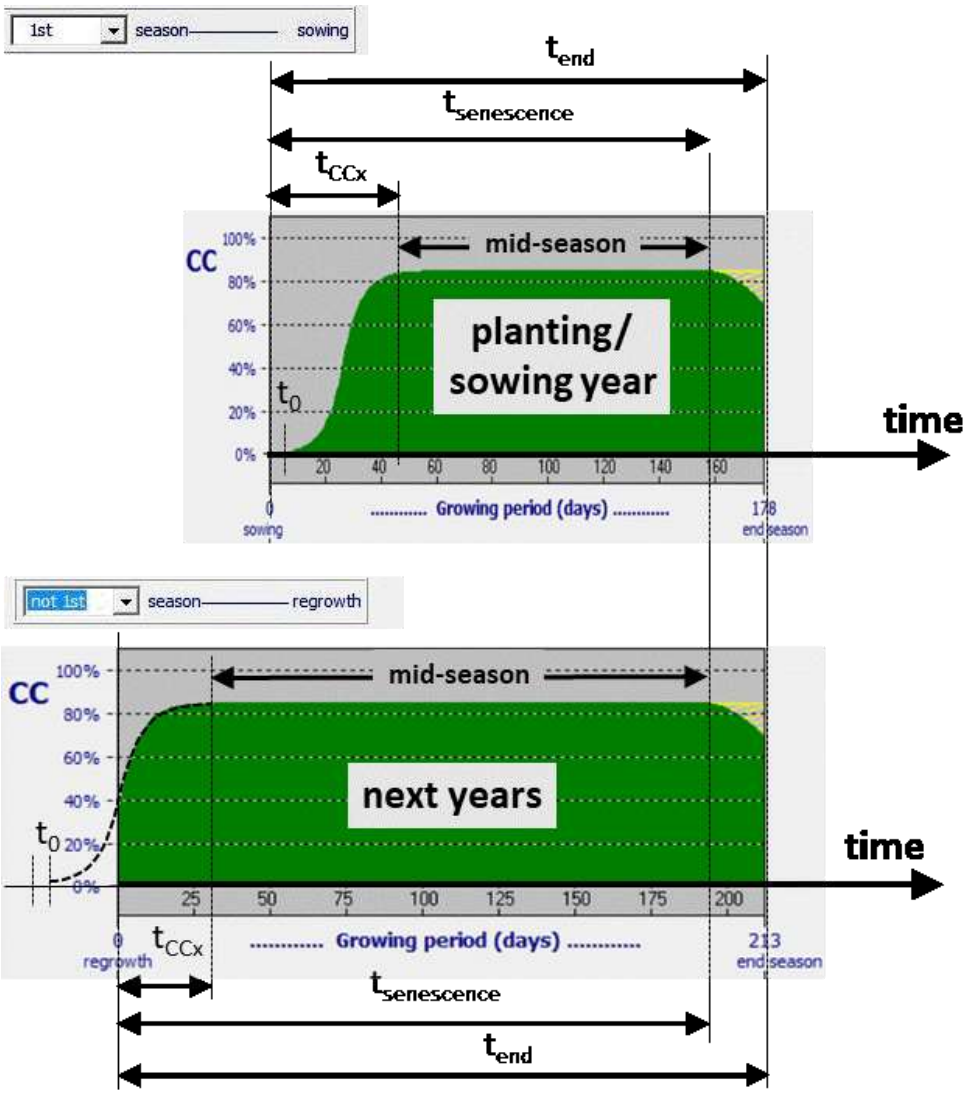


Figure 2.10f3/c – Canopy development for perennial herbaceous forage crops in a 1st and not a 1st season.

The Canopy development starts at sowing or replanting in the 1st season. In not a 1st season, the canopy starts as regrowth. Procedures have been worked out to guarantee that the length of the growing cycle in any type of season remains between the (fixed or generated) start and end dates of the season. It consisted in stretching the length of the mid-season in not a first year, so that the time to reach senescence and crop maturity remains identical for a '1st' and a 'not 1st season' (Fig. 2.10f3/c). The mid-season starts when the maximum canopy cover (CCx) is reached till the start of the natural canopy senescence at the end of the season.

- **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).

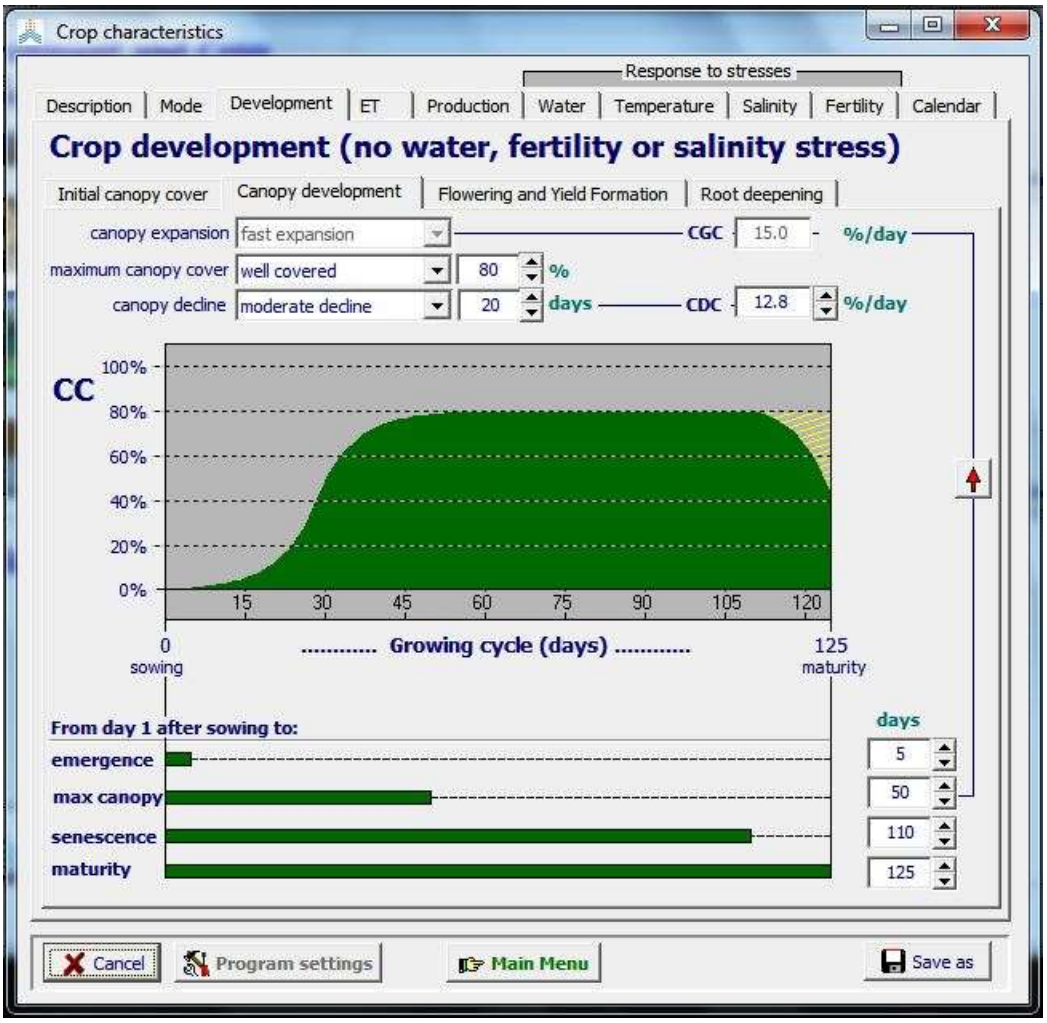


Figure 2.10f4 – Specification of canopy development in the *Crop characteristics* menu

***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.

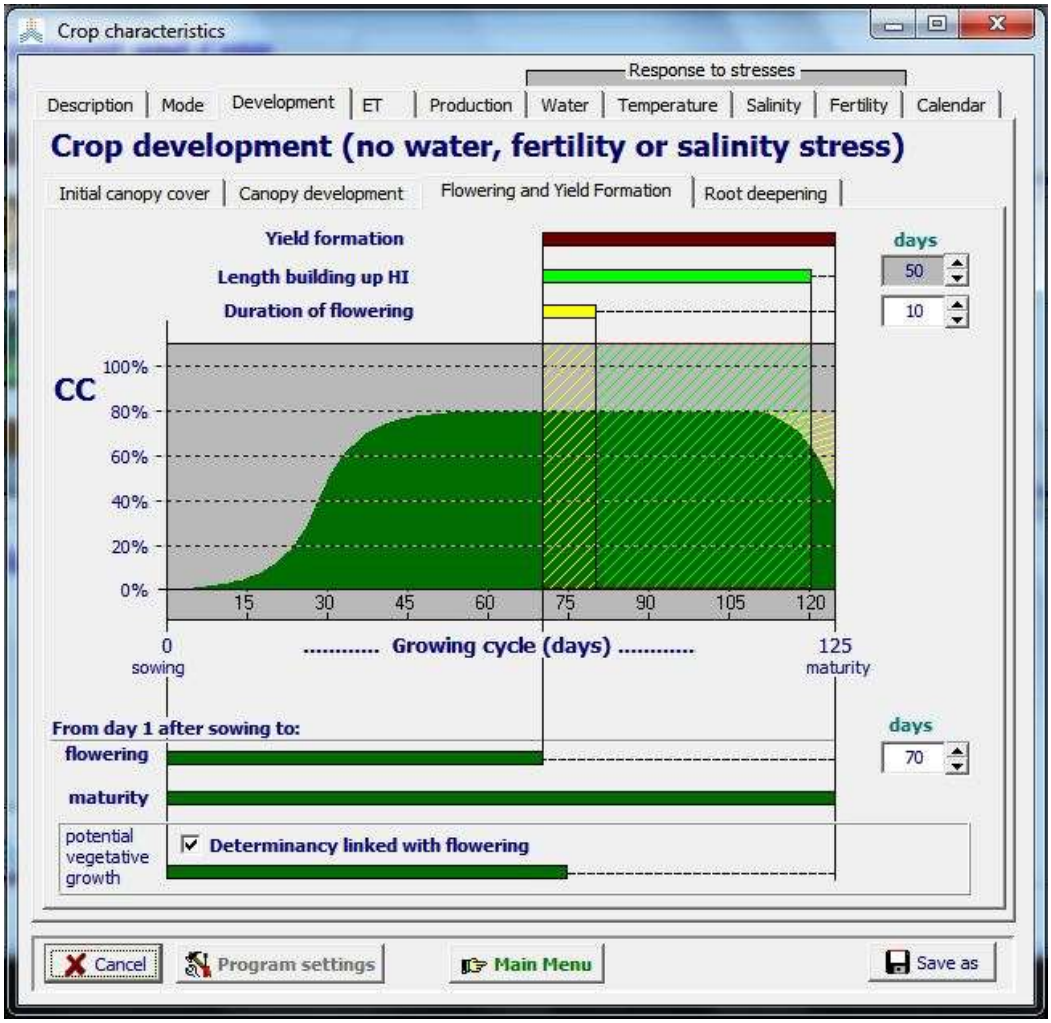


Figure 2.10f5 – Specification of flowering and time required to build up the Harvest Index for fruit/grain producing crops in the *Crop characteristic* menu for a crop where determinancy is linked with flowering

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.

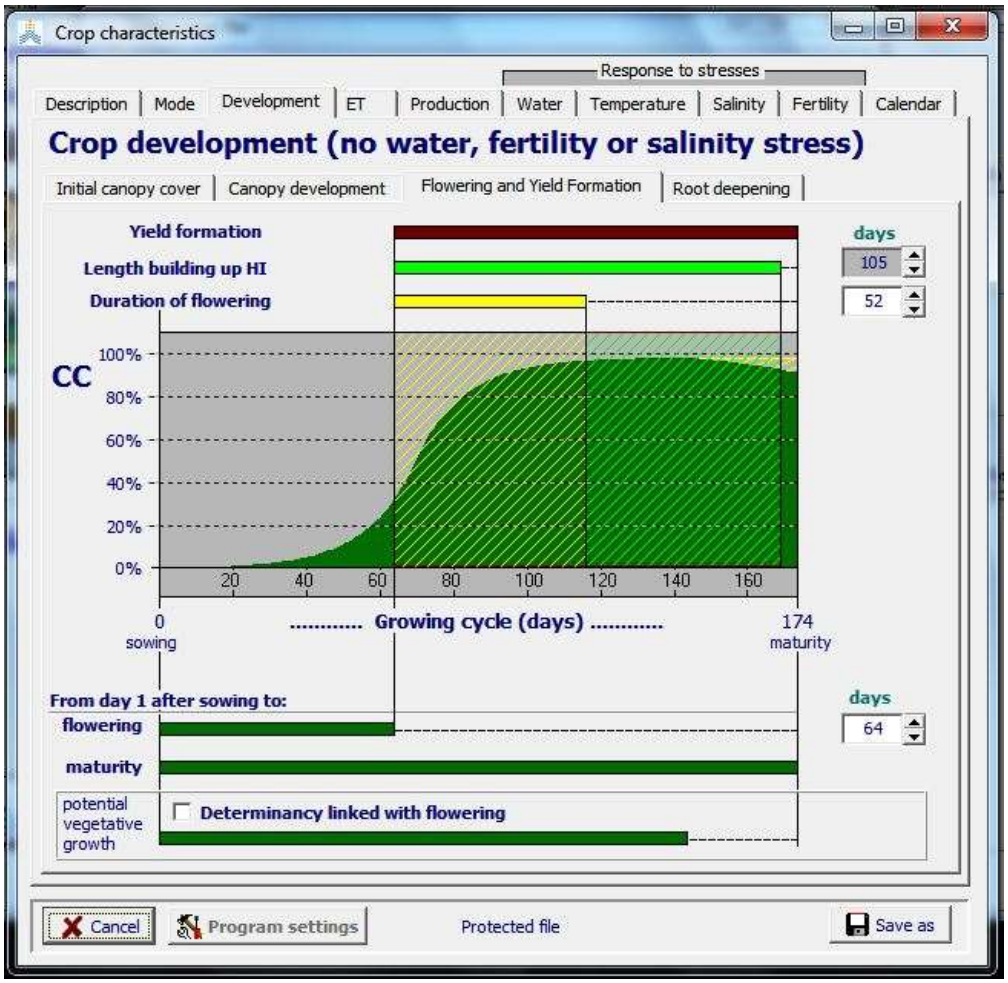


Figure 2.10f6 – Specification of flowering and time required to build up the Harvest Index for fruit/grain producing crops in the *Crop characteristic* menu for a crop where determinancy is not linked with flowering, such as cotton

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.

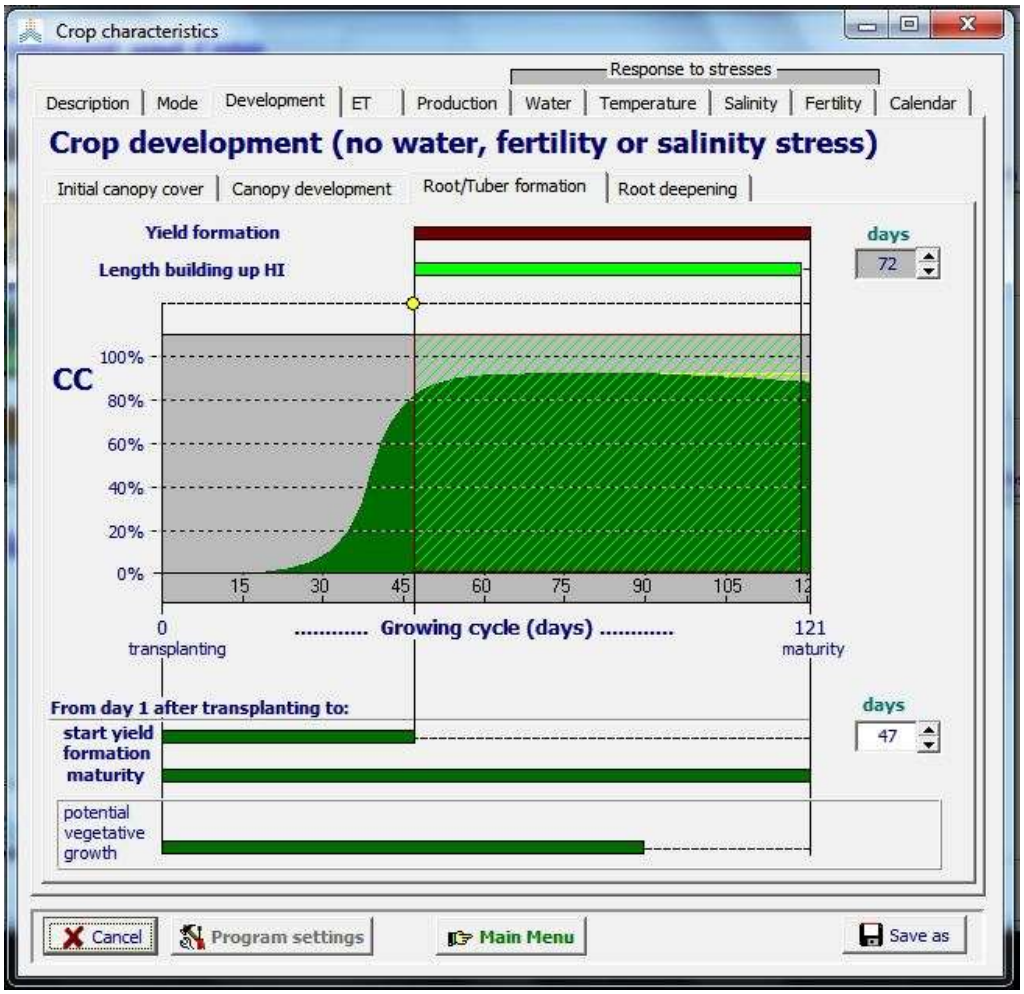


Figure 2.10f7 – Specification of the start of yield formation and the time required to build up the Harvest Index for root/tuber crops in the *Crop characteristic* menu

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.

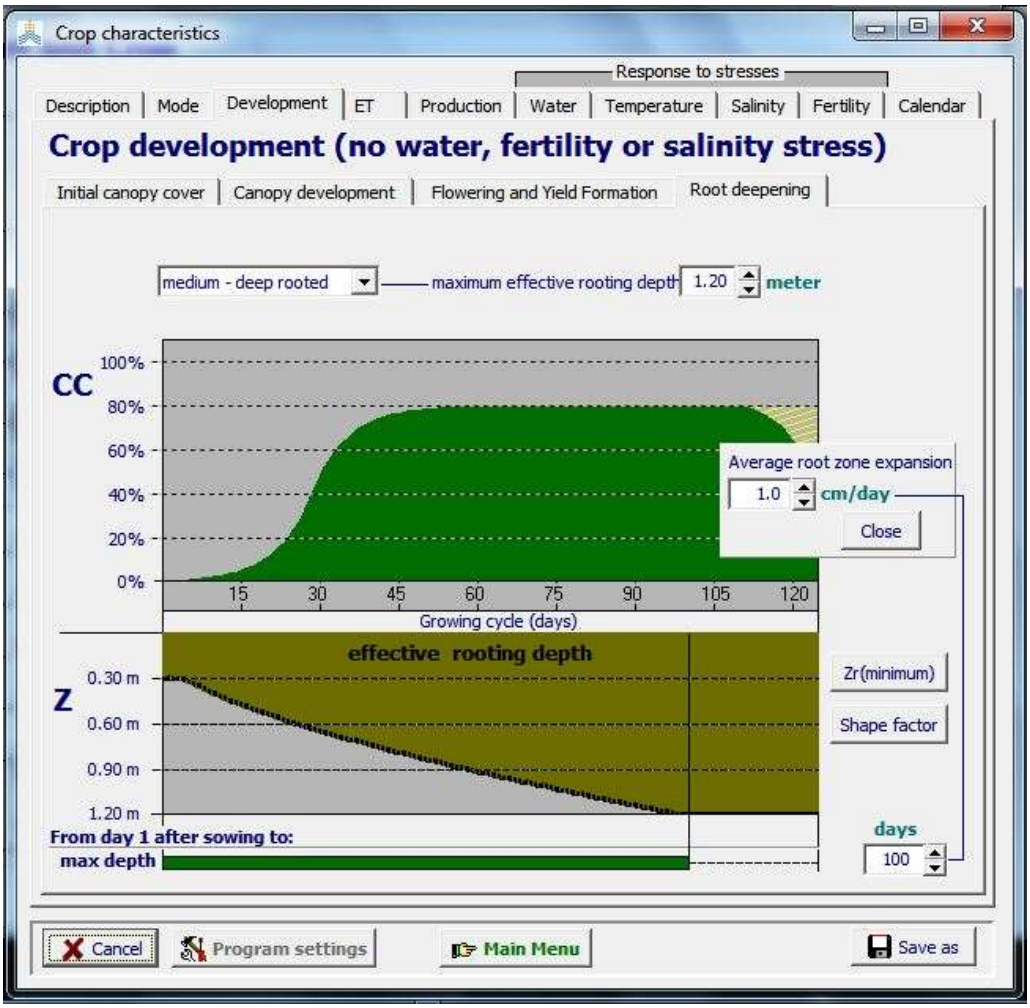


Figure 2.10f8 – Specification of root deepening in the *Crop characteristic* menu

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).

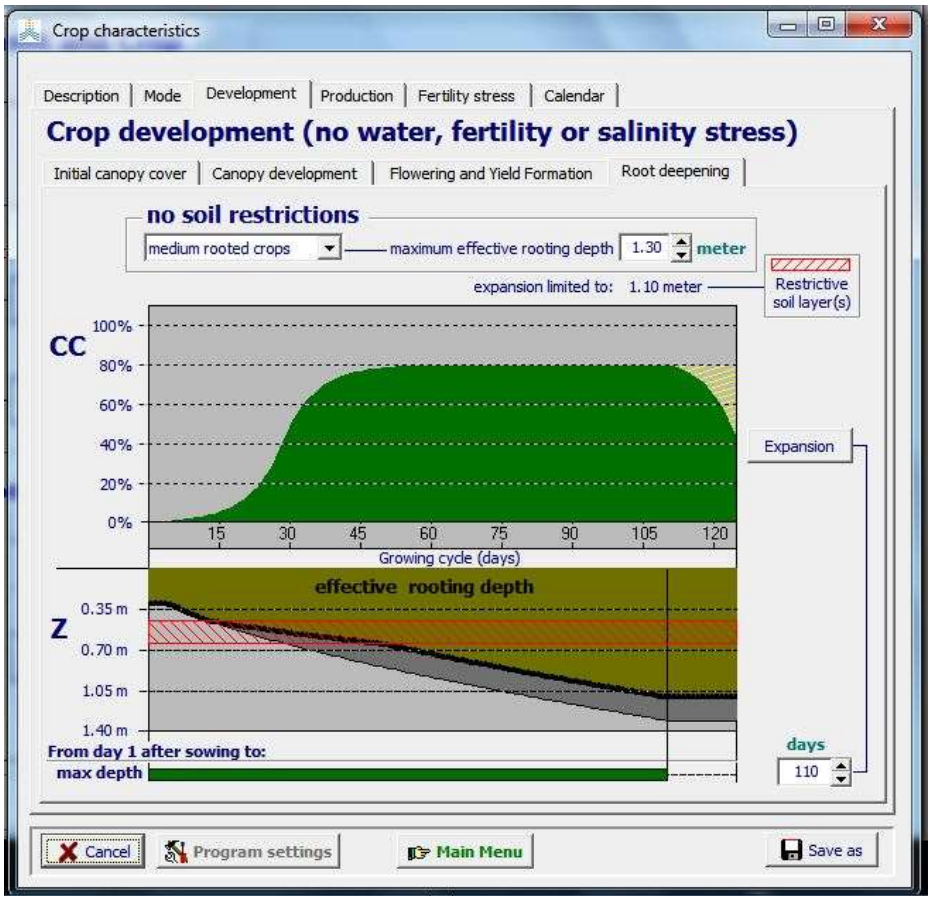


Figure 2.10f9 – Effect of a restrictive soil layer on root development

The ***root deepening for perennial herbaceous forage crops in a non-planting/sowing year*** differs from the root deeping in the 1st season. By switching between '1st season' and 'not 1st season', AquaCrop displays the corresponding development of the root deepening (Fig. 2.10f9/b). In the root deepening tab-sheet, the root development (depth and rate of deepening) is specified for the 1st year (planting/sowing year). For the other years the rooting depth is assumed to be constant and equal to the maximum rooting depth.

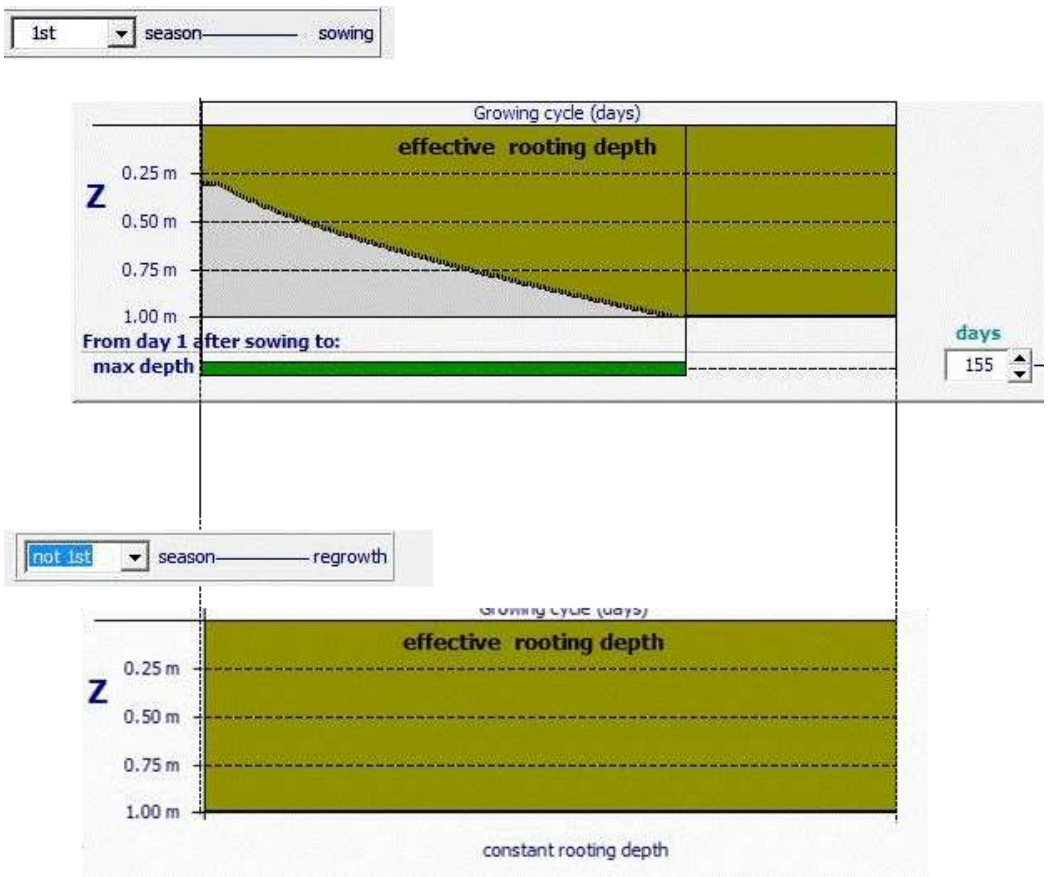


Figure 2.10f9/b – Root deepening for perennial herbaceous forage crops in a 1st and not a 1st season.

- **Self-thinning (only for perennial herbaceous forage crops)**

The initial plant population of perennials progressively self-thins over the years. In AquaCrop this natural self-thinning (induced by climatic factors such as killing frost) is specified in the crop file.

There are two alternative ways to calibrate the natural self-thinning in the ***Perennial cop characteristics menu:*** by specifying (i) the drop in biomass production (Fig. 2.10f9/c) or (ii) the drop in maximum canopy cover (Fig. 2.10f9/d) over the successive years.

- Specify the number of years (between 3 and 127) at which the maximum biomass production (for optimal crop development) drops below a specific percentage (between 50 and 95%), and specify if the annual decline in biomass production is gradual, medium or sharp (Fig. 2.10f9/c). AquaCrop plots the corresponding relative biomass production over the successive years;

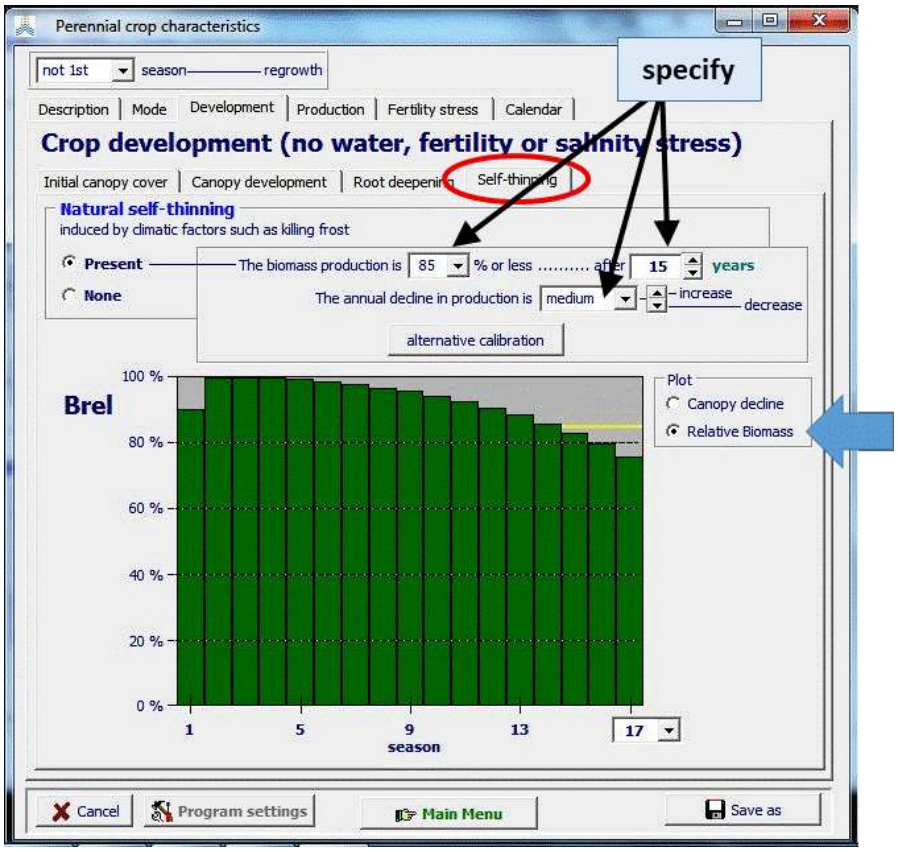


Figure 2.10f9/c – Calibrating the self-thinning of perennial herbaceous forage crops, by specifying the drop in biomass production over the successive seasons.

- Specify the number of years (between 2 and 127) at which the maximum canopy cover (CC_x) declines to 90% of its initial value of the 1st year, and specify if the annual decline of the maximum canopy cover (CCx) is gradual, medium or sharp (Fig. 2.10f9/d). AquaCrop plot the corresponding decline of the initial (CCini) and maximum (CCx) canopy cover over the successive years.

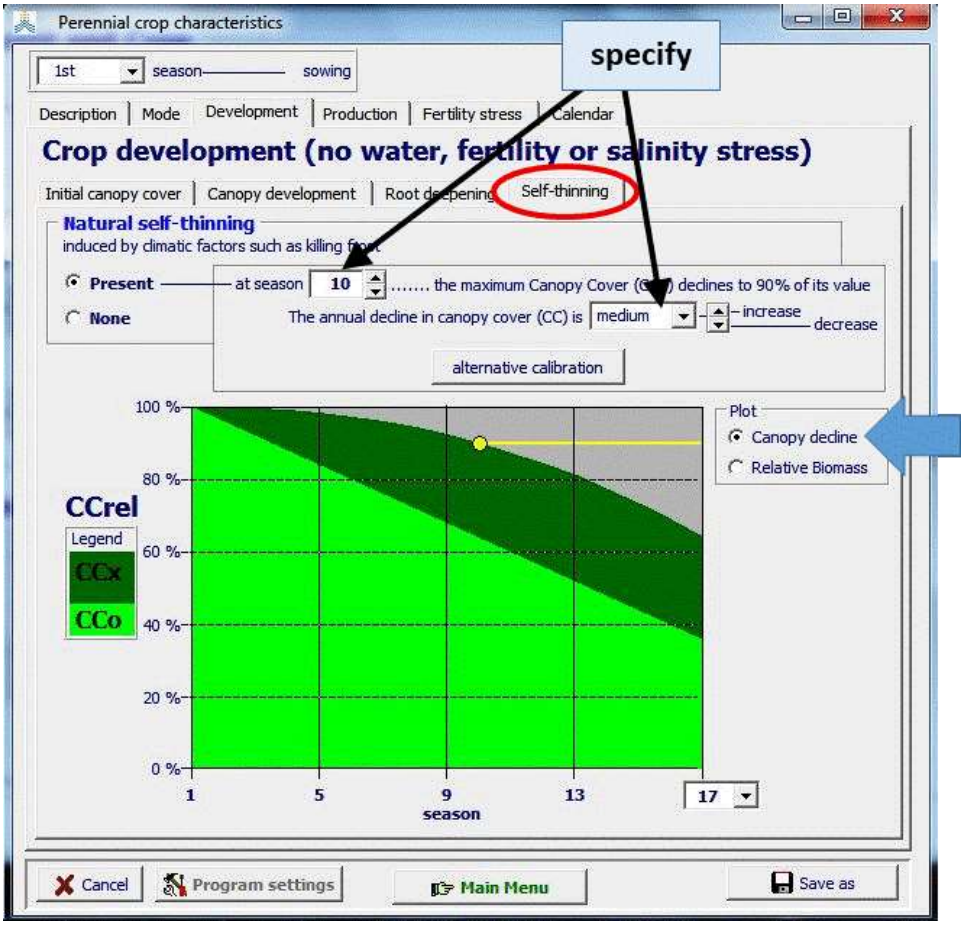


Figure 2.10f9/d – Calibrating the self-thinning of perennial herbaceous forage crops, by specifying the drop in maximum canopy cover (CCx) over the successive seasons.

The corresponding canopy development over the successive years as simulated by AquaCrop is plotted in Figure Fig. 2.10f9/e. To maintain high yielding stands, re-establishment of the stand might be required after 6 to 7 years.

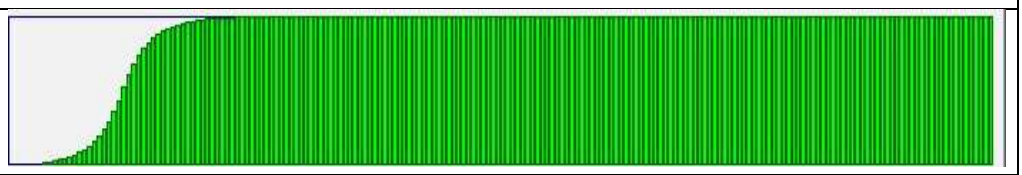
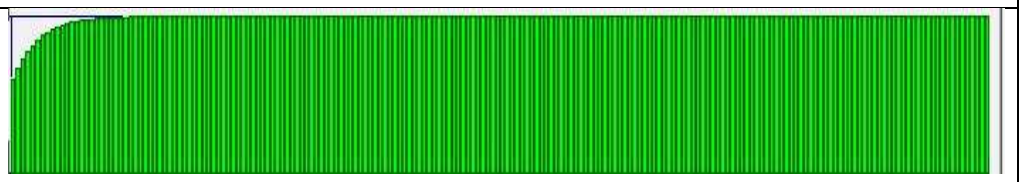
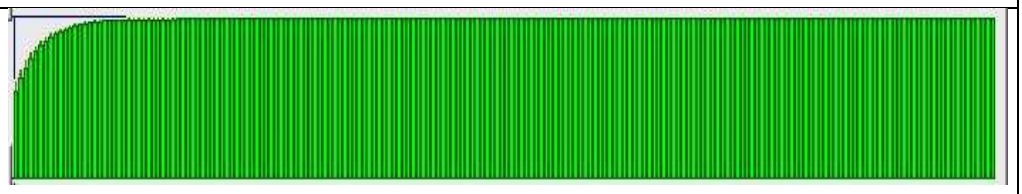
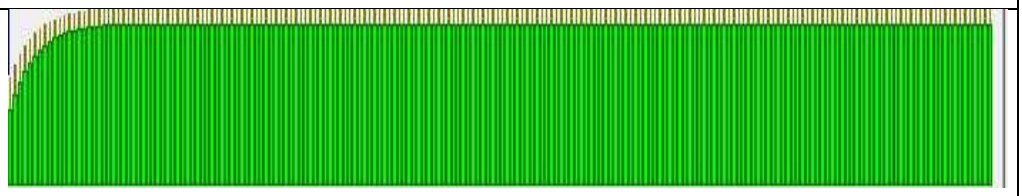
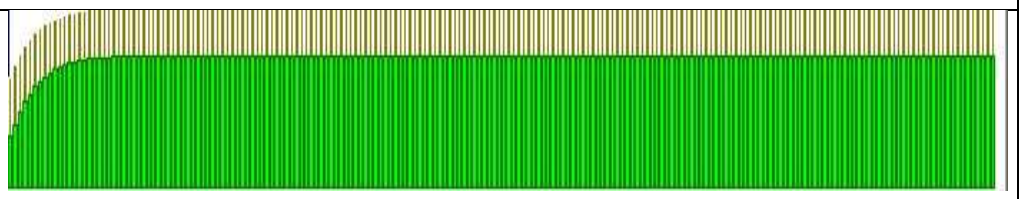
Season	Canopy cover
1	
2	
5	
10	
15	

Figure 2.10f9/e – Example of the reduction of canopy cover (CC) of perennial herbaceous forage crops in susccesive seasons, due to the natural self-thinning of the plant population as simulated by AquaCrop.

2.10.7 Tabular sheet: Evapotranspiration

- **Coefficients**

<u>Crop coefficient for maximum transpiration ($Kc_{Tr,x}$)</u>

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). The same apply for perennial forage crop. However, since the canopy is harvested at each cut, the ageing is reset at each harvest.

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

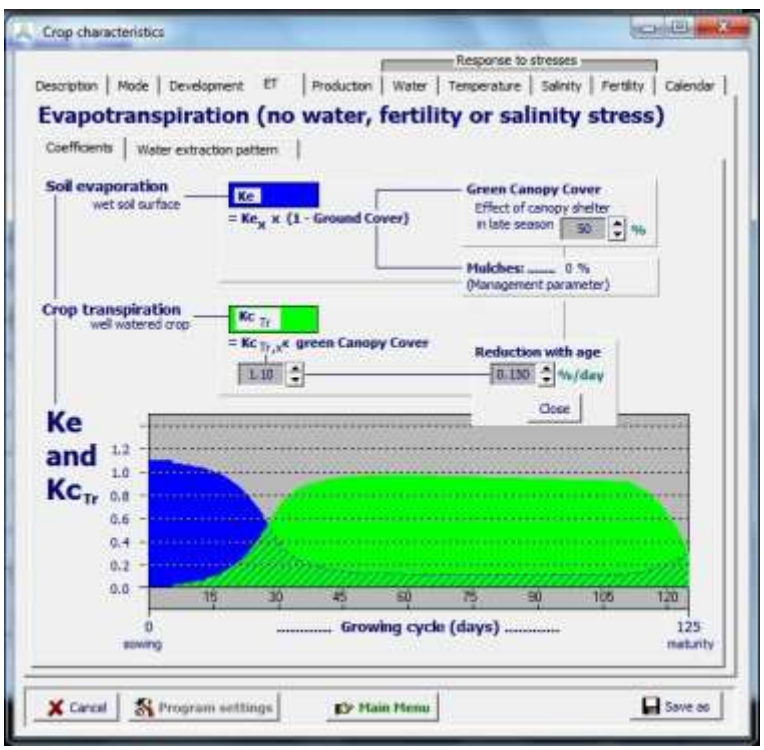


Figure 2.10g1 – Response of the soil evaporation (Ke) and the crop transpiration (Kc_{Tr}) coefficients to canopy development and decline during the growing cycle for non-limiting conditions

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).

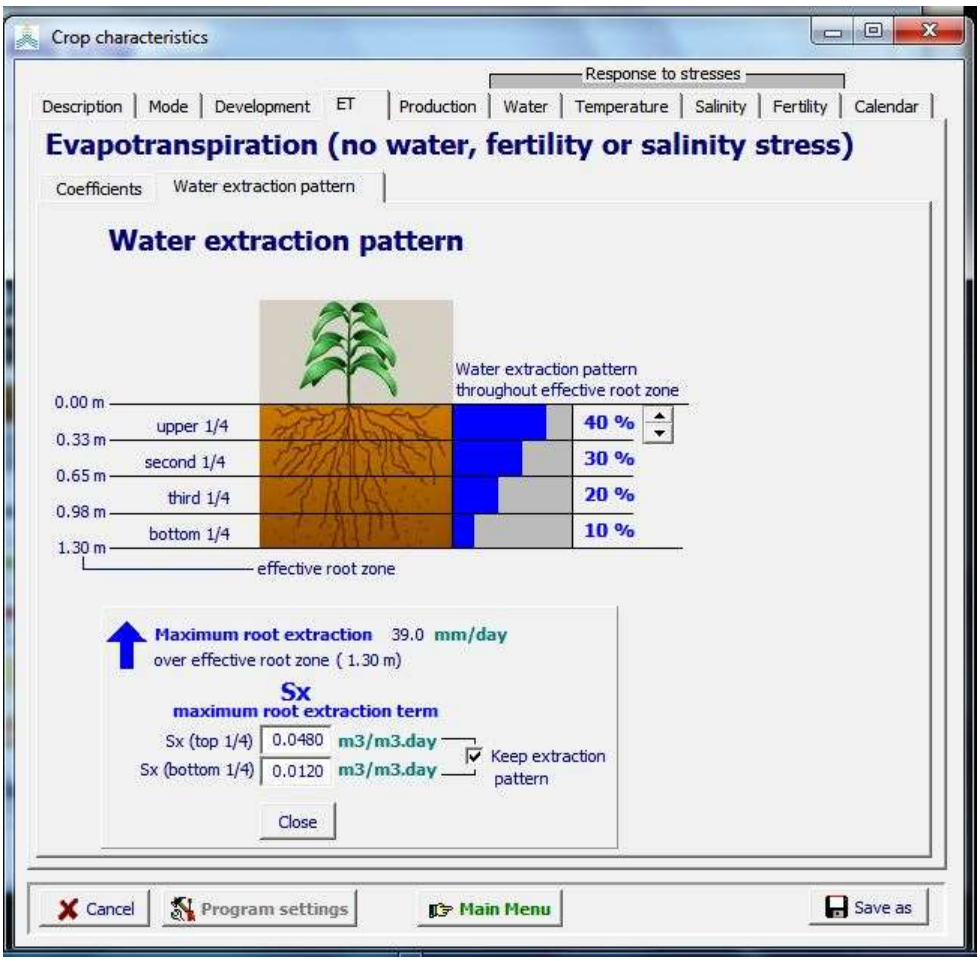


Figure 2.10g2 – Derived maximum extraction terms (S_x) at the top and bottom of the root zone after the specification of the water extraction pattern and the maximum root extraction

- **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 Sx are given in Table 2.10g.

Table 2.10g – The range and default values for the maximum root extraction at the top (Sx(top ¼)) and bottom (Sx(bottom ¼)) quarter of the root zone for various maximum rooting depths (Zx)

Variable	Range Sx	Default Sx	*Condition for Zx*
	m^3(water) per m^3(soil) per day		meter
Sx(top ¼)	0.001 – 0.060	0.048	$Zx \leq 2$
		$0.030 + 0.018\frac{4 - Zx}{2}$	$2 < Zx \leq 4$
Sx(bottom ¼)	0.001 – 0.060	$Sx_{(top\,1/4)}\frac{P_4}{P_1}$	-

By specifying the water extraction pattern throughout the root zone, and values for the Sx at the top and bottom quarter of the root zone, AquaCrop derives the Sx 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 Sx at the bottom of the root zone and alters the root distribution (water extraction pattern) in the top soil (Fig. 2.10g3).

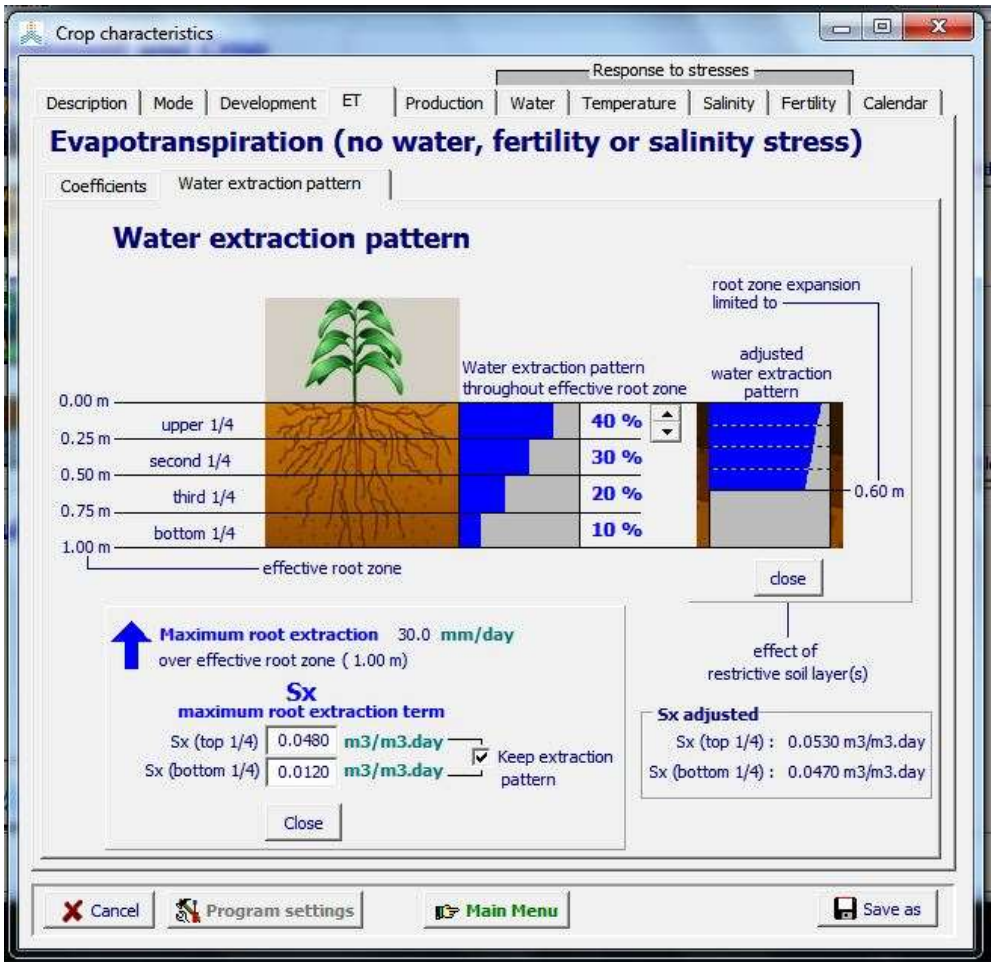


Figure 2.10g3 – Maximum water extraction pattern (root distribution) when maximum rooting depth of 1 meter is reached, and the adjusted pattern in the soil profile when a layer at 0.6 m blocks completely the further development of the root zone as displayed in the 'ET' tabular sheet of the *Crop characteristics* 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 CO_2 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).

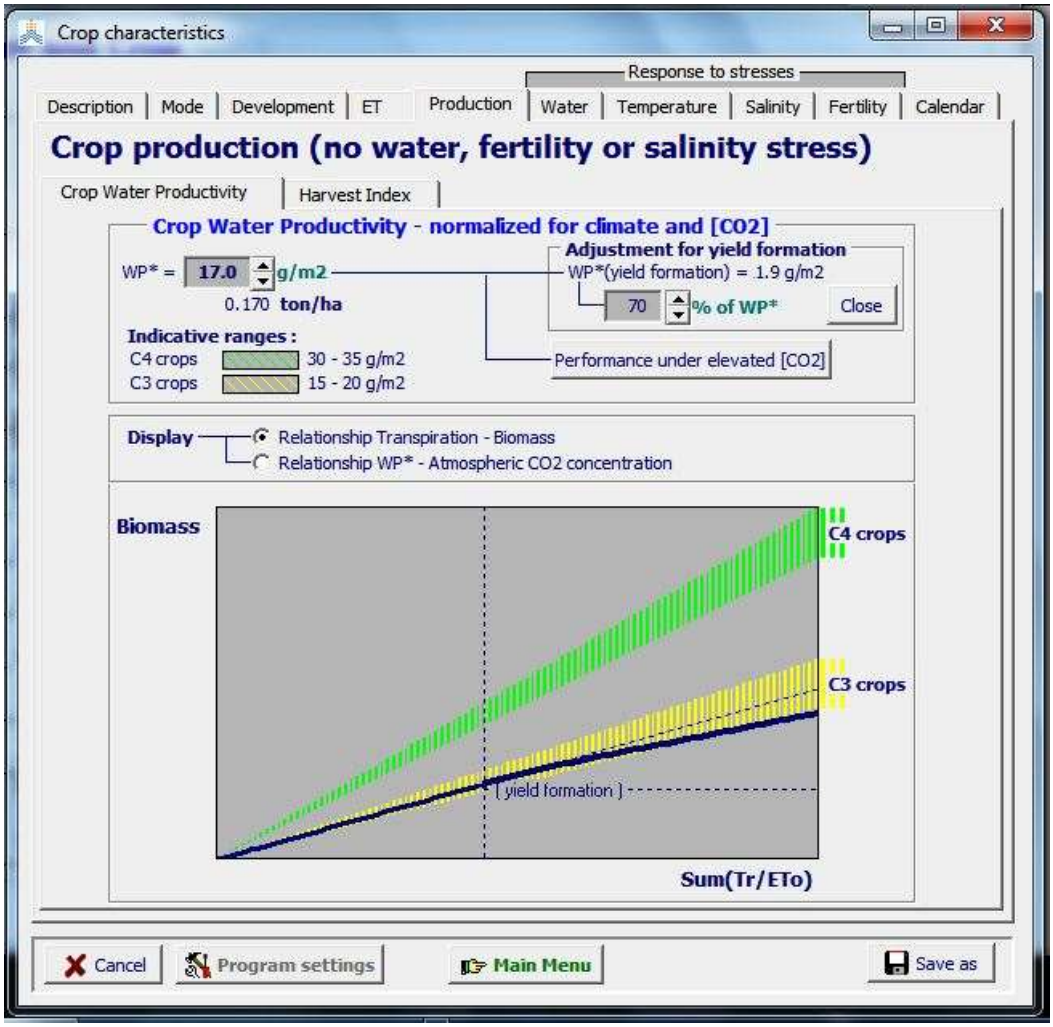


Figure 2.10h1 – The water productivity normalized for climate and atmospheric CO_2 and its adjustment if the harvestable organs are rich in oil and/or proteins

- **Performance under elevated atmospheric CO2 concentration**

WP* is adjusted when running a simulation with an atmospheric CO_2 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').

In Figure 2.10h2/a, the correction factor for WP* is plotted for CO_2 concentrations up to 550 ppm (which is the CO_2 concentration maintained in most FACE experiments).

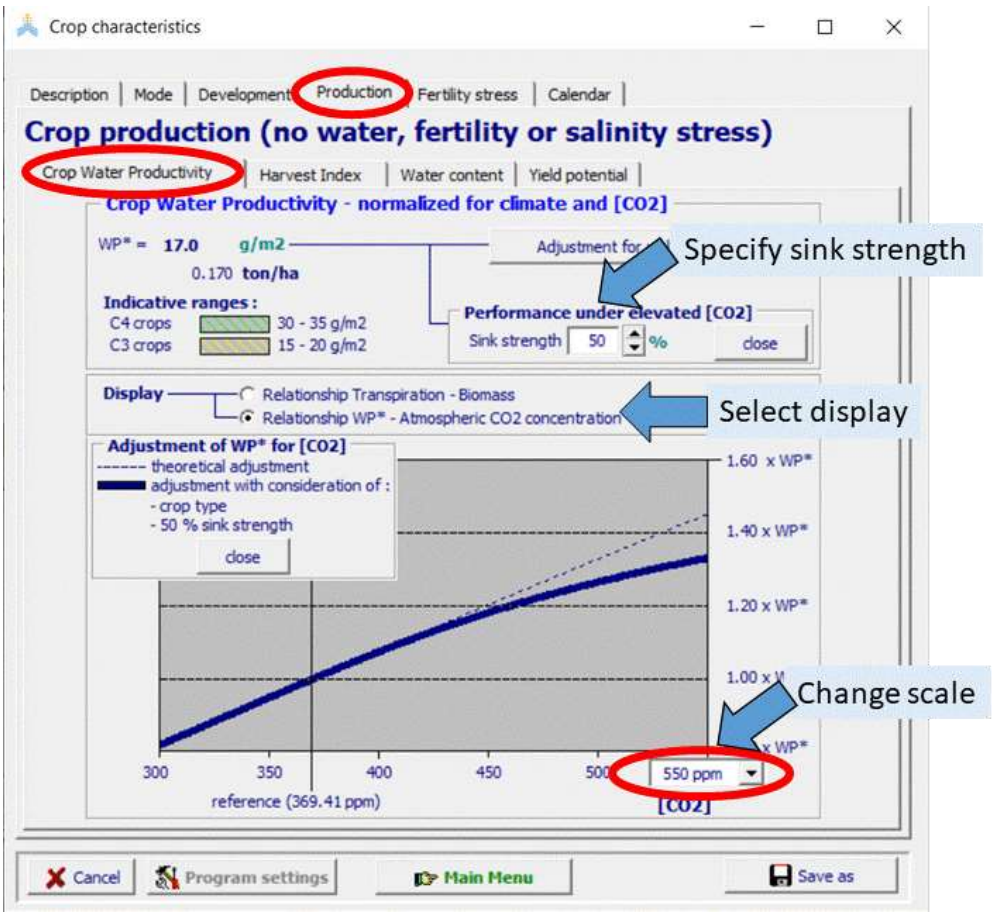


Figure 2.10h2/a – The water productivity adjusted to atmospheric CO_2 concentration from 300 up to 550 ppm by considering crop type and crop sink strength

In Figure 2.10h2/b, the correction factor for WP* is plotted for CO_2 concentrations up to 800 ppm. The correction coefficients for CO_2 concentrations above 550 ppm should be used with care since they describe only the general trend.

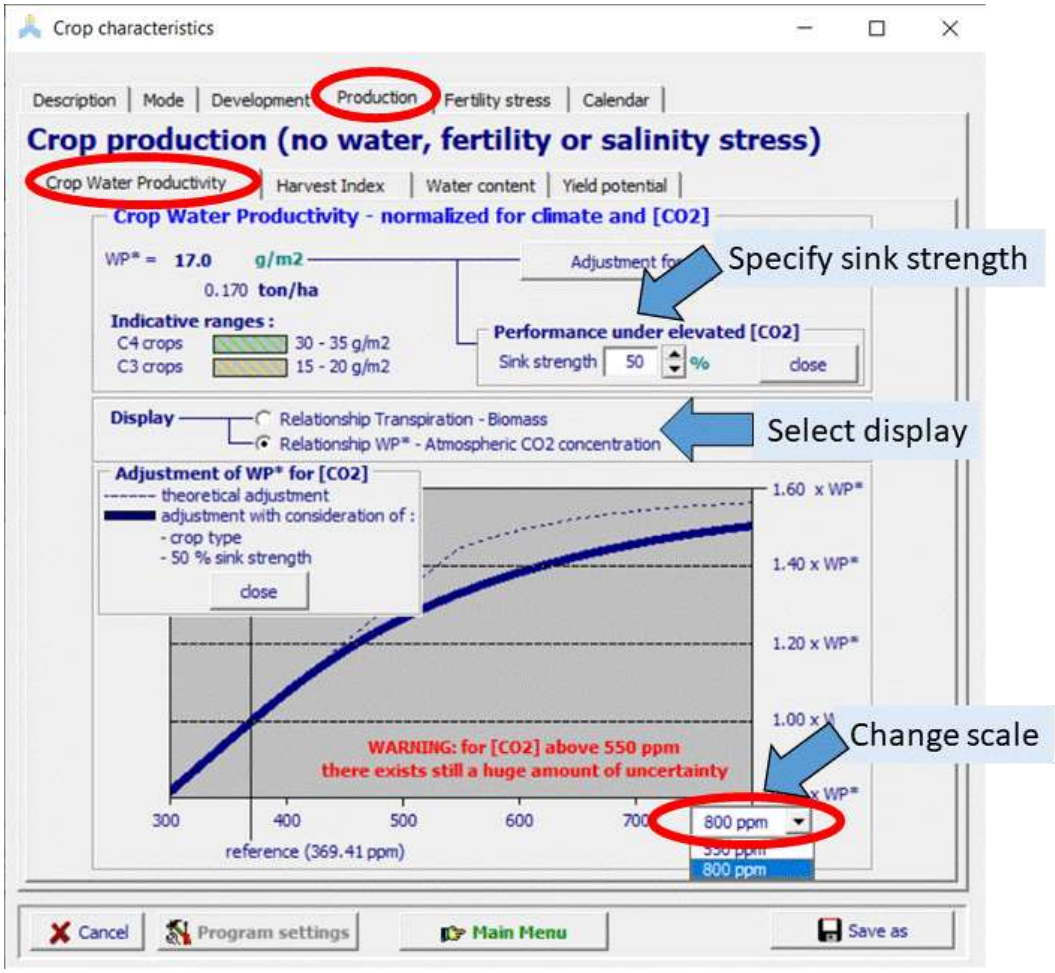


Figure 2.10h2/b – The water productivity adjusted to atmospheric CO_2 concentration from 300 up to 800 ppm by considering crop type and crop sink strength. The correction coefficients for CO_2 concentrations above 550 ppm should be used with care since they describe only the general trend.

The theoretical adjustment might not be entirely valid when (i) soil fertility is not properly adjusted to the higher productivity under elevated CO_2 concentration, and/or (ii) the sink capacity of the current crop variety is yet not able to take care of the elevated CO_2 concentration. The performance of the crop under elevated atmospheric CO_2 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/a and /b). Ranges for indicative values for sink strengths are given in Table 2.10h.

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 (Z. mays L.), Rice (Oryza sativa L.), Wheat (Triticum aestivum L.) Sunflower (Helianthus annuus L.)	Low (0.00–0.20)
Legumes: Soybean (Glycine max (L.) Merr.)	Moderate low (0.20–0.40)
Indeterminate growth habit: Tomato (Solanum lycopersicum L.), Quinoa (Chenopodium quinoa Willd.)	Moderate low (0.20–0.40)
Woody species: Cotton (Gossypium hirsutum L.)	Moderate high (0.40–0.60)
Root and tuber crops: Potato (S. tuberosum L.), Sugar beet (Beta vulgaris L.)	High (0.60–0.80)
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. 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).	
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.	

- **Reference Harvest Index (HIo)**

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.

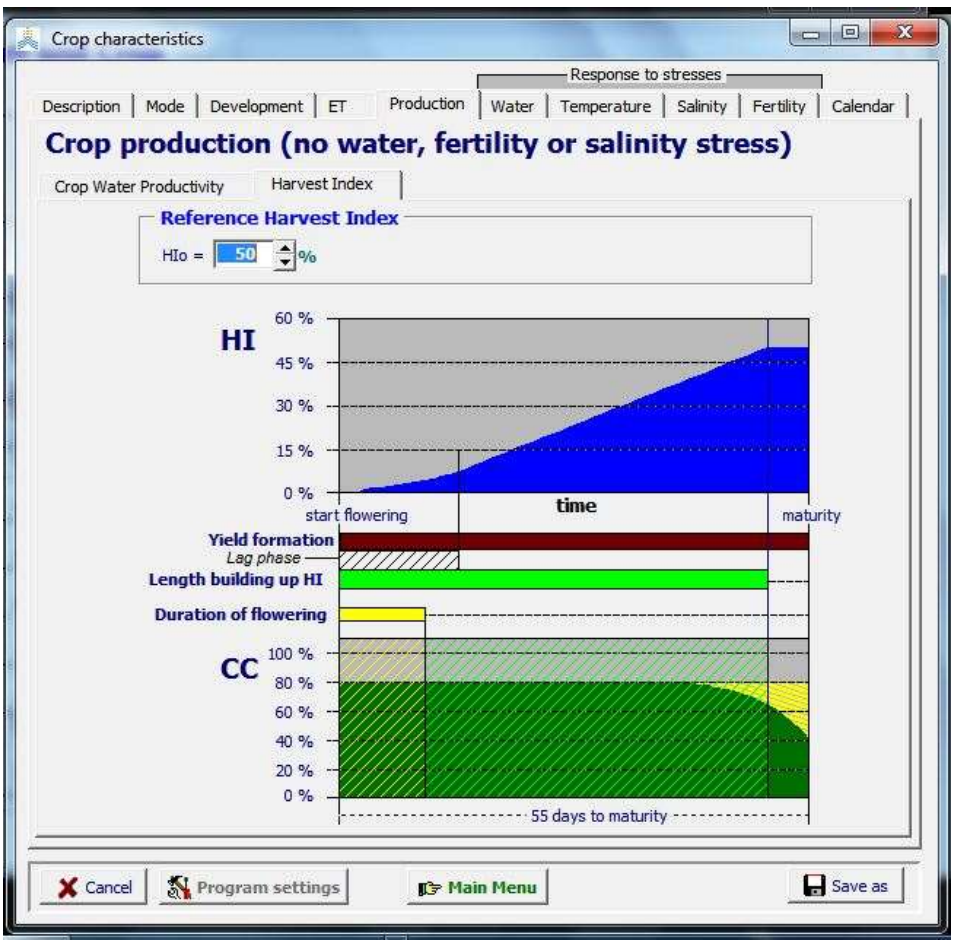


Figure 2.10h3 – Specification of the reference harvest index (HI_o) and the display of the building up of the Harvest Index from flowering to physiological maturity for a fruit or grain producing crop

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.

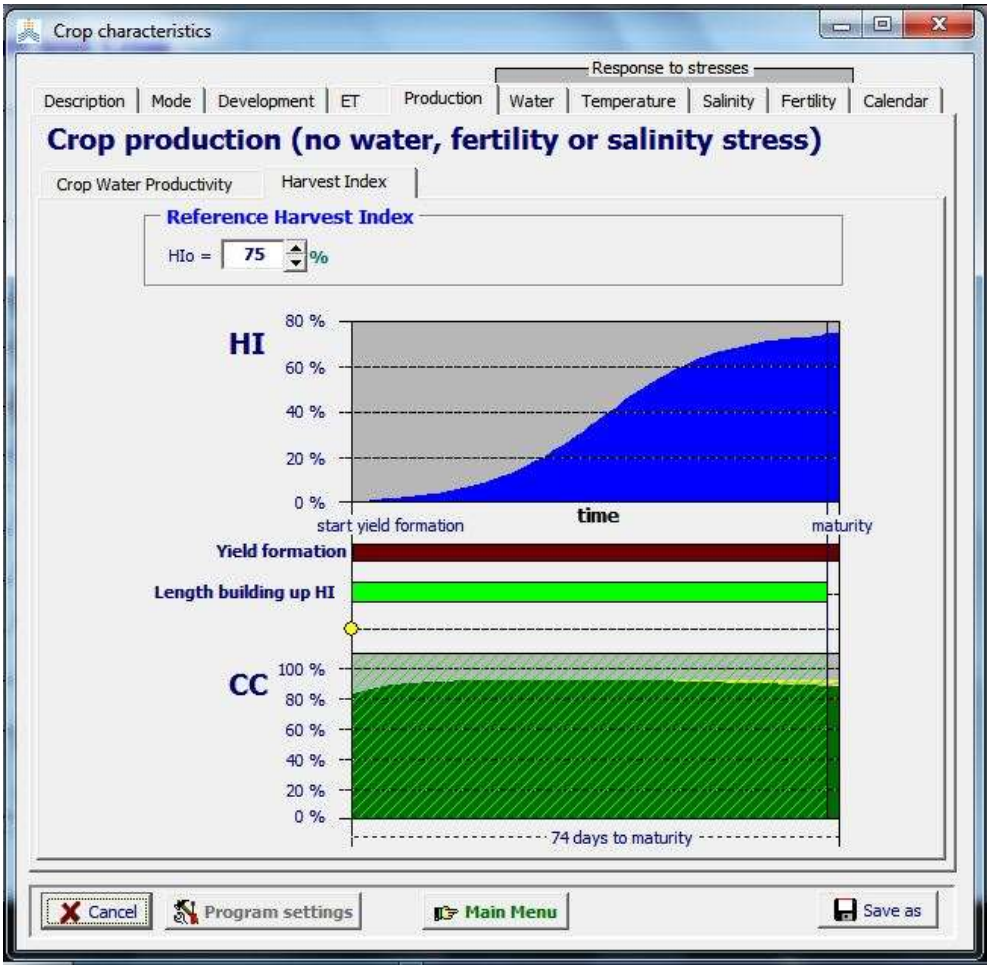


Figure 2.10h4 – Specification of the reference harvest index (HI_o) and the display of the building up of the Harvest Index from the tuber formation or root enlargement to physiological maturity for roots and tubers

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 HI_o is expressed as the number of days after germination. AquaCrop displays the corresponding percentage of the growing cycle.

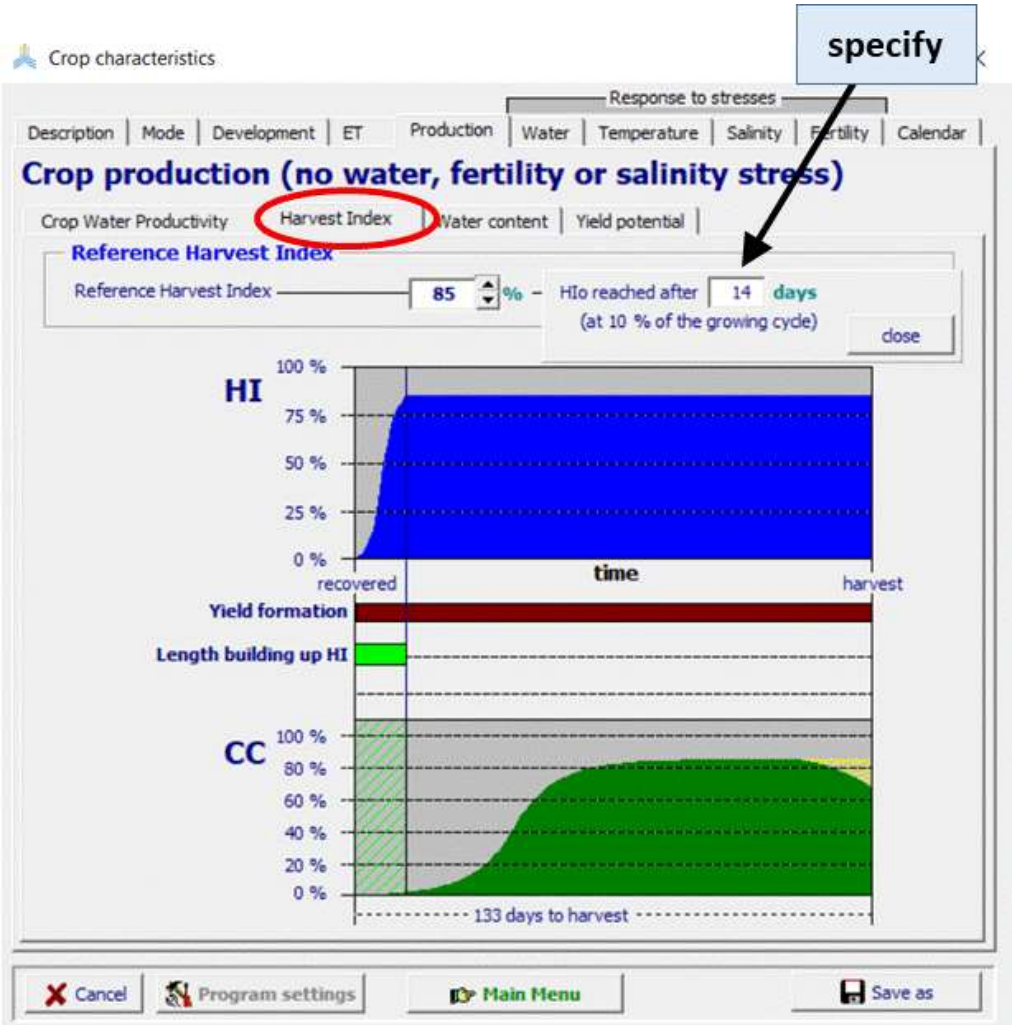


Figure 2.10h5 – Specification of the reference harvest index (HI_o) and the time to reach HI_o for leafy vegetable crops

Perennial herbaceous forage crops

As for leafy vegetable crops, the time to reach HIo is expressed as as the number of days after germination. For a 'not 1st season', the Harvest Index is constant from the start (where the crop starts as regrowth) till the end of the season, and equal to the reference Harvest Index (Fig. 2.10h5/b).

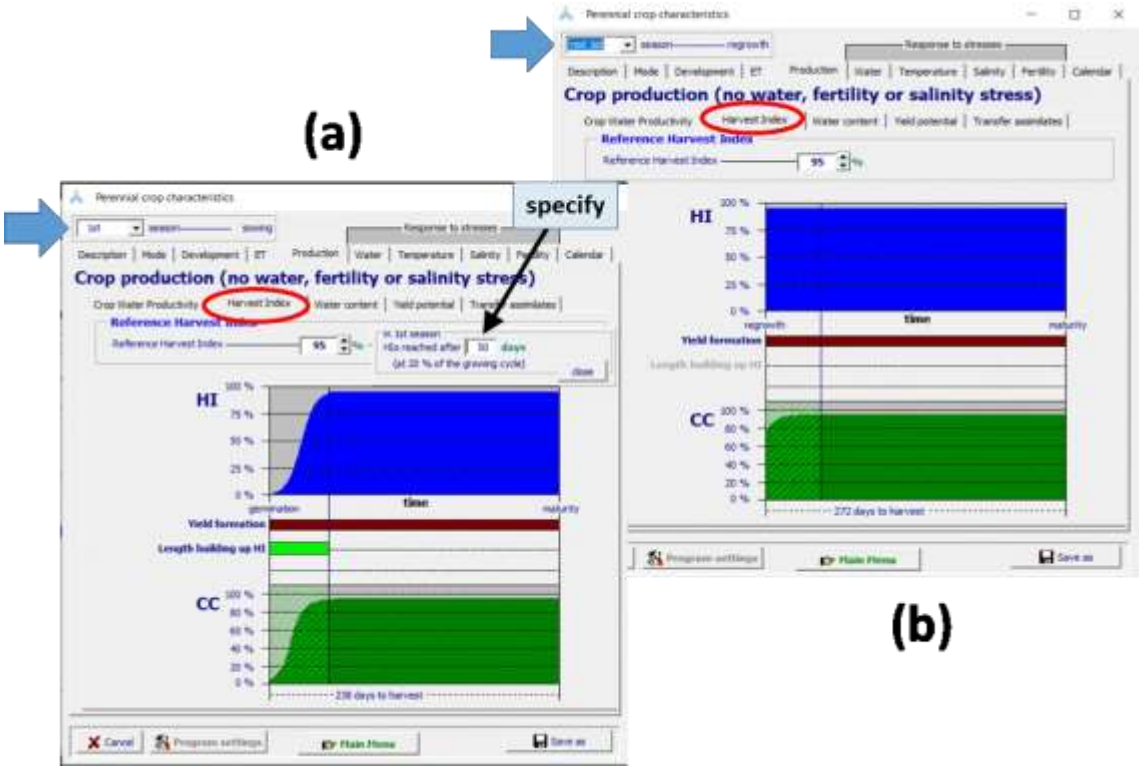


Figure 2.10h5/b. – Specification of the reference Harvest Index (HIo) and the time to reach HIo for perennial herbaceous forage crops for (a) a 1st season, and (b) a not 1st season

- **Specifying the water or dry matter content in the Crop characteristic menu**

In AquaCrop biomass (B) and crop yield (Y) are expressed as the mass of dry matter per unit of surface (ton/ha). The dry yield is a fraction of the fresh yield. The fraction expresses the dry matter content of the fresh yield. The water content (or dry matter content) of fresh yield is specified and can be adjusted in percentage in the tab sheet 'Water content' of the 'Production' tab-sheet of the ***Crop characteristics*** menu (Fig. 2.10h5/c). Some indicative values for various group of crops can be displayed in the menu. The water (dry matter) content is not a conservative crop parameter.

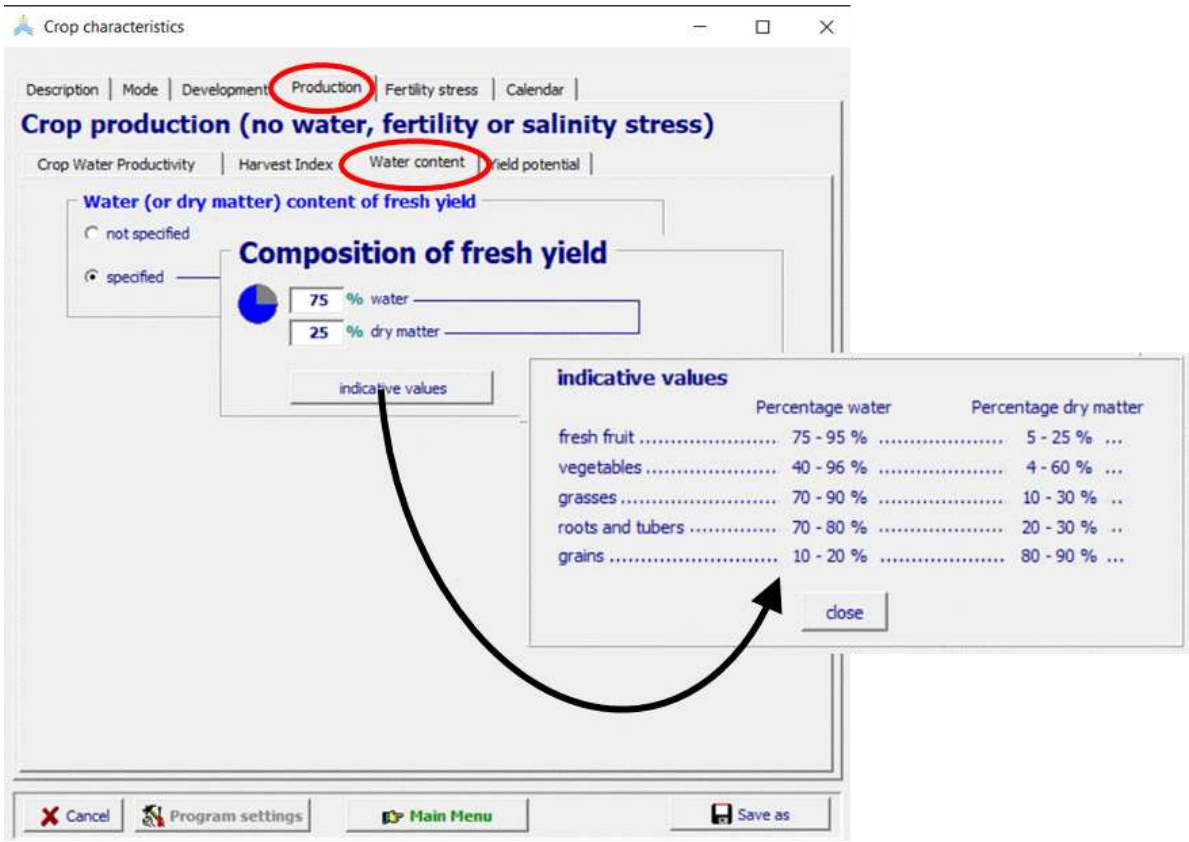


Figure 2.10h5/c. – Specification of the water or dry matter content in the *Crop characteristics* menu

- **Yield Potential**

For the selected climatic conditions and the specified planting date, AquaCrop displays the potential crop production in the tab sheet 'Yield potential' of the 'Production' tab-sheet of the ***Crop characteristics*** menu (Fig. 2.10h5/d and /e).

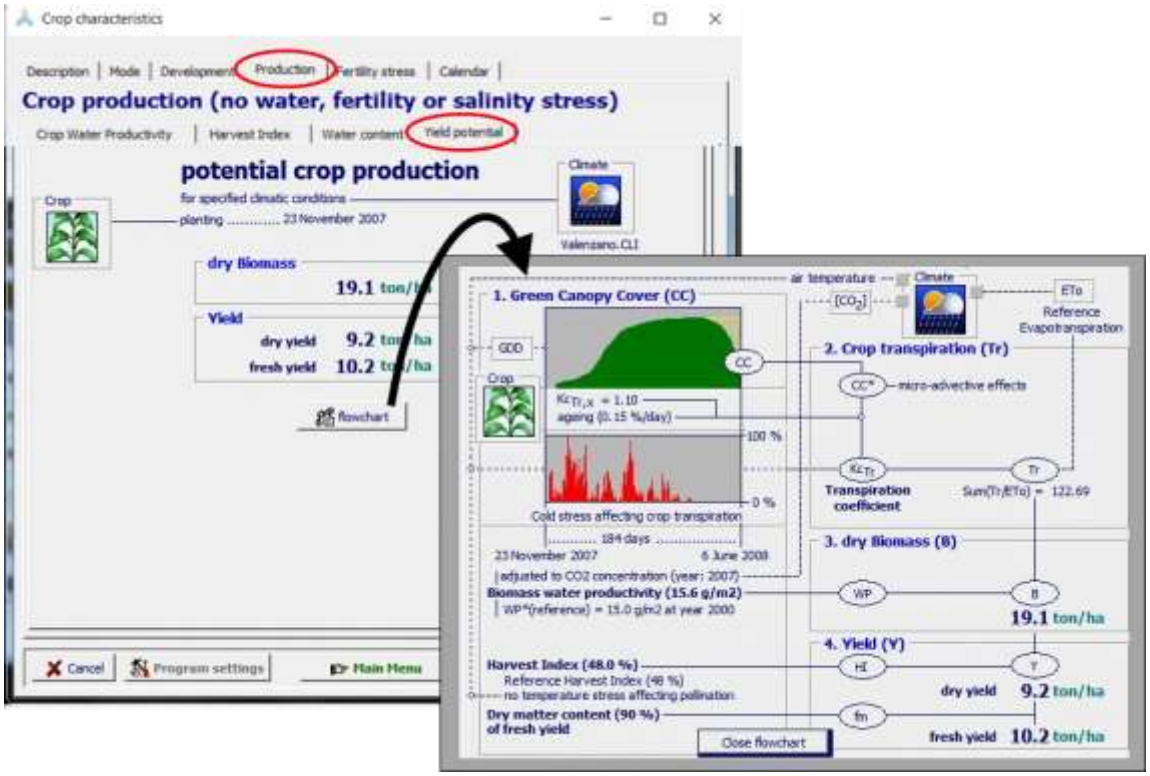


Figure 2.10h5/d – Display of the potential crop production of winter wheat in the *Crop characteristics* menu, with details of the estimate in the flowchart. In the example, low air temperature in the winter period stretched the growing cycle to 184 days, and cold stress affected crop transpiration.

In the tab sheet 'Yield potential' the crop production of the selected cultivar is displayed that can be expected for the selected planting date in the region in absence of water, soil fertility and salinity stress, weed infestation, pest and diseases, or any other environmental constraint that might affect crop production. In the estimate, only stresses by air temperature, which are specific to the climate and planting date, are considered. A low average air temperature might produce insufficient Growing Degree Days (GDD) for the crop, slowing down its canopy development, inducing cold stress which limits stomatal conduction and affects crop transpiration (Fig. 2.10h5/d). A too low or a too high air temperature during flowering might also induce cold or heat stress affecting pollination and as a consequence resulting in a Harvest Index below its reference value (Fig. 2.10h5/e).

By clicking on the < **Flowchart** > button, the details of the estimate of the crop production are displayed (Fig. 2.10h5/d and /e):

1. AquaCrop simulates the Canopy Cover (CC) by considering the characteristics of the crop cultivar. By running simulations in Growing Degree Days (GDD), the canopy development is adjusted to the temperature regime during the crop cycle;
2. AquaCrop estimates the crop transpiration (Tr) by considering the daily crop transpiration coefficient (Kc_{Tr}), reference evapotranspiration (ETo), and the reduction in stomatal conduction at low air temperature (cold stress). The crop transpiration coefficient (Kc_{Tr}) is obtained by multiplying the simulated green Canopy Cover corrected for the micro-advective effects when canopy cover is incomplete (CC*) with the coefficient for maximum crop transpiration ($Kc_{Tr,x}$) adjusted for ageing effects;
3. Dry above-ground biomass production (B) is simulated by multiplying the sum of the ratio (Tr/ETo), with the biomass water productivity (WP) adjusted for atmospheric CO_2 concentration of the year in which the crop is cultivated, and by considering eventually the reduction in WP during yield formation when products rich in lipids or proteins are synthesized (e.g. sunflowers, soybean);
4. Dry yield (Y) is obtained by multiplying B with the Harvest Index (HI). If cold or heat stress affects pollination, the Harvest Index might become smaller than the Reference Harvest Index (Fig. 2.10h5/e). The fresh yield is derived from the dry yield by considering the dry matter content of the fresh yield (f_m).

For a ***perennial herbaceous forage crop***, the potential yield for a 1st or a not 1st season can be displayed in the tab-sheet 'Yield potential' for the selected climatic conditions, crop cultivar and planting date. The yield potential does not consider:

- the transfer of assimilates to the above ground parts at the start of the season;
- the transfer of assimilates to the root system at the end of the season;
- the (natural) self-thinning;
- the effect of multiple harvests during the season

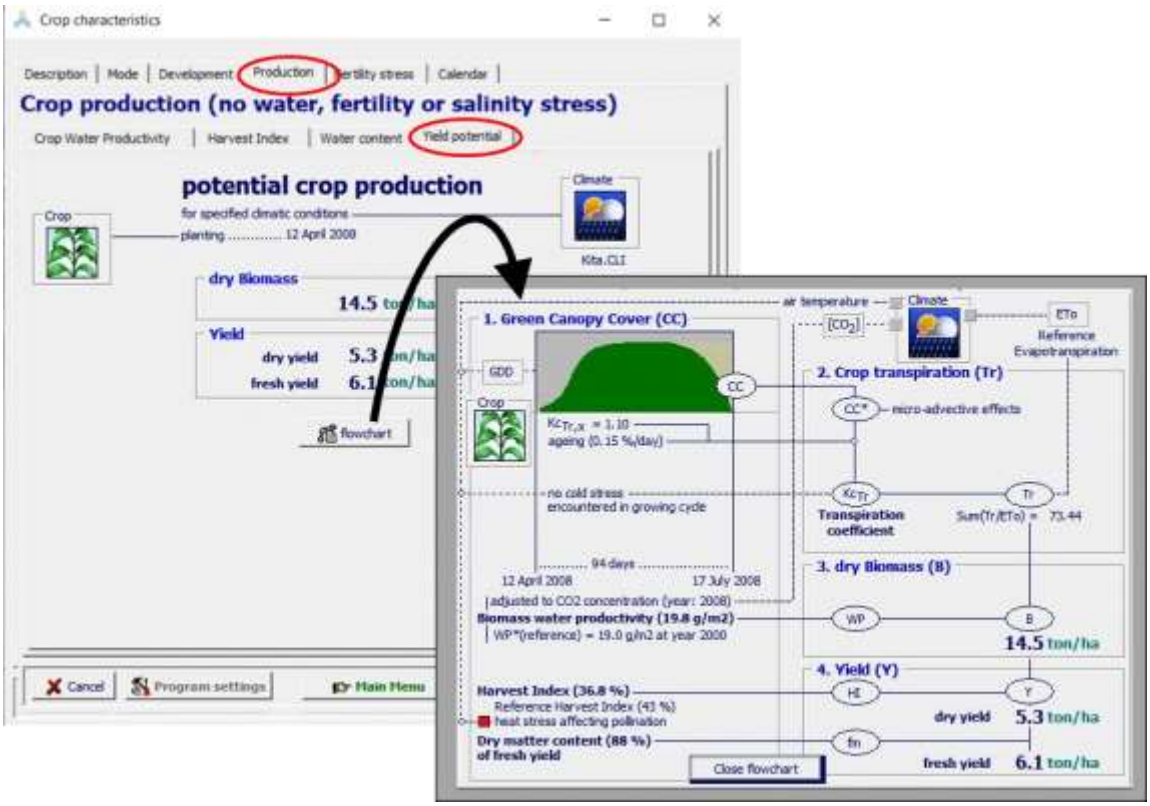


Figure 2.10h5/e – Display of the potential crop production of paddy rice in the *Crop characteristics* menu, with details of the estimate in the flowchart. In the example, heat stress during flowering affected pollination and resulted in a Harvest Index below its reference value.

- **Transfer of assimilates (only for perennial herbaceous forage crops)**

Perennial herbaceous forage crops transfer a considerable fraction of the assimilates to their root system after mid-season. At the start of the next season, a fraction of the stored assimilates are mobilized by transferring them from the root system to the above ground parts of the crop. The rest is assumed to be lost during the off-season by respiration and natural self-thinning, or remain stored in underground organs.

In the Transfer assimilates tab-sheet of the Production tab-sheet in the ***Perennial Crop characteristics*** menu, the seasonal transfer of the assimilates between the above and below ground parts of the crop is specified (Fig. 2.10h5/f).

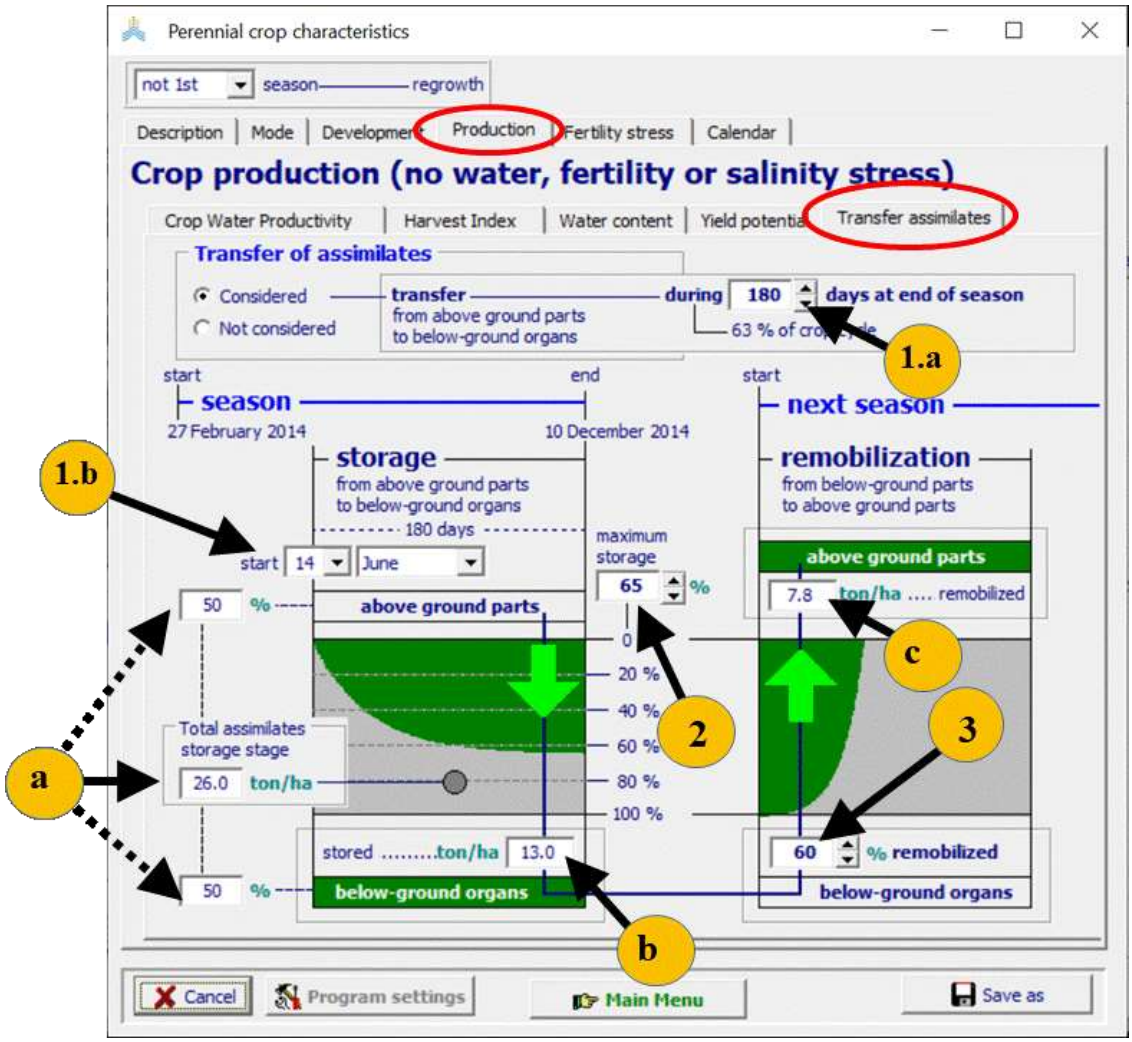


Figure 2.10h5/f – Input (1 to 3) and information (a to c) on the transfer of assimilates in the "Transfer assimilates" tab-sheet in the *Crop characteristic*s menu

If the transfer of assimilates is considered, the user can change:

1. The **duration of the transfer period** in which assimilates are stored in the root system at the end of the season, by specifying (1.a) the number of days or (1.b) the starting date (day and month) of the storage stage. By knowing the total length of the

crop cycle and the specified duration of the storage stage, AquaCrop obtains from the input, the time in calendar days at which the transfer starts;

2. **The fraction of produced assimilates that are stored in the root system during the storage stage**, by specifying the percentage at the last day of the storage stage (when the storage is at its maximum);
3. The **percentage of the stored assimilates that are mobilized** at the start of the next season.

With this information AquaCrop calculates and displays (Fig 2.10h5/f):

a) the total mass of assimilates than can be produced during the storage stage in the absence of water, fertility or salinity stress, and the percentages stored in the above ground parts and root system;
b) the mass of assimilates that were stored to the root system;
c) the mass of assimilates that will be transferred from the root system to the above ground parts, at the start of the next season.

2.10.9 Tabular sheet: Water stress

- **Water stress coefficient (Ks)**

Effects of water stress on canopy expansion, stomatal conductance, and early canopy senescence are described by water stress coefficients Ks. Above an upper threshold of soil water depletion in the root zone, water stress is not considered and Ks is 1. Below a lower threshold, the stress is at its full effect and Ks 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.

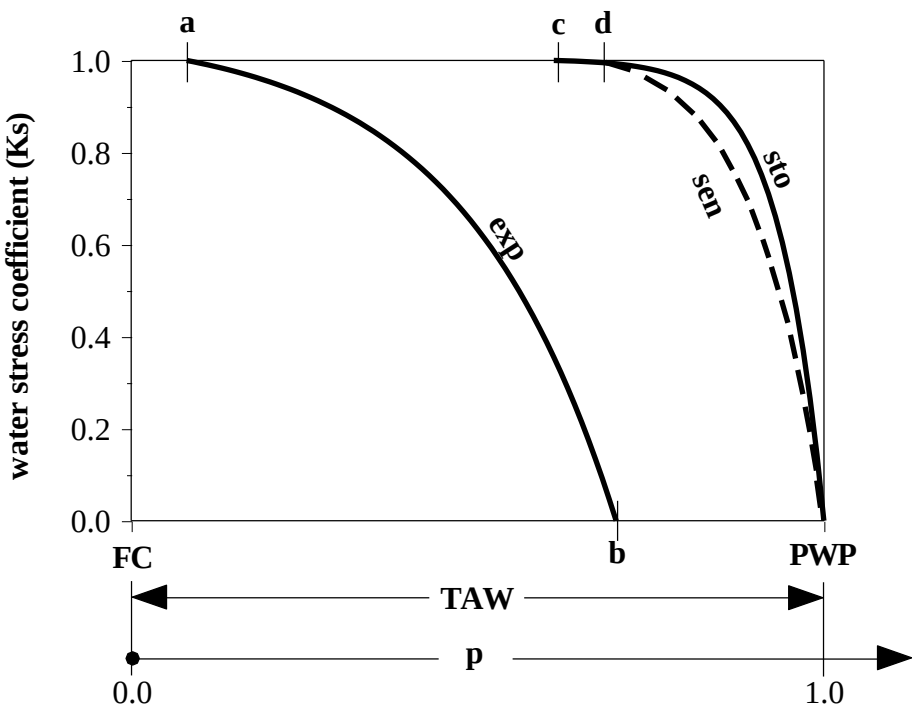


Figure 2.10i1 – Examples of the variation of the water stress coefficient for leaf expansion (exp), stomatal conductance (sto) and canopy senescence (sen) for various soil water depletions in the root zone

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 ($p < 1$), where as for stomata and senescence the lower threshold is fixed at PWP ($p = 1$).

Shape of Ks curve: Between the upper and lower thresholds the shape of the Ks 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).

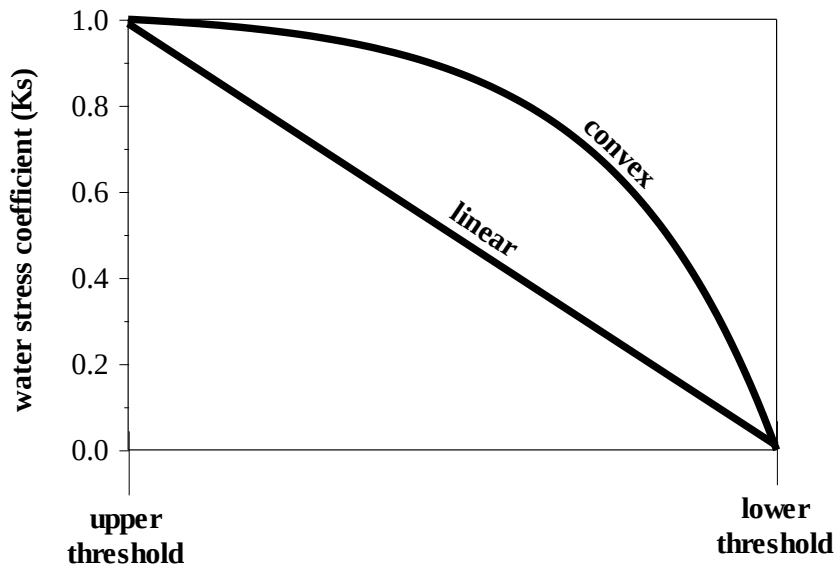


Figure 2.10i2 – Convex and linear shapes of the Ks curve

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 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 ETo. The adjustment is not considered if the correction for ETo 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(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(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(upper)	p(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

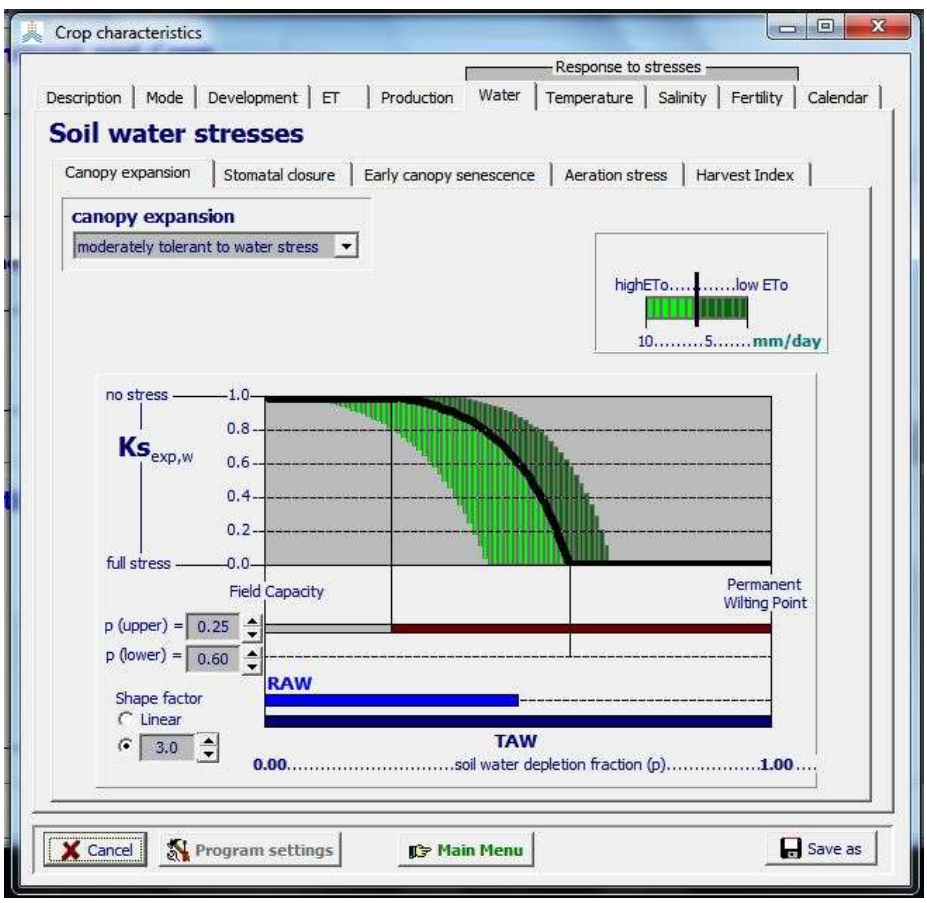


Figure 2.10i3 – Specification of the upper and lower thresholds and the shape of the Ks curve for the effect of water stress on canopy expansion ($Ks_{exp,w}$)

- **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

Under severe water stress, AquaCrop triggers canopy senescence. Once the soil water content in the root zone drops below the threshold value for early canopy senescence, the green canopy cover (CC) gradually declines. In the absence of rain and/or irrigation during early senescence, CC will finally become zero.

Since the process of early canopy senescence is difficult to calibrate, the moment of permanent wilting is very uncertain. Therefore, AquaCrop offers the option to specify a dormant period (Fig. 2.10i4/1). During the dormant period it is assumed that the crop is not yet permanently wilted and can still recover upon rewatering. By expressing the dormant period as a sum of daily ETo, its length is determined by the weather conditions. Hot dry weather shortens the dormant period, while cool weather lengthens the period. During the dormant period, AquaCrop keeps CC above zero, to allow the simulation of canopy expansion as soon as sufficient water becomes available for plant recovery. If at the end of the dormant period, the crop wasn't able to recover, CC drops to zero and the crop is considered as permanently wilted.

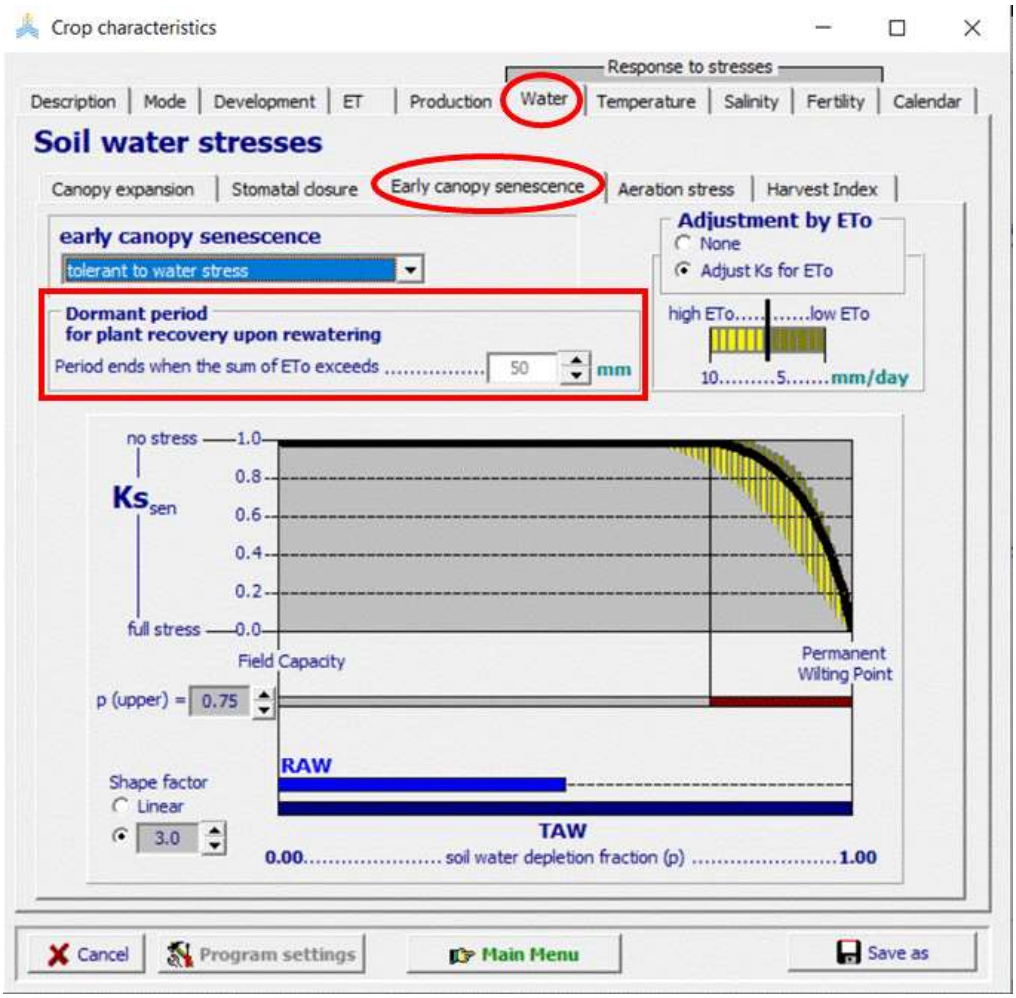


Figure 2.10i4/1 – Specification of the dormant period for plant recovery upon rewatering, as a sum of daily ETo, in the 'Early canopy senescence' tab-sheet of the *Crop characteristics* menu.

During the dormant period CC gradually decreases from an initial 5% to CCo. If CCo is greater than 5 %, CC remains at CCo during the whole of the dormant period. Once regrowth is activated, the ageing of the canopy (inducing a progressive though small reduction in crop transpiration and photosynthetic capacity) is reset to zero.

Although the plant will survive upon rewatering during the dormant period, regrowth can only occur during the period of potential vegetative growth. For determinant crops, once peak flowering is passed and fruits or grains begin to fill, CC can no longer increase. For indeterminant crops the canopy development stage is stretched till canopy senescence. In Figure 2.10i4/2, an example of regrowth upon rewatering is presented.

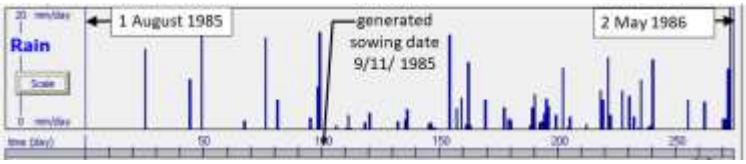
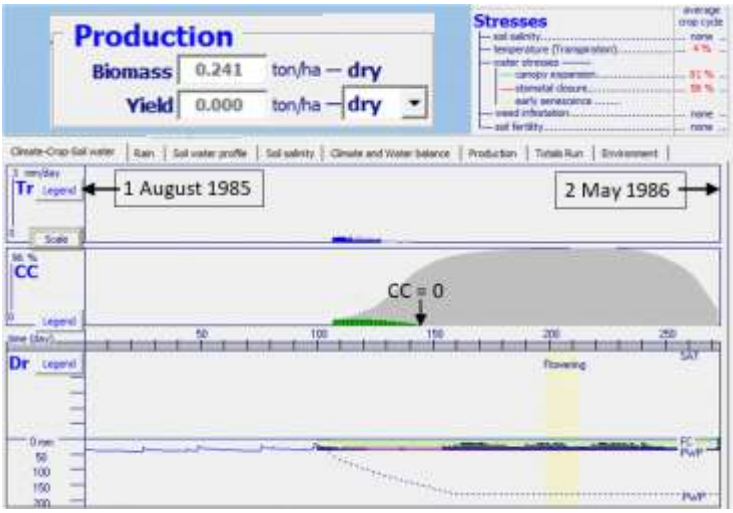
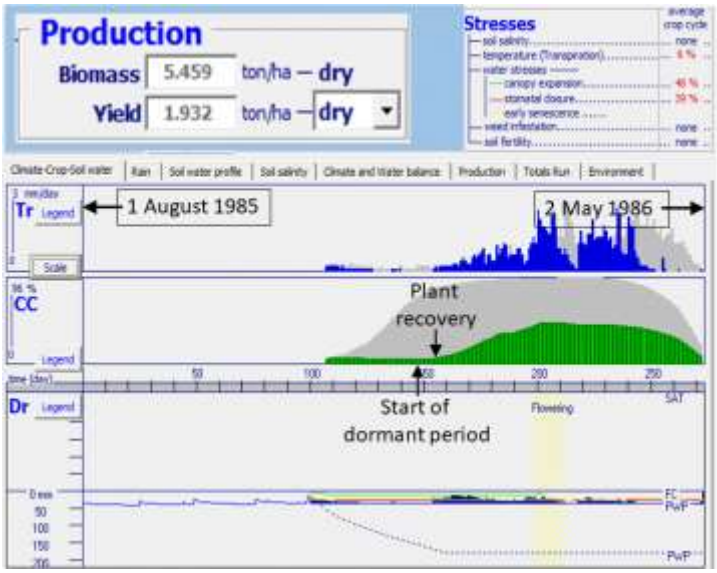
Distribution of rainfall Period: from 1 August 1985 to 2 May 1986 (total: 304 mm)	
No dormant period Simulated biomass, crop yield and green canopy cover (CC) after germination (10 days after sowing. On 25 December 1985 (day 146), early canopy senescence was completed and CC became zero.	
With dormant period Simulated biomass, crop yield and green canopy cover (CC) after germination (10 days after sowing). During the dormant period, CC remained at CCo = 6.75 %. Recovery was simulated as a result of a rain shower of 15.6 mm on 2 January 1986 (day 154).	

Figure 2.10i4/2 – Distribution of rainfall, and simulation results in the *Run menu* of AquaCrop, for winter wheat in Tunis (season 1985/1986) with and without a dormant period for plant recovery on rewatering.

- **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.

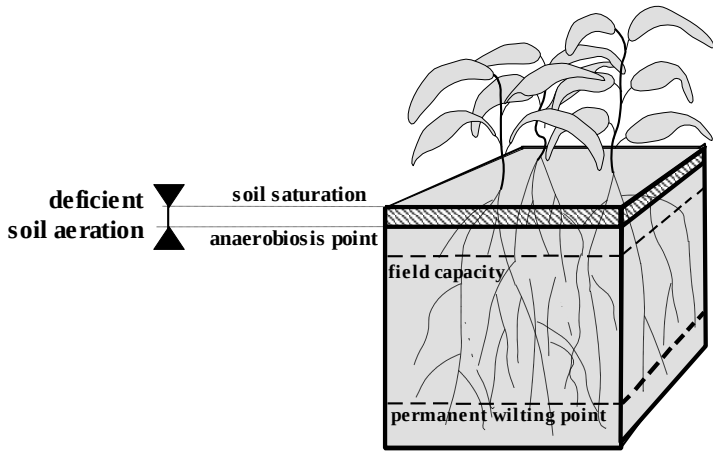


Figure 2.10i5 – Zone (dark area) of restricted soil water extraction as a result of deficient soil aeration

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

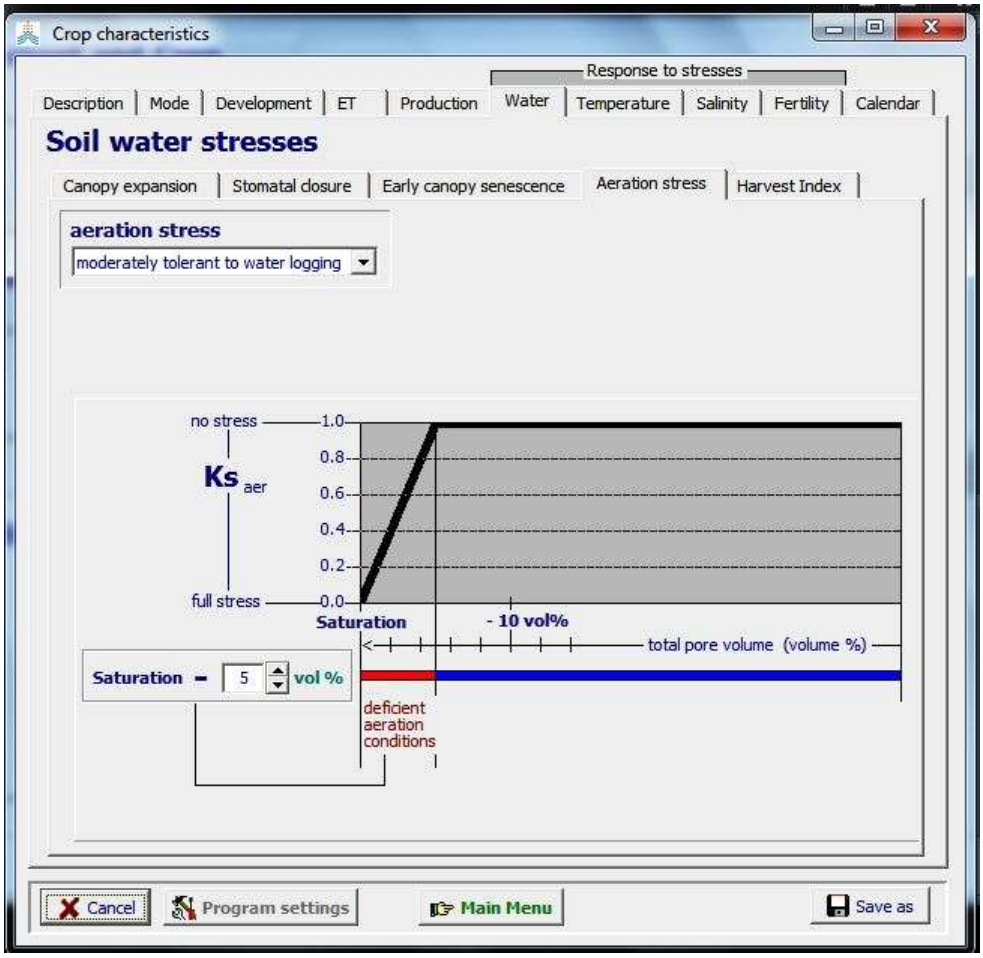


Figure 2.10i6 – Specification of the soil water content below saturation at which poor aeration no longer limits transpiration

- **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).

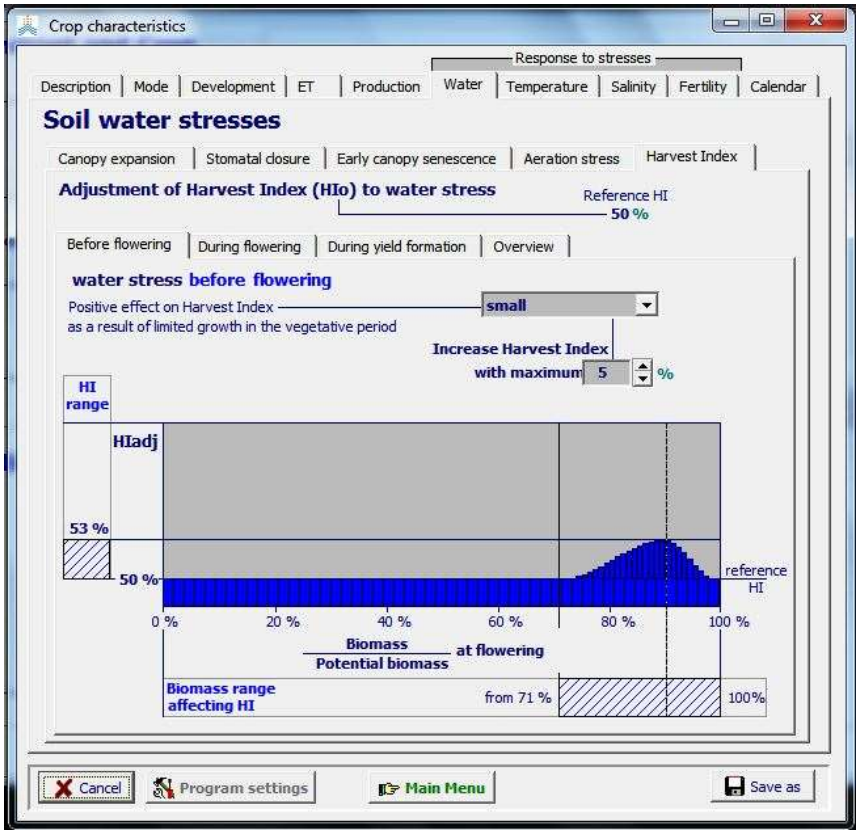


Figure 2.10i7 – Positive effect on Harvest Index of pre-anthesis water stress affecting biomass production

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 (Ks). 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 Ks_{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).

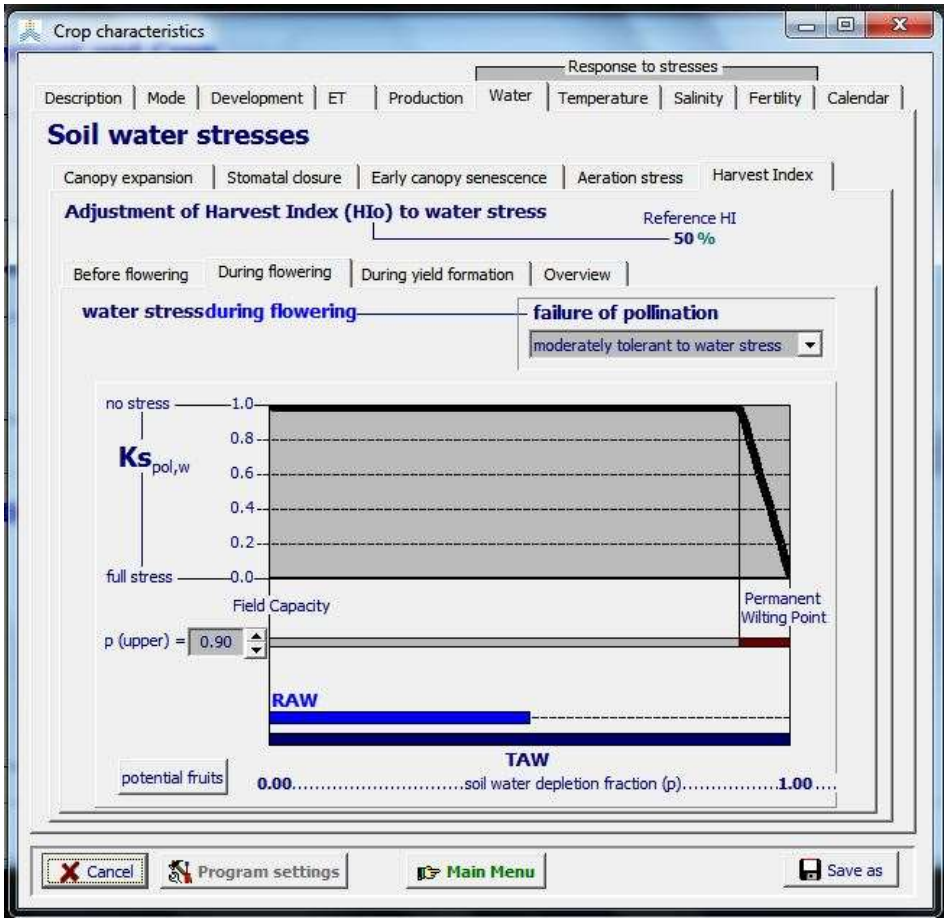


Figure 2.10i8 – Specification of the upper thresholds for the effect of water stress on failure of pollination

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 Ks for leaf growth and with positive stress effect on HI. The magnitude of this effect as a function of Ks 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

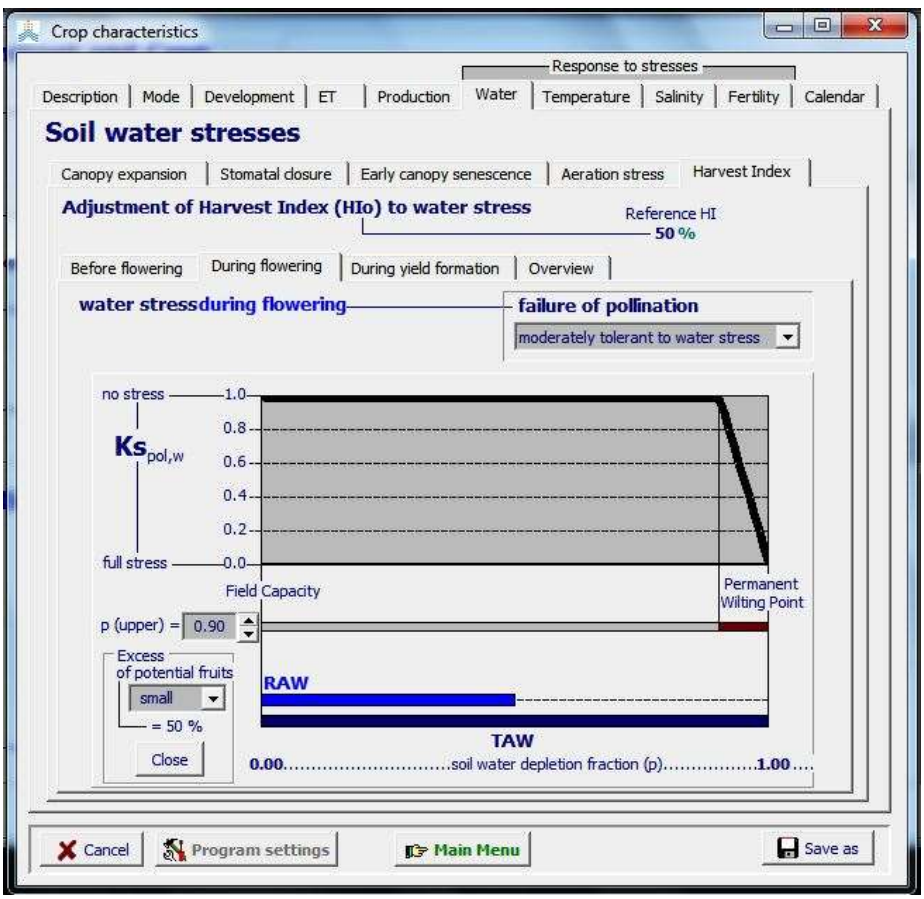


Figure 2.10i9 – Specification of the extent of excessive potential fruits

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

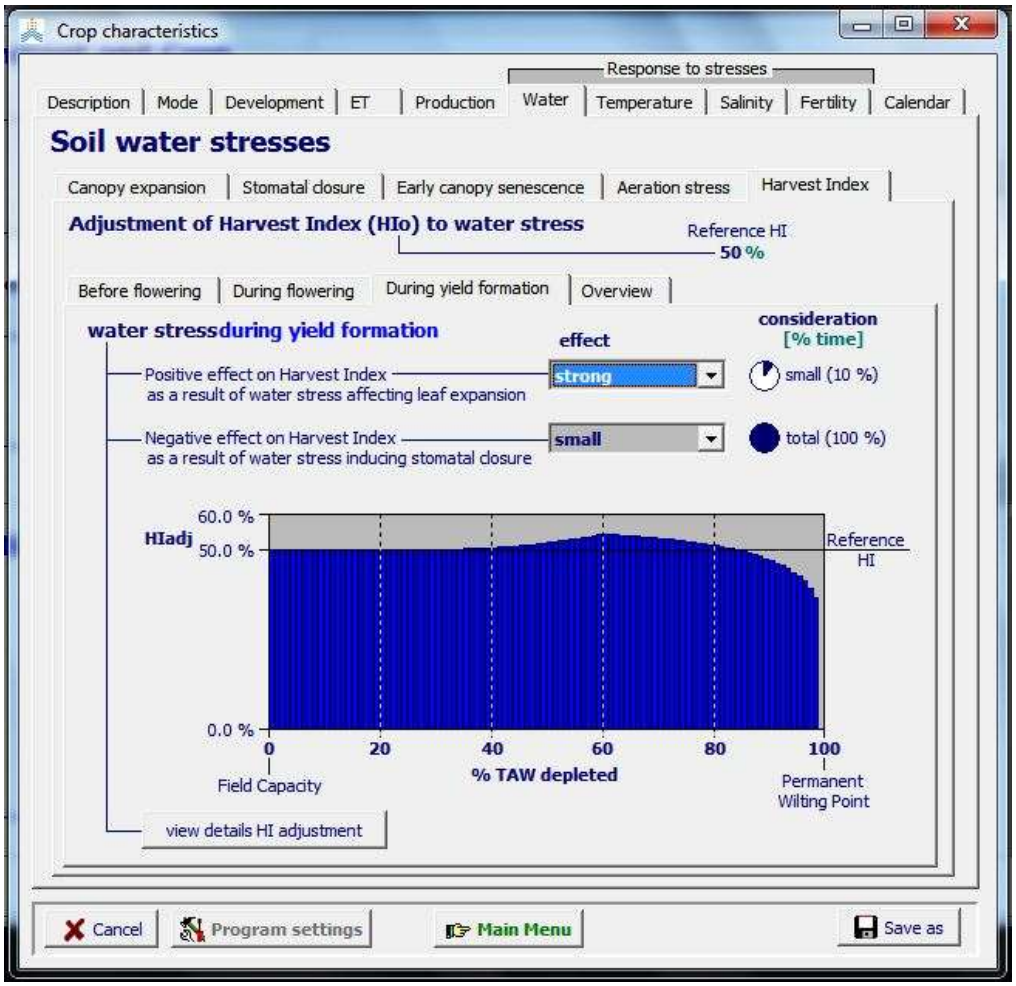


Figure 2.10i10 – Effect on Harvest Index of post-anthesis water stress for various degrees of root zone depletion (% TAW depleted)

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.

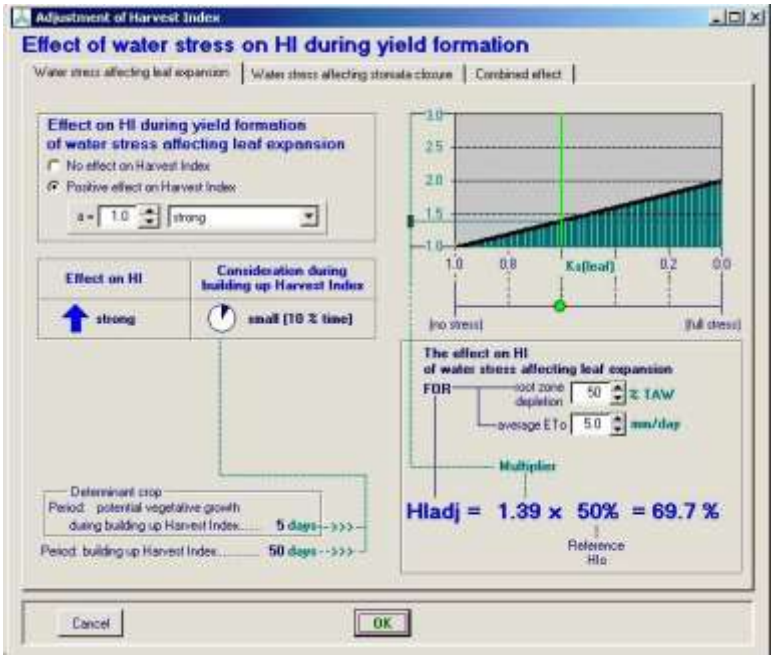


Figure 2.10i11

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

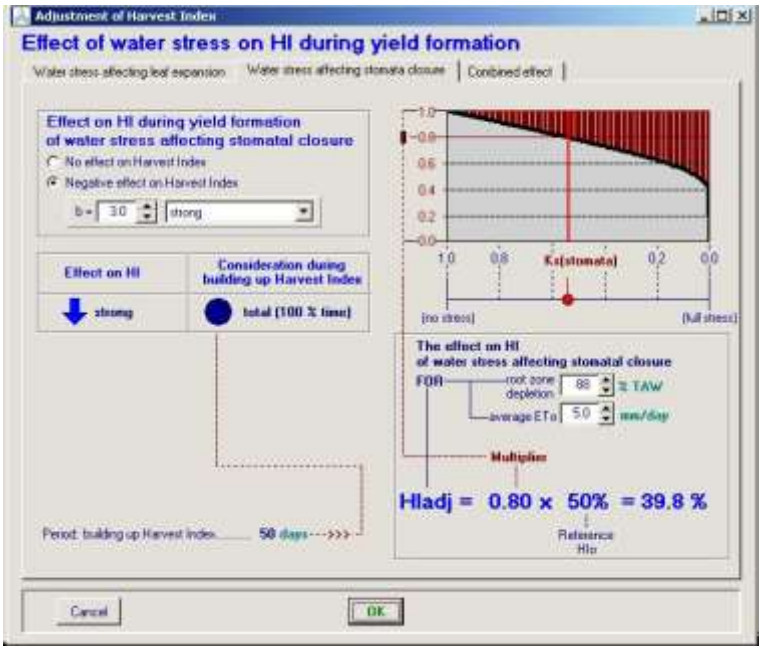


Figure 2.10i12

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).

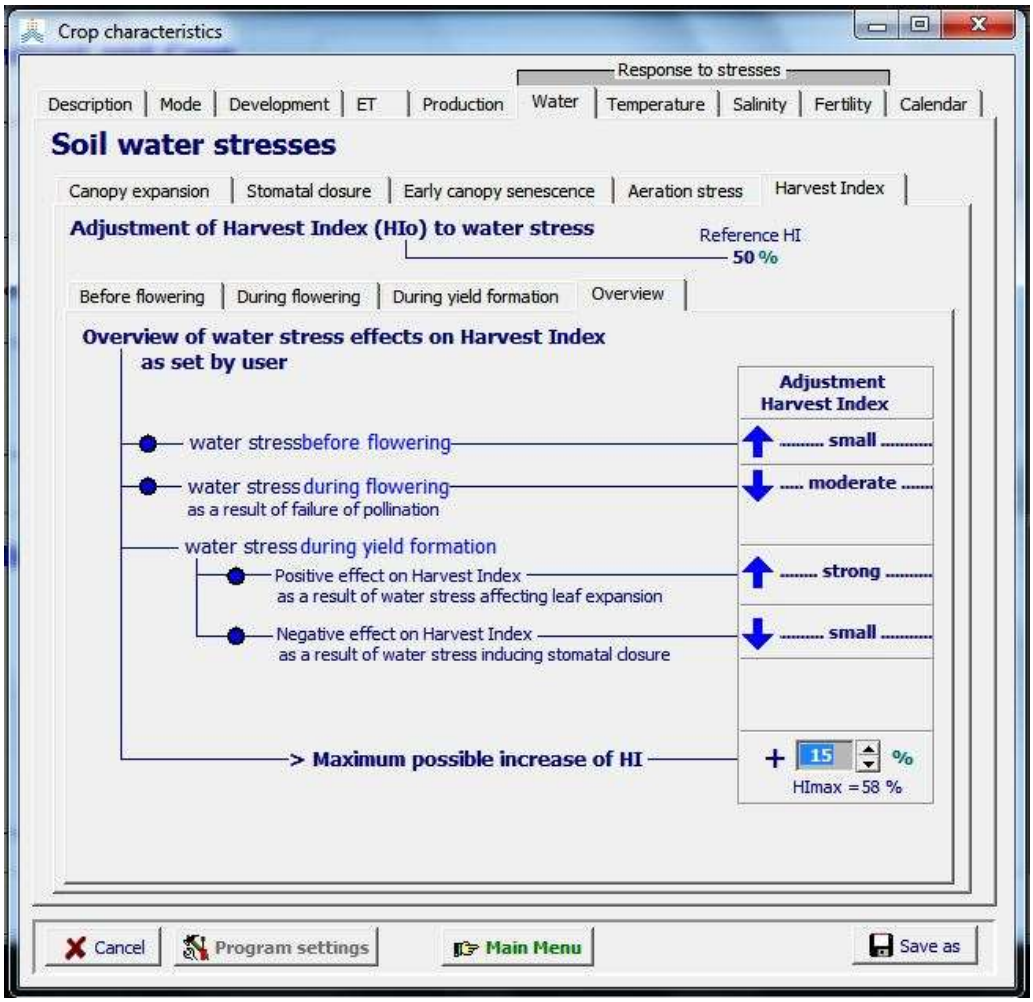


Figure 2.10i13 – Combined effect of water stress on harvest index

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 (Ks) 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.

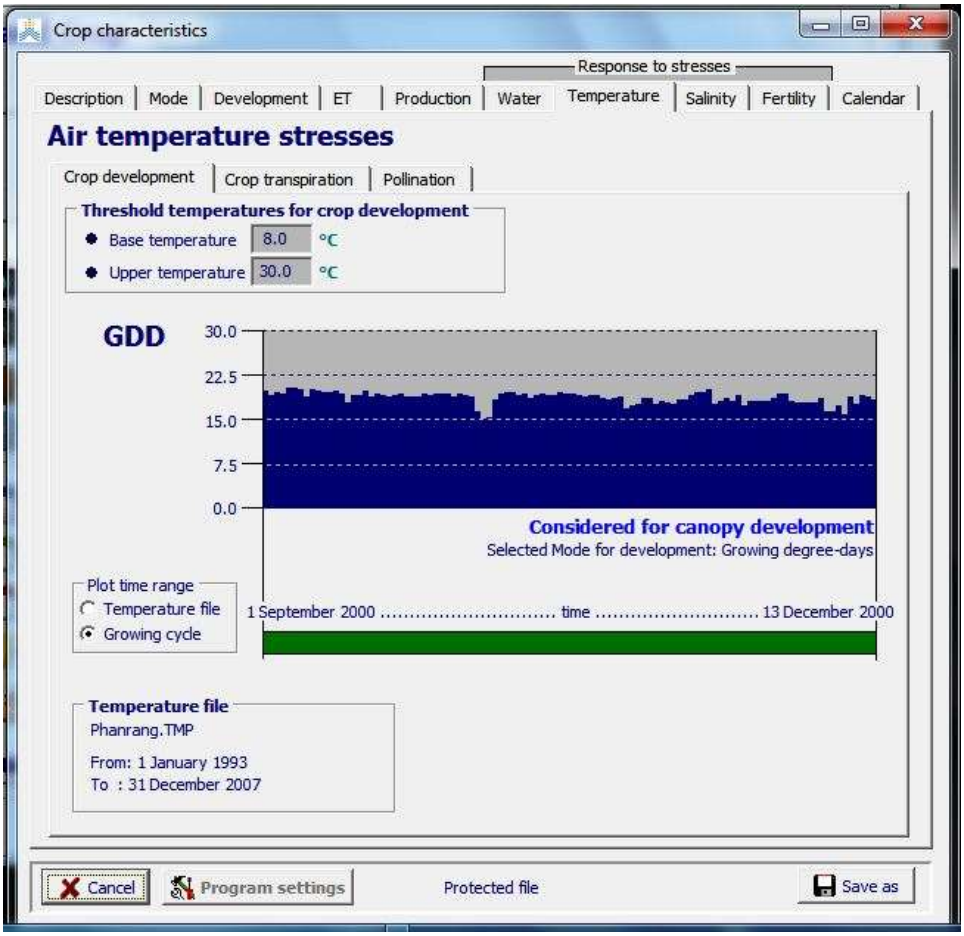


Figure 2.10j1 – The Base and Upper threshold temperatures for crop development in the 'Crop development' sheet of the 'Temperature' stress tabular sheet, and the corresponding growing degrees in Phanrang (Vietnam)

- **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 Ks 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 Ks curve is logistic.

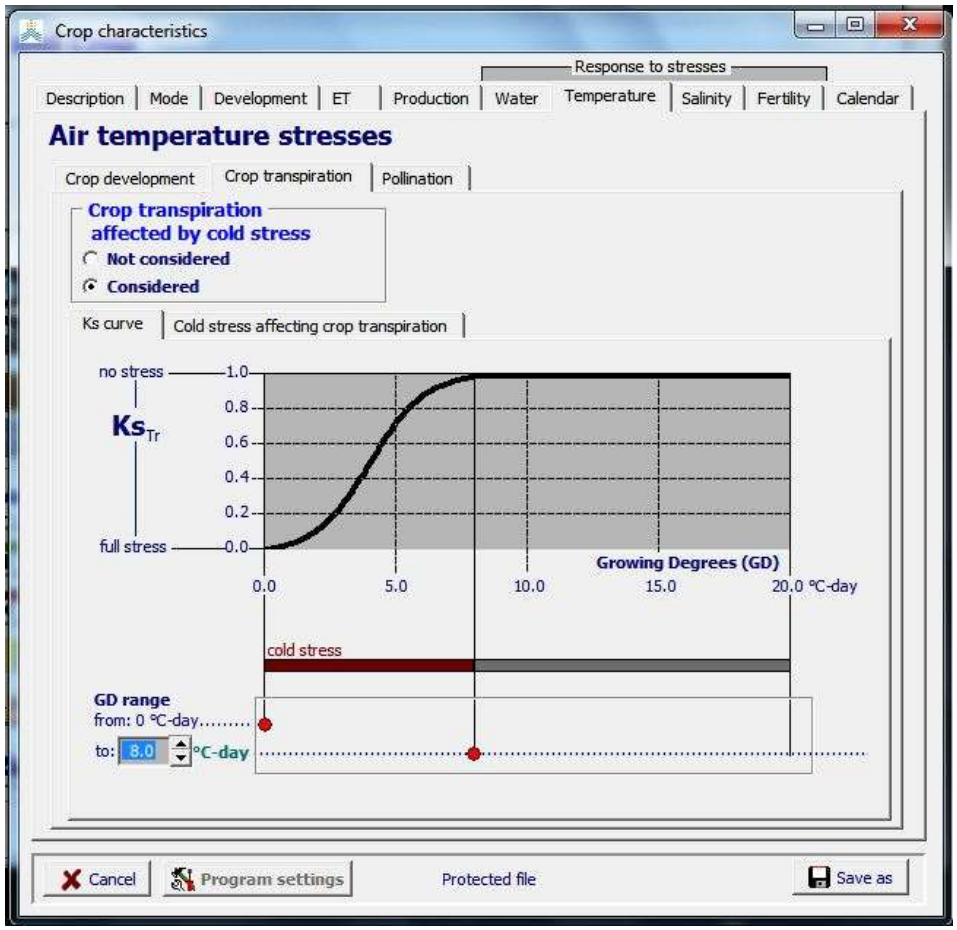


Figure 2.10j2 – The temperature threshold (expressed in growing degree-days) for crop transpiration in the 'Crop transpiration' sheet of the 'Temperature' stress tabular sheet

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).

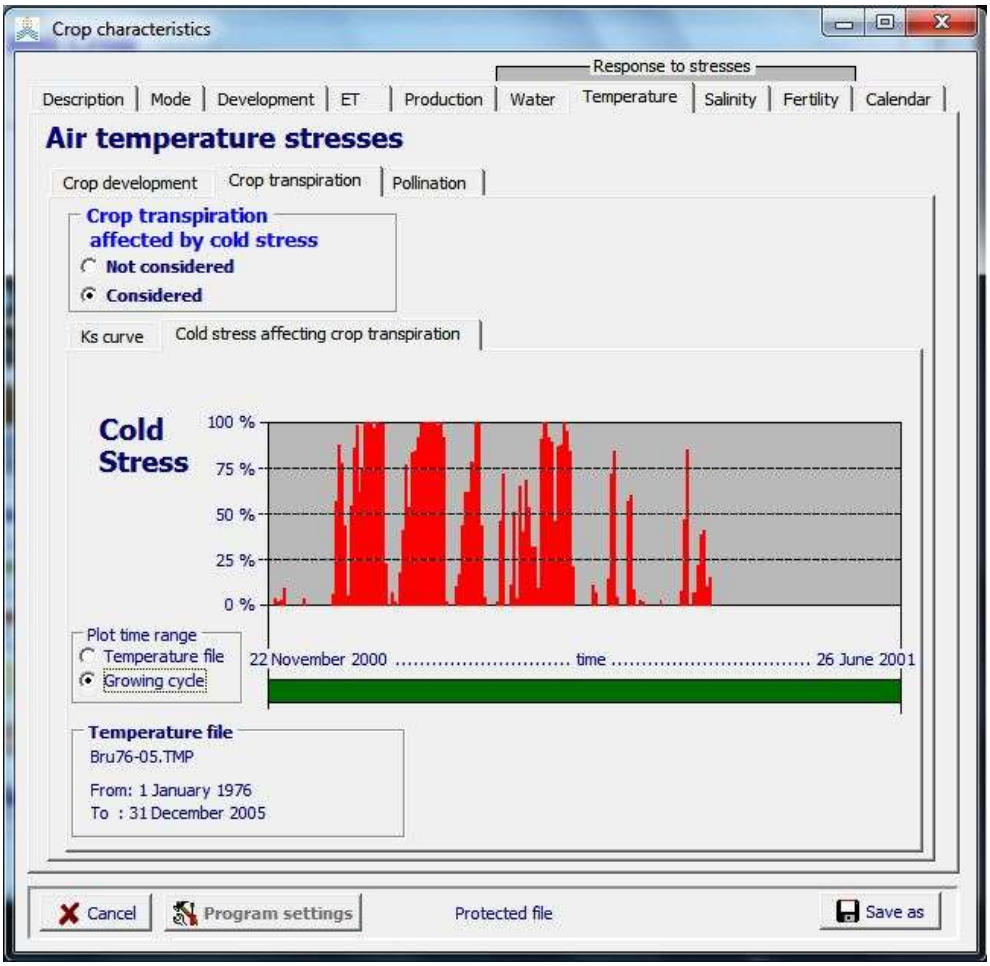


Figure 2.10j3 – The percentage of cold stress in Brussels (Belgium) during the growing cycle for the specified temperature threshold for crop transpiration

- **Pollination**

Cold and heat stress might affect pollination. The temperature stress is specified by a Ks coefficient, which varies from 0 to 1 between threshold temperatures. For the cold stress Ks is 0 at the lower threshold and 1 at the upper temperature threshold. For the heat stress Ks 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 Ks curves are logistic.

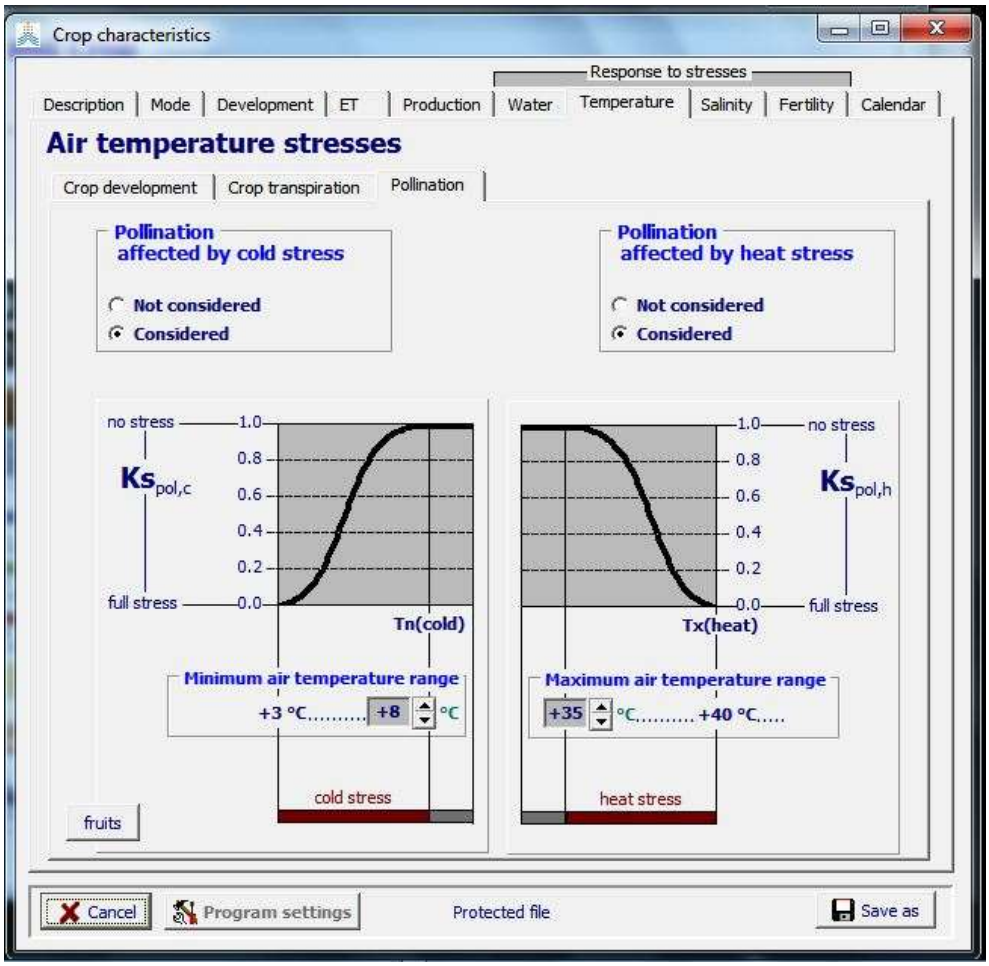


Figure 2.10j4 – Specification of the thresholds for cold and heat stress on pollination

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 (Ks = 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 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).

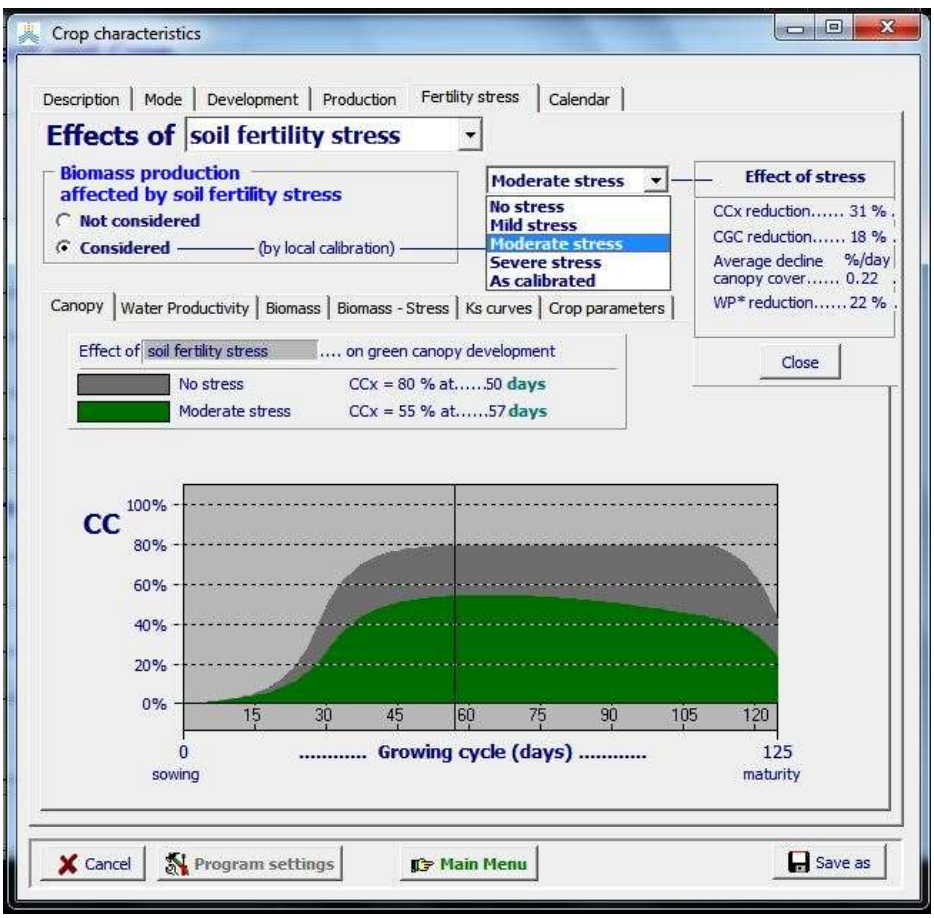


Figure 2.10k1 – The effect of moderate soil fertility stress on canopy development

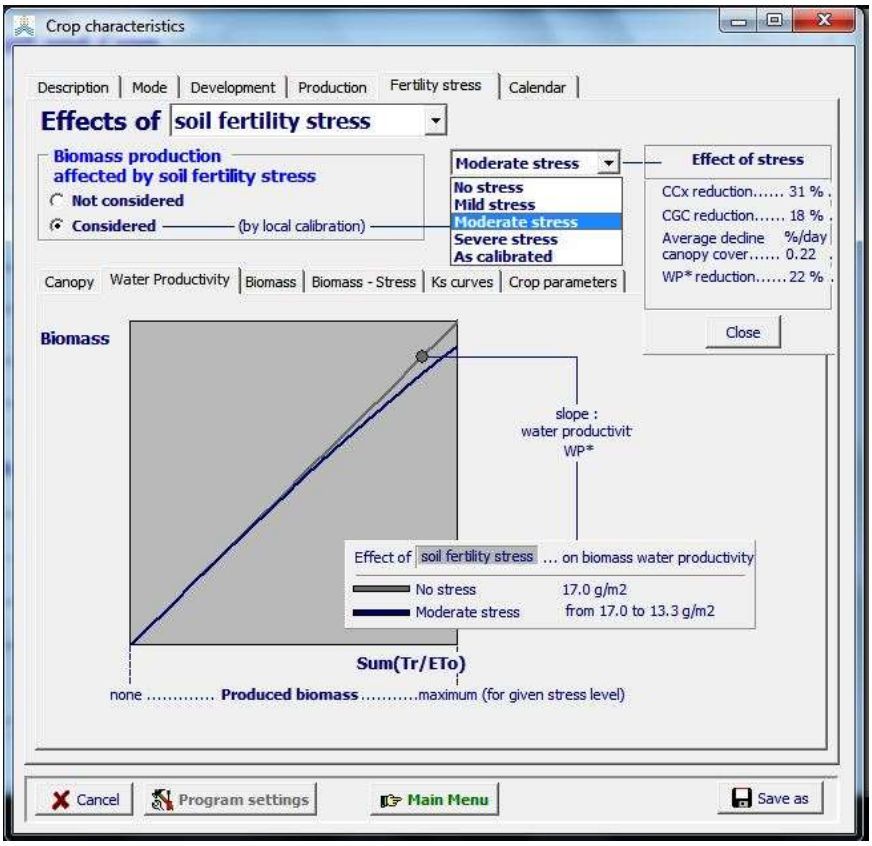


Figure 2.10k2 – The effect of moderate soil fertility stress on biomass production

- **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

	**Crop characteristics:** How does the crop responds to soil fertility stress ?
	**Field management:** What is the soil fertility level in the field ?

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**

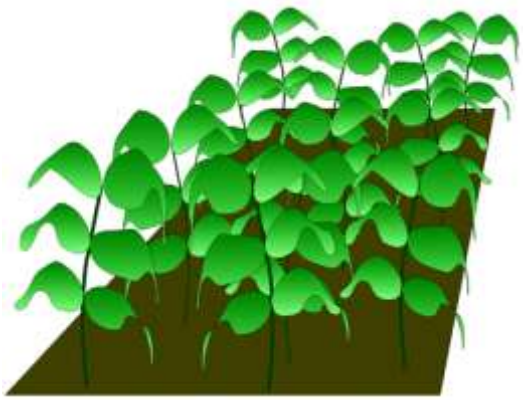
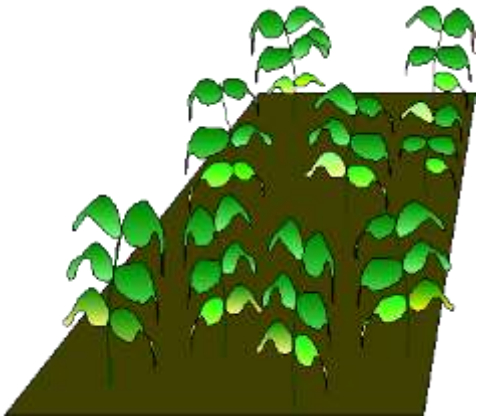
	
Reference field - well-watered field - no soil fertility stress	**Stressed field** - well-watered field - soil fertility stress
Observations: B_{ref} and CC_{ref}	**Observations:** B_{stress} and CC_{stress}

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 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 (Ks) 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		
$Ks_{exp,f}$	Stress coefficient for canopy expansion	Canopy Growth Coefficient (CGC)
Ks_{CCx}	Stress coefficient for maximum canopy cover	Maximum canopy cover (CCx)
$f_{CDecline}$	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		
Ks_{WP}	Stress coefficient for biomass water productivity	Biomass water productivity (WP*)

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

<u>The calibration process</u>

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:

1. 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_{stress}/B_{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').

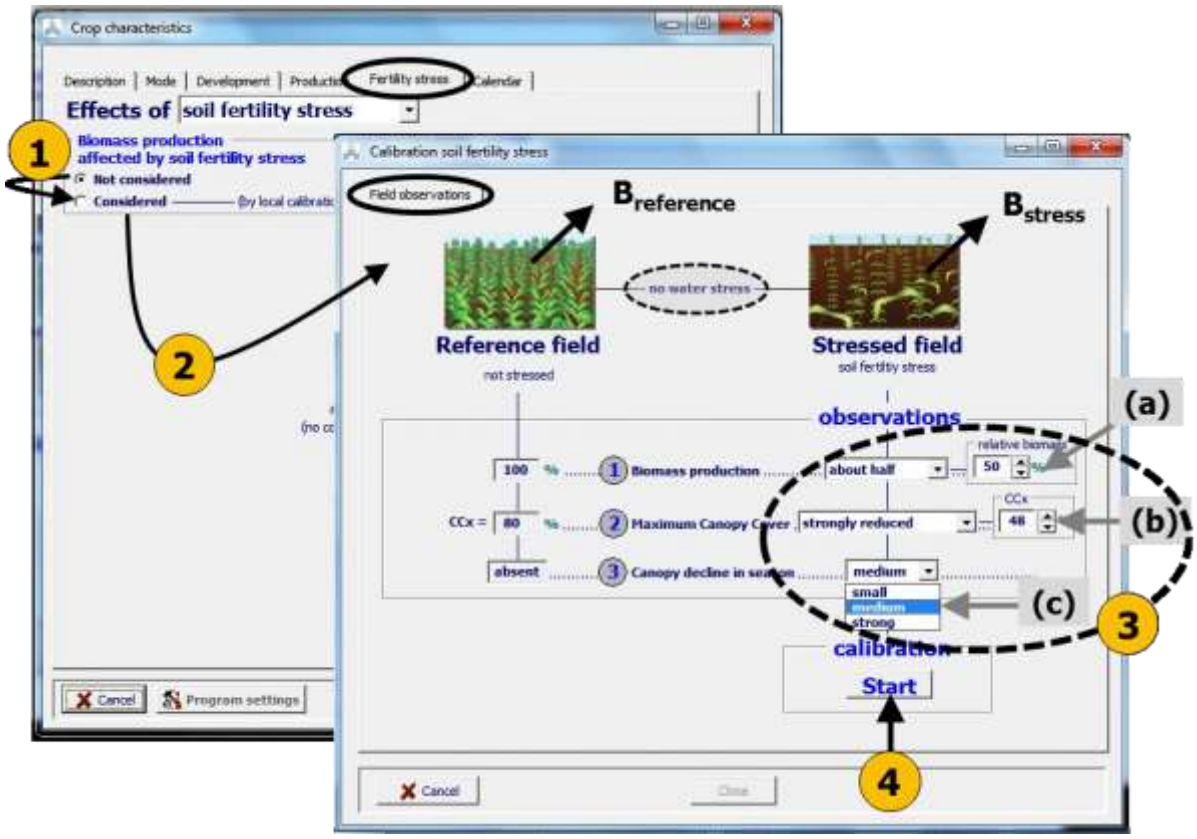


Figure 2.10m3 – (1) By selecting 'Considered' in the 'Fertility-stress' tabular sheet, (2) the 'Field observations' tabular sheet of the *Calibration soil fertility stress* menu becomes available in which the user (3) specifies the observed or expected (a) relative biomass production, (b) maximum canopy 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 ($Ks_{exp,f}$, Ks_{CCx}, Ks_{WP}, $f_{CDecline}$) 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).

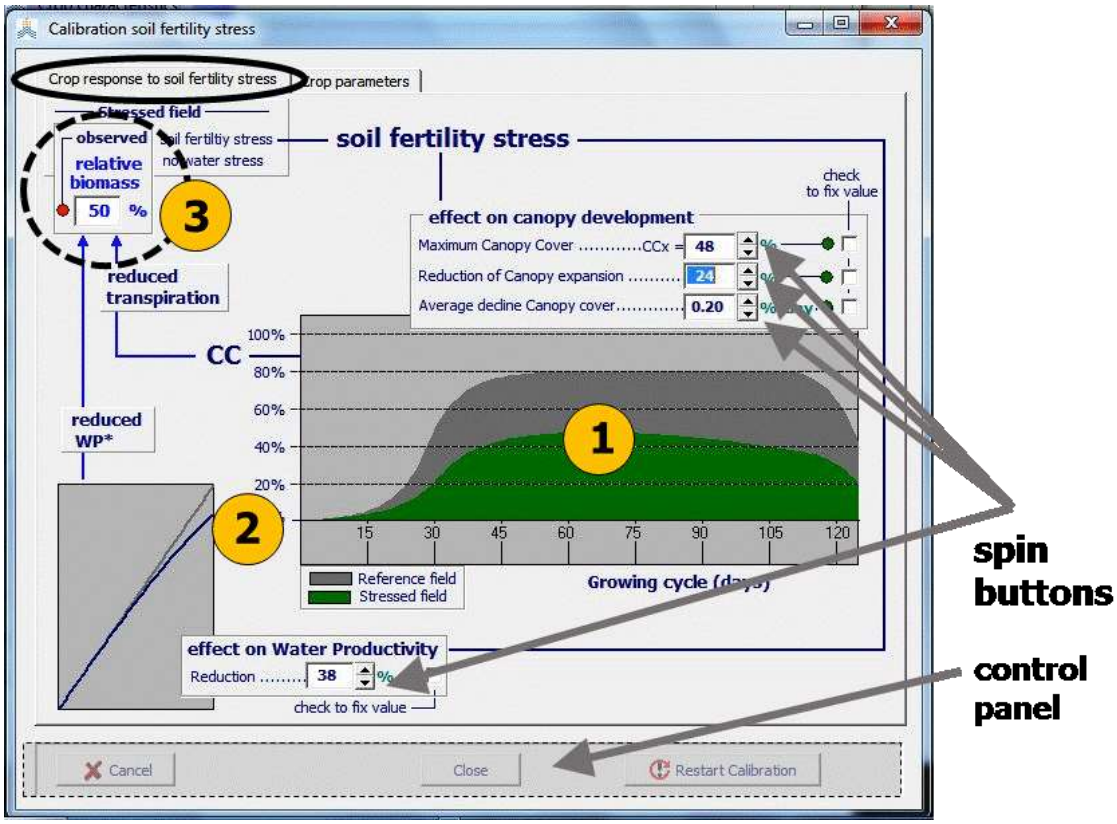


Figure 2.10m4 – The 'Crop response to soil fertility stress' tabular sheet of the *Calibration soil fertility stress* menu in which the effect of soil fertility stress (1) on canopy cover and (2) on the decline of WP* during the season, is plotted and is fine-tuned by means of the four spin buttons and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

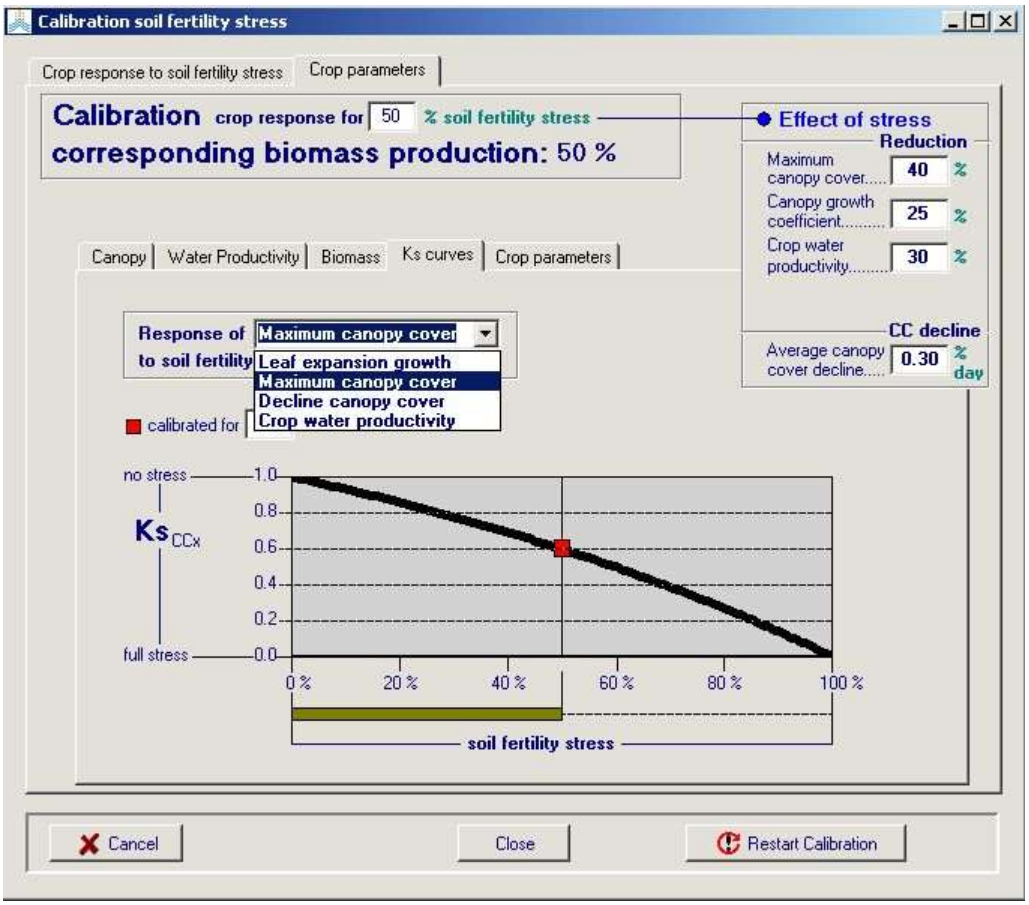


Figure 2.10m5 – The Ks curve for Maximum canopy cover as displayed in the tab-sheet 'Ks-curves' of the ***Calibration soil fertility stress*** menu

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:

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

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 CCx by 40 % (CCx_{stress} = 0.6 CCx_{ref}), Ks_{CCx} is 0.6 at the soil fertility/salinity stress of 50 % (Fig. 2.10m5).

Once a curve is calibrated, the Ks corresponding to other soil fertility/salinity stresses can be obtained from the curves. With reference to Fig. 2.10m5, CCx will be reduced by 20 % (Ks_{CCx} = 0.80 or CCx = 0.8 CCx_{ref}) for a soil fertility stress of 27 %, and by 60 % (Ks_{CCx} = 0.40 or CCx = 0.4 CCx_{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 (CCx), (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 CCx, CGC, canopy decline, and WP*, as described in each of the Ks 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 CCx, on CGC, on canopy decline, and on WP* are described in the individual calibrated Ks and reduction curves (Fig. 2.10m5). Since the shapes of the Ks 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).

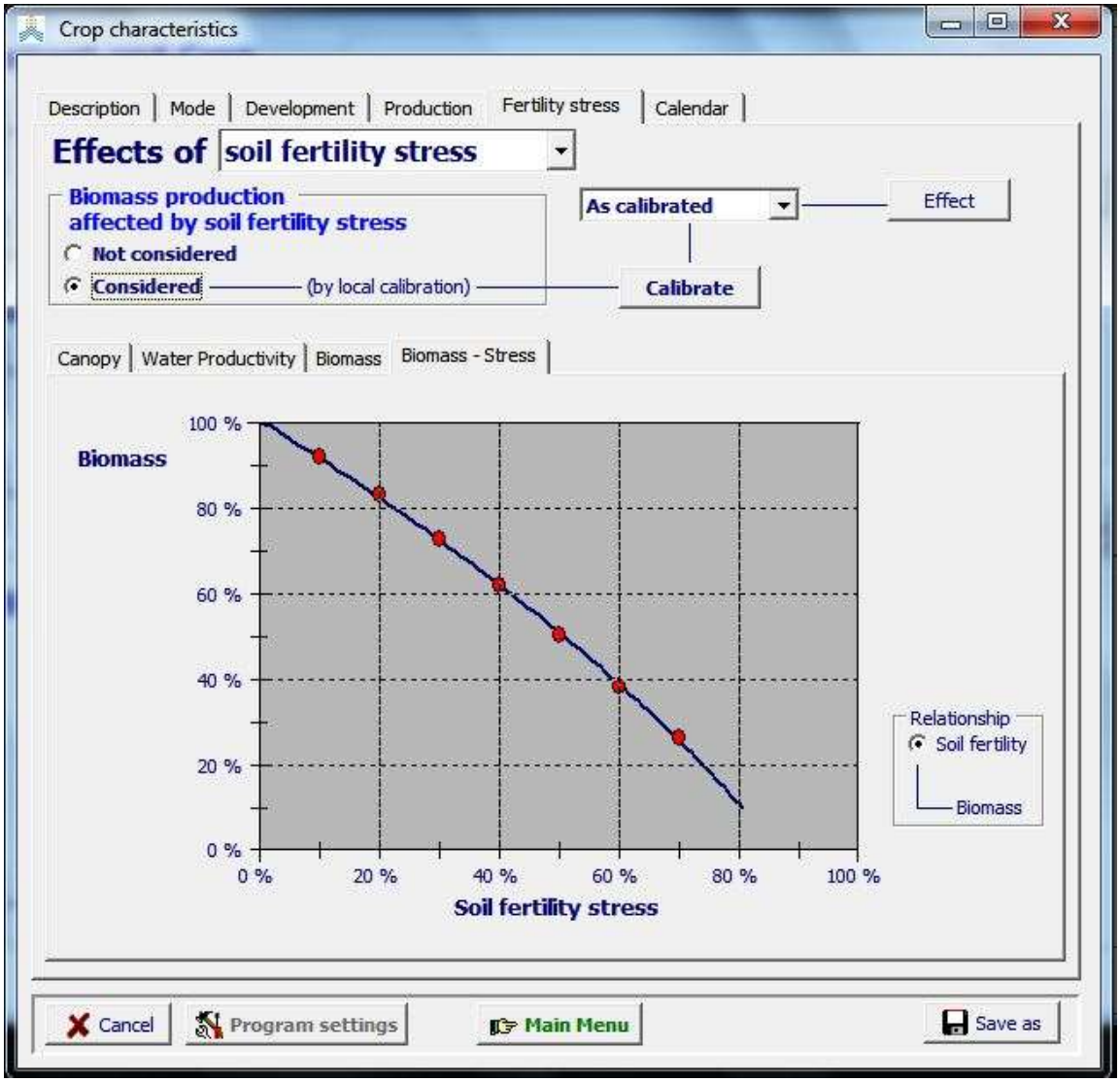


Figure 2.10m6 – Display of the relationship between Biomass and soil fertility stress in the 'Biomass-Stress' tab-sheet of the ***Crop characteristics*** menu.

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).

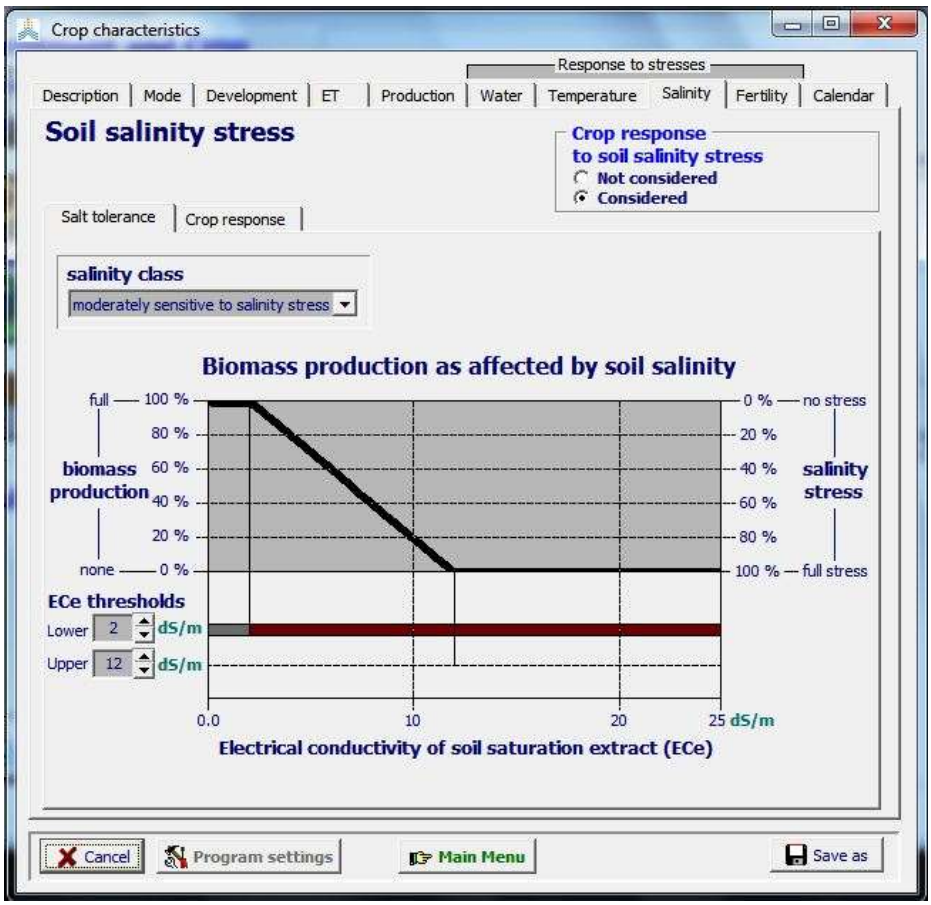


Figure 2.10n1 – Specification of the upper and lower thresholds of the electrical conductivity of soil saturation extract (ECe) with the corresponding salinity class, and the display of the 'Biomass – ECe' relationship in the 'Salt tolerance' tab sheet.

- **'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’).

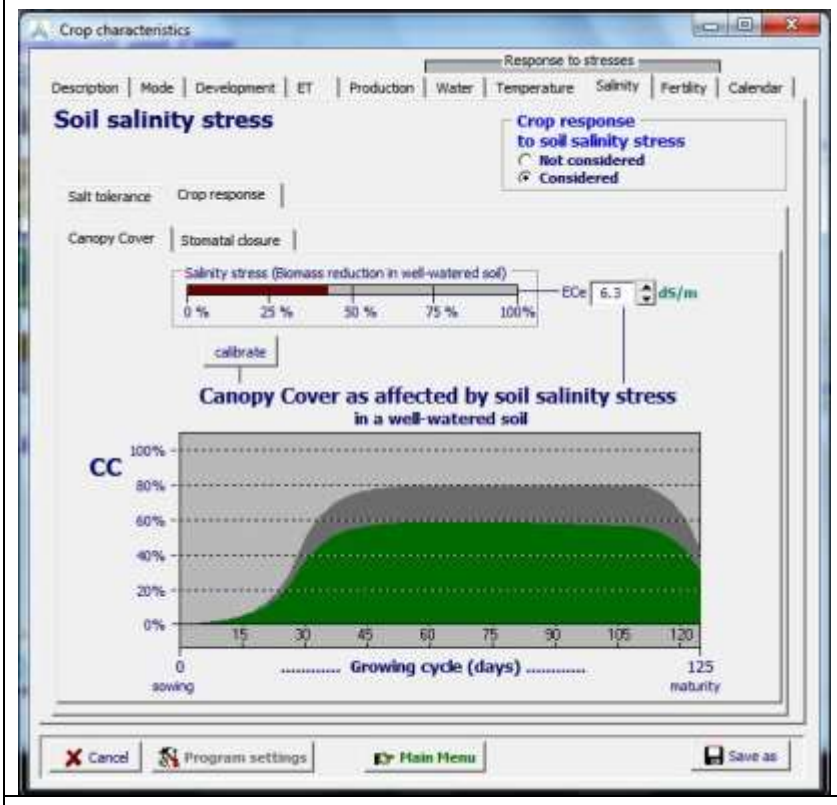


Figure 2.10n2

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

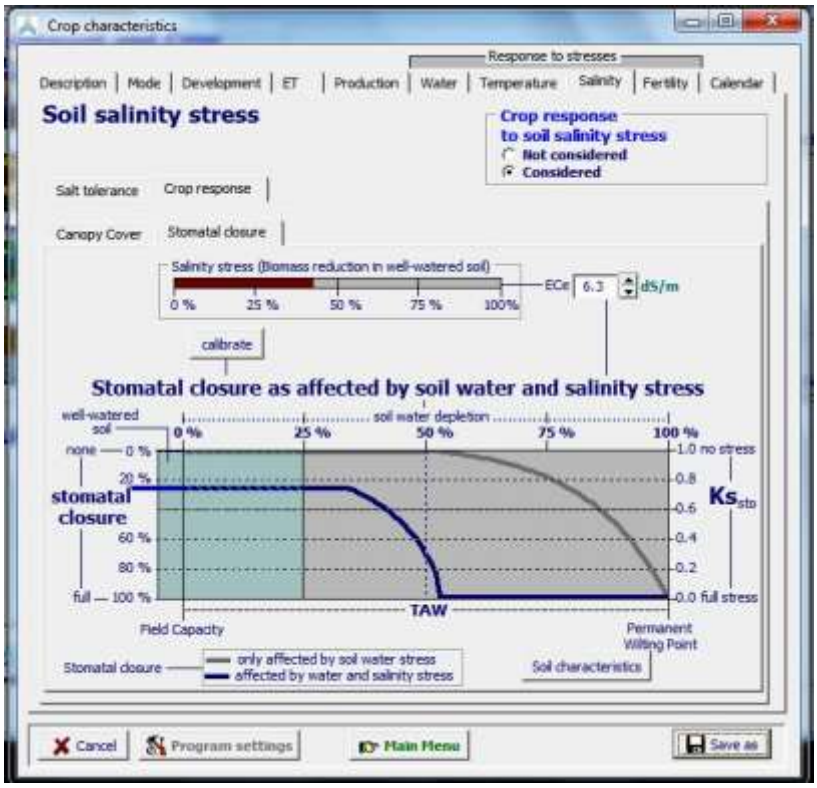


Figure 2.10n3

Stomatal closure for a soil salinity stress of 43% (ECe = 6.3 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**

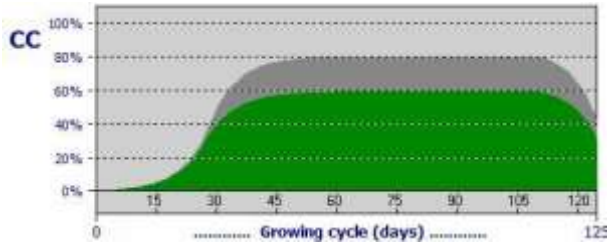
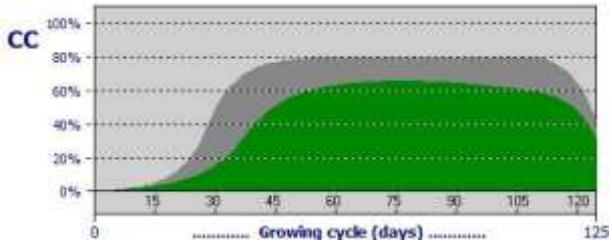
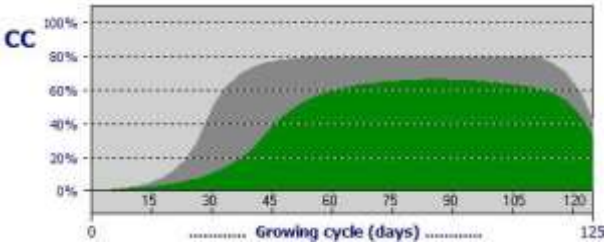
In a well-watered saline soil, and in the absence of any other stresses than salt stress, AquaCrop obtains the relative biomass production from the 'Biomass – ECe' relationship (Fig. 2.10n1). The reduction in biomass is the result of the integrated effect of four processes: (i) a slow canopy expansion, (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 CCx. 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 CCx (and a smaller degree of stomata closure). If only the reduction of the maximum canopy cover (CCx) is available from field observations, the plot of the CCx 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	

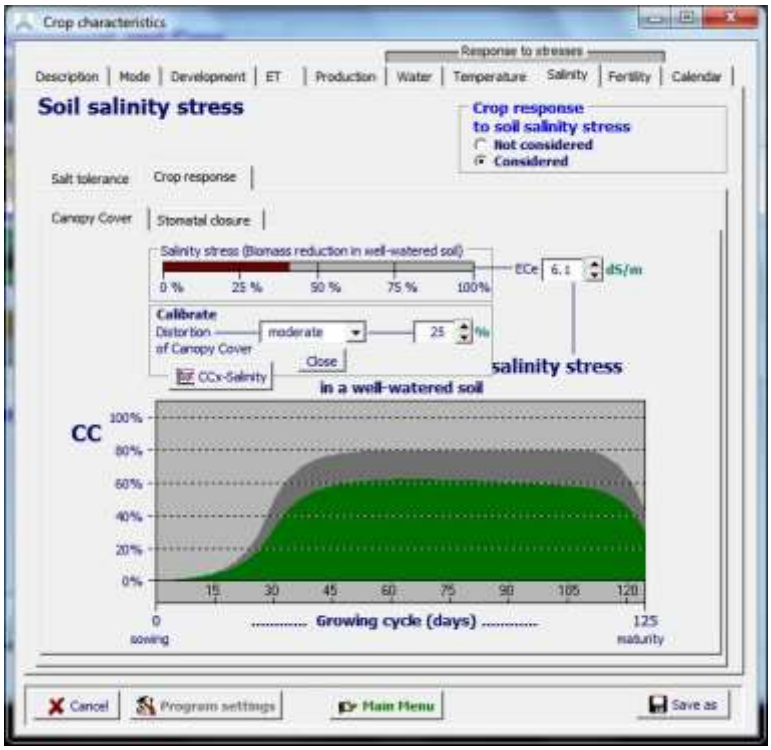


Figure 2.10p2 –The calibration of the effect of salinity stress on the development of the canopy cover in a well-watered soil, consists in selecting a class of canopy distortion or by specifying the percentage of the distortion in the 'Canopy Cover' tabular sheet.

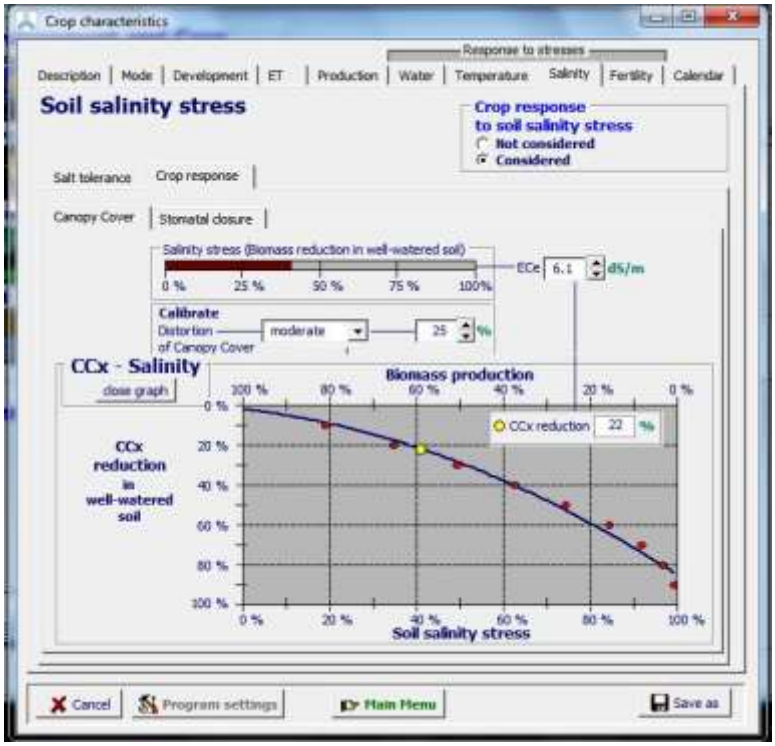


Figure 2.10p3 – Display of the effect of salinity stress on the reduction of the maximum canopy cover (CCx) in a well-watered soil in the 'Canopy Cover' tabular sheet. The percentage of stomatal closure in a well-watered soil is considered as identical.

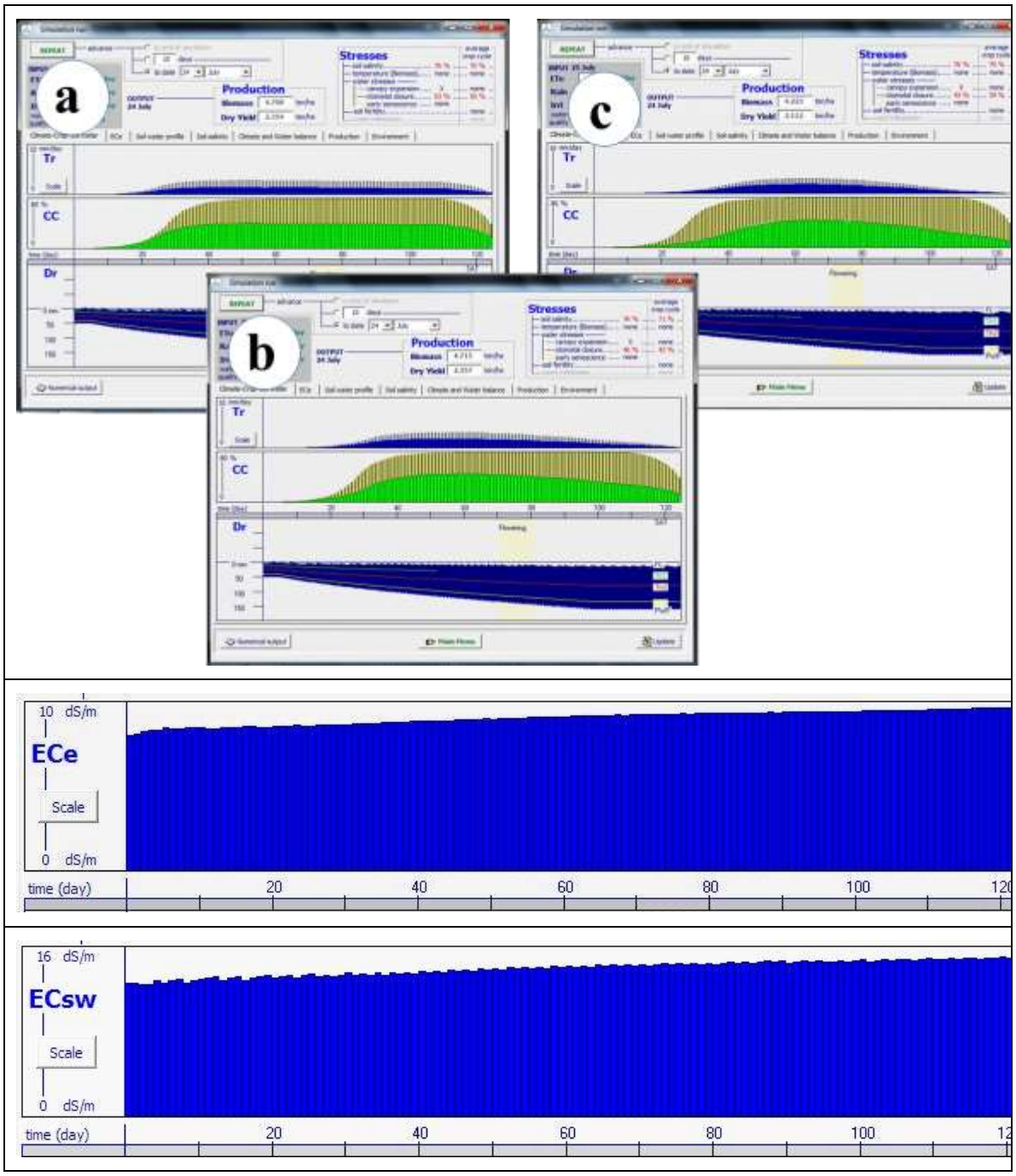


Figure 2.10p4 – Simulation of canopy development (CC) and biomass production and crop yield in a saline soil for (a) no canopy distortion, (b) an intermediate distortion of 50%, and (c) a very strong distortion of 100 %, and the corresponding Electrical Conductivity of the soil saturation extract (ECe)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

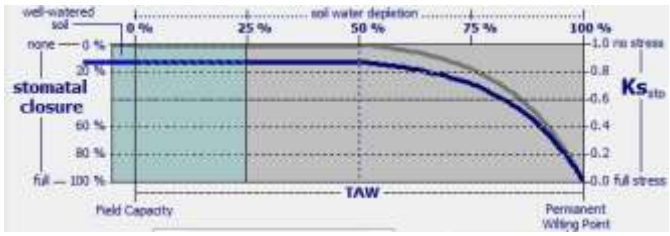
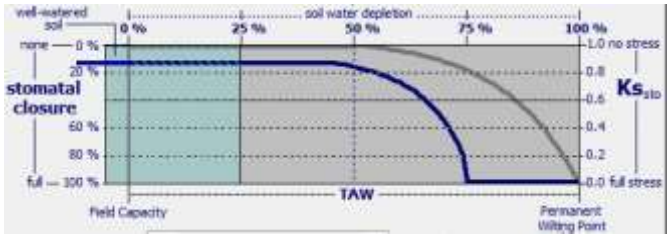
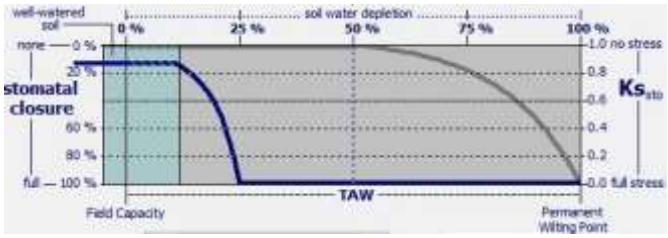
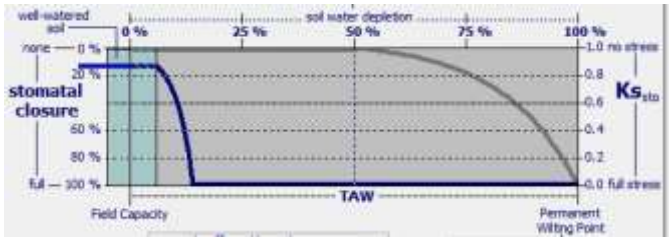
In each of the three simulations presented in Fig. 2.10p4, the salinity stress throughout the season remained fairly constant (70 %) and the biomass production was very similar (about 30 % of the production in the absence of any stress). In this example the loamy soil was well-watered by a very frequent 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 stomata 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 (ECsw). 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 ECsw		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	

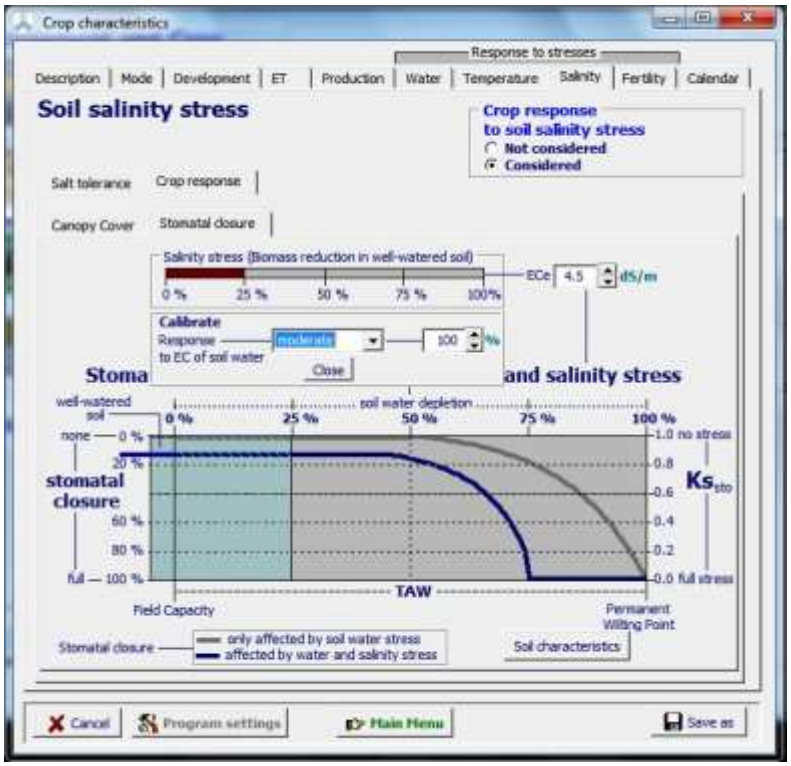


Figure 2.10p5 –The calibration of the effect on stomatal closure of salt concentration in a depleting root zone, consists in selecting a class of the response to the Electrical Conductivity of the soil water (ECsw) or by specifying the percentage of the response in the 'Stomatal closure' tabular sheet.

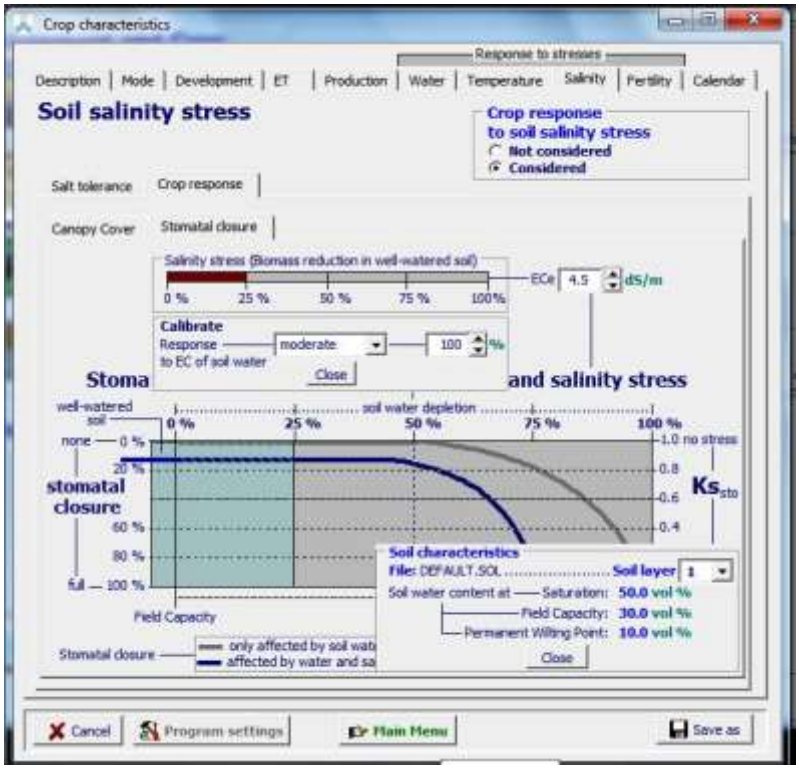


Figure 2.10p6 – Display of the soil physical characteristics of the soil layer for which the response to ECsw is valid.

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.

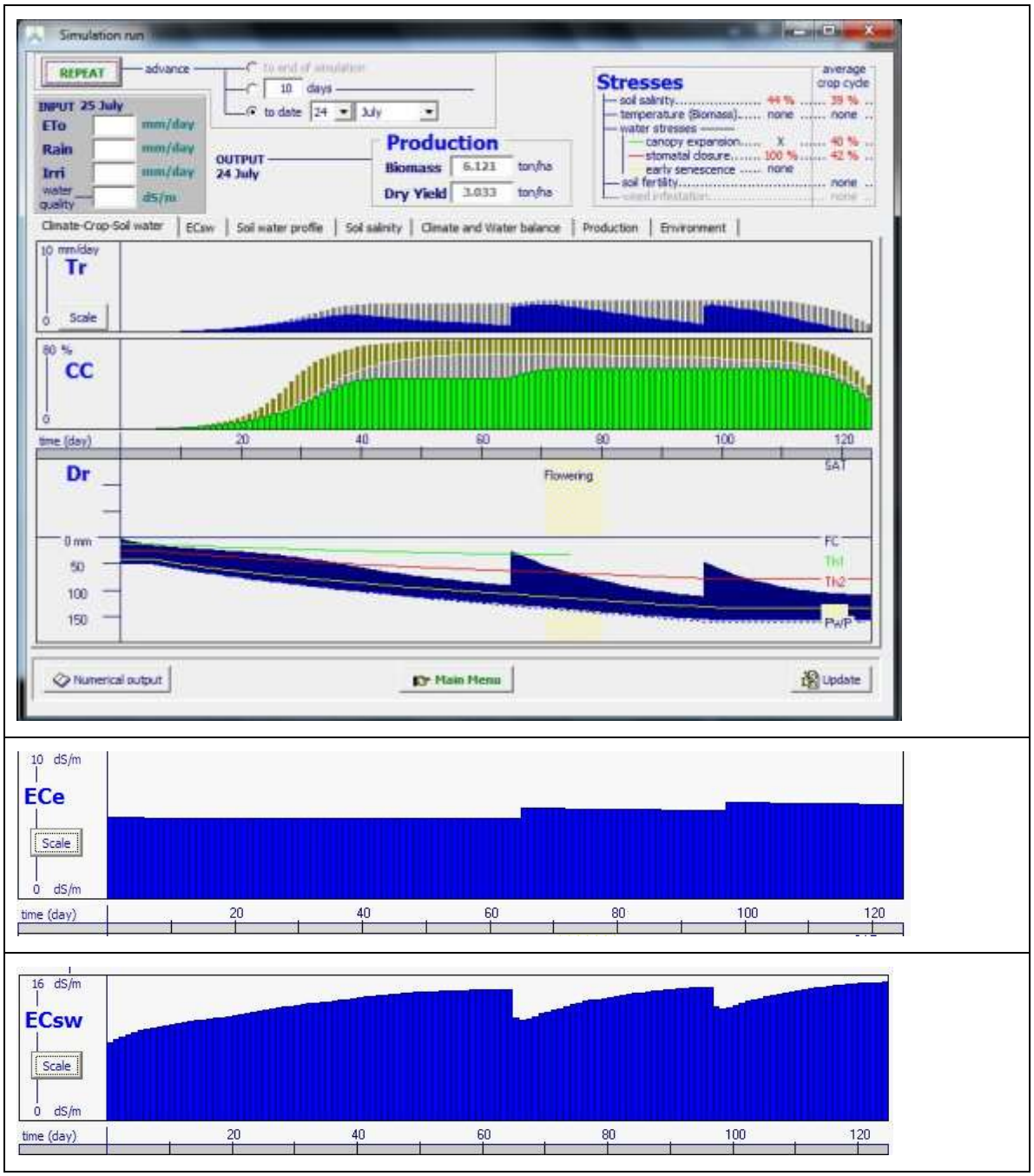


Figure 2.10p7 – Simulation of crop transpiration (Tr) and Canopy Cover (CC) in a saline soil with strong root zone depletions, and the corresponding simulated Electrical Conductivity of the soil saturation extract (ECe) and of the soil water (ECsw). The Canopy Cover that could have been reached in a 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 (ECe_n = 2 dS/m and ECe_x = 12 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 (ECsw) was selected as moderate (100%). At the start of the simulation process the whole soil profile was at Field Capacity, and soil salinity (ECe) 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 % (ECe 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 (annual and perennial crops)

- **Annual crops**

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 (if not yet defined by a calendar file – see 2.11 'Start of the growing cycle') and length of the different growth stages can be adjusted with the help of spin buttons.

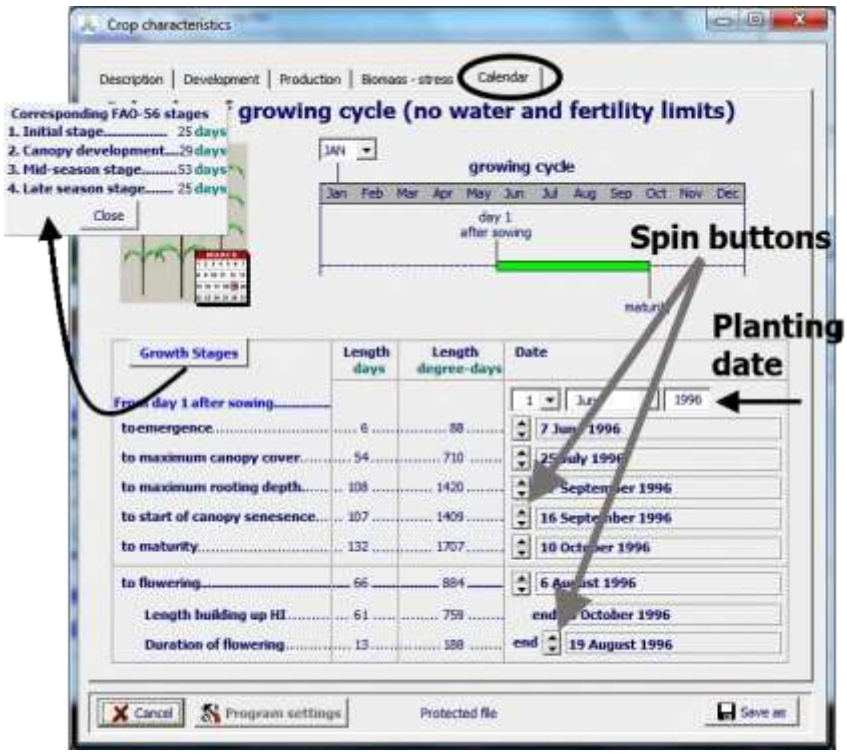


Figure 2.10q – Crop calendar to inspect of update the calendar of the growing cycle with indication of the FAO-56 growth stages

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 then 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.

- **Perennial herbaceous forage crops**

For perennial crops (herbaceous forage crops), the restart and end of growth is determined by crop characteristics and weather conditions for the selected year.

Only for the planting/sowing year, the observed or planned sowing/planting of the crop can be explicitly specified (in the absence of a calendar file), or generated with the help of a calendar file (See 2.11 'Start of the growing cycle'). For non-planting/sowing years, there is no way to explicitly adjust the growing period of perennial crops, since the restart and end of growth are automatically adjusted to the thermal regime of the simulation year by rules embedded in an internal calendar integrated in the crop file (see 2.10.16 'Internal crop calendar').

By clicking on the **<modify>** command at the bottom of the 'Calendar' tabular sheet of the ***Perennial crop characteristics*** menu, the user get access to the ***Internal crop calendar (perennial crops)*** menu (Fig.) in which the Restart and End of growth are specified (See 2.11 'Start of the growing cycle').

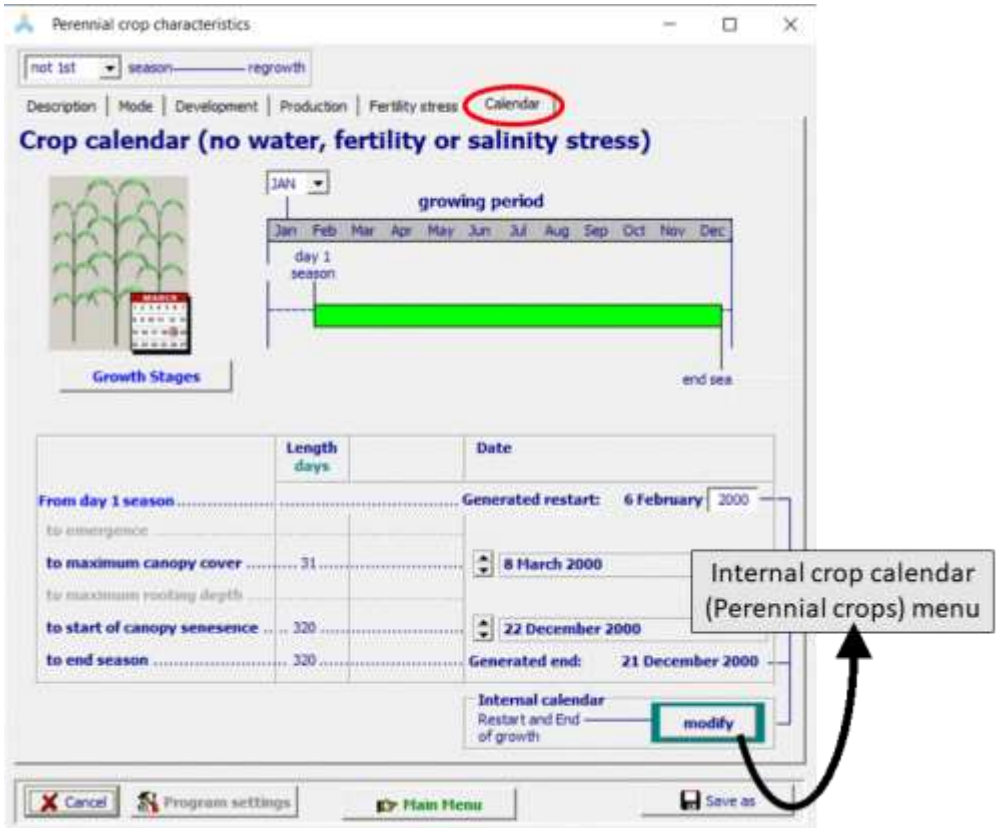


Figure 2.10q/b – The 'Calendar' tabular sheet in the *Perennial crop characteristics* menu, with access to the *Internal crop calendar (perennial crops)* menu

2.10.16 Internal crop calendar (perennial herbaceous forage crops)

- **Options for the Restart and End of growth**

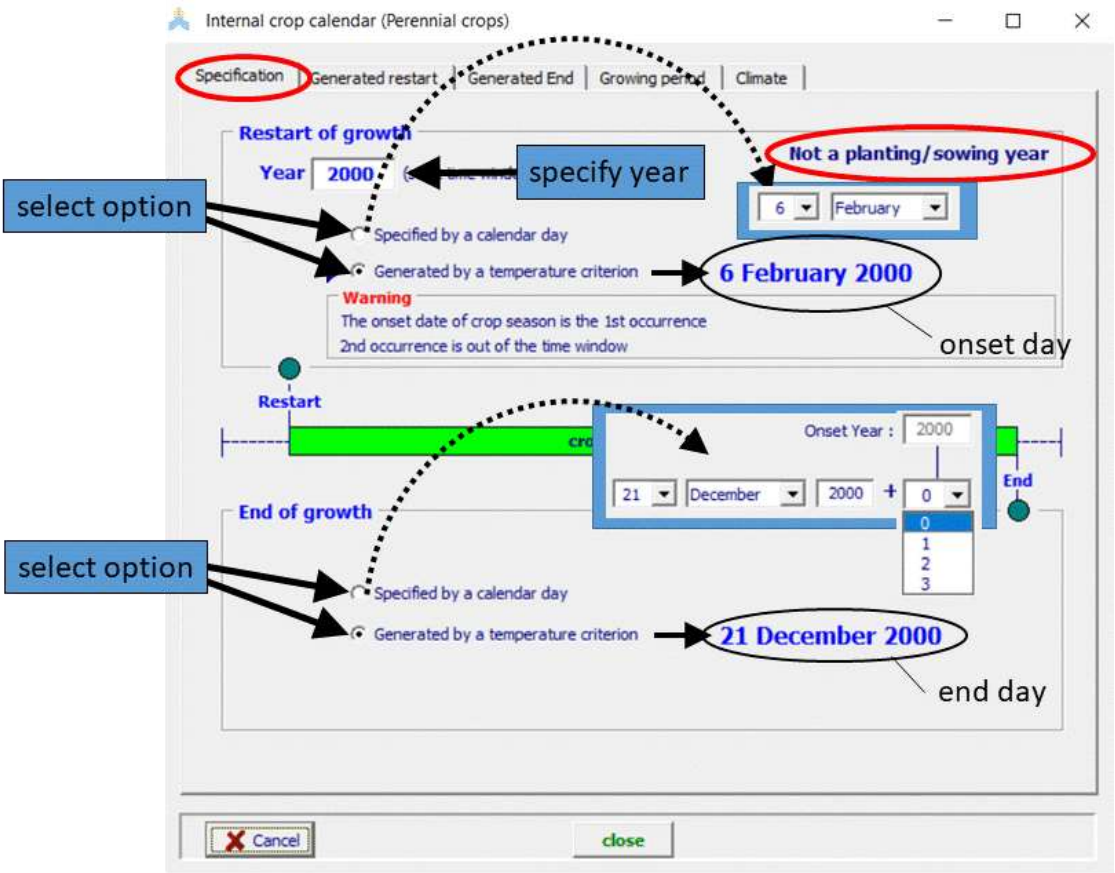


Figure 2.10r1 – The 'Specification' tabular sheet of the *Internal crop calendar* menu, in which a year is specified, options to specify the Restart and End can be selected, and the corresponding Restart and End of the growing period for the specified year are displayed

<u>Year:</u>

A non-planting/sowing year is always assumed in the ***Internal crop calendar*** **menu** (Fig. 2.10r1). For a planting/sowing year, the user can specify in the ***Main Menu*** the day of the observed or planned sowing/planting (in the absence of a calendar file), or generate a date with the help of a calendar file (See 2.1 'Start of the growing cycle').

A date specified in the internal crop calendar consists only of a day and month (e.g. 6 February) and is not linked to a specific year. Also rules to generate the Restart and End of growth do not change with the selected year.

Nevertheless, a year can be specified in ***Internal crop calendar*** menu, since this allows the user to evaluate changes in the crop calendar due to varying weather conditions in the years. The program generates and displays the corresponding Restart and End of growth for the selected (non-planting/sowing) year.

The Restart of growth (for a non-planting/sowing year):

The options to specify the restart of growth are:

- **Specified by a pre-set calendar day**: When selecting this option, a panel becomes visible in which the user can specify the day and month at which the growth will always restart in a non-planting/sowing year (Fig. 2.10r1);
- **Generated by a Temperature criterion**: With this option the restart of growth is adjusted to the thermal regime of the selected year. The option might be suitable not only for the current years but also for future years, since climate change is likely to increase the air temperature in many regions.

The End of growth:

The options to specify the End of growth are applicable to both the first year in which the crop is sown or planted and for non-planting/sowing years:

- **Specified by a pre-set calendar day**: When selecting this option, a panel becomes visible in which the user can specify the day and month at which the growth will always stop in a year (Fig. 2.10r1). Additionally, extra years can be specified in this panel, if the growing period spans over several years;
- **Generated by a Temperature criterion**: With this option the end of growth is adjusted to the thermal regime of the selected year. The option might be suitable not only for current years but also for future years, since climate change is likely to increase the air temperature in many regions.

- **Generated Restart of growth based on air temperature**

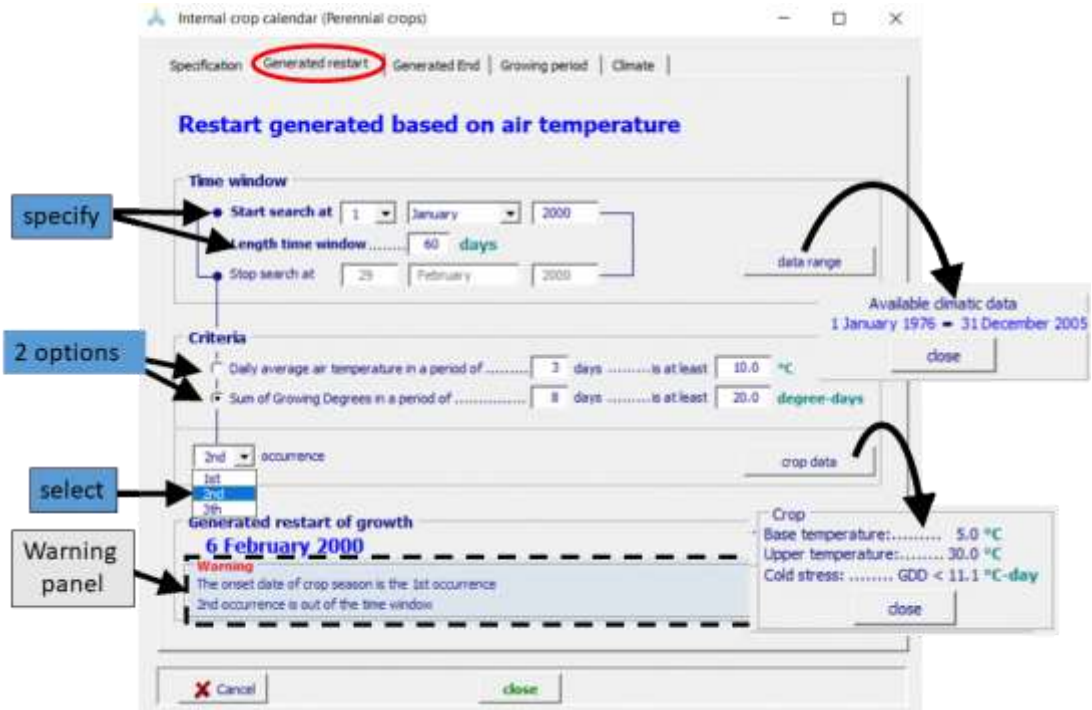


Figure 2.10r2 – The 'Generated restart' tabular sheet in which the Restart of growth is determined by the 2nd occurrence when the sum of the growing degrees in a period of 8 days is at least 20 degree-days, counting from 1 January (start of the time window) for the year 2000

Data range:

By clicking on the **<data range>** command, AquaCrop displays the time range for which climatic data is available in the climate file.

Time window:

By selecting one or another Temperature criterion, the restart of growth is determined by appraising the air temperature data specified in the selected Air temperature data file for the selected year. By specifying the first day and the length of a time window at the top of the Menu, only air temperature within the specified window are evaluated (Fig. 2.10r2).

Air temperature criteria:

The following two criteria are available to determine the Start of growth based on air temperature, within the specified time window:

- The ***daily average air temperature***, in each day of a given number of successive days, is equal to or exceeds the pre-set average air temperature;

- The ***sum of Growing Degrees in a number of successive days*** is equal to or exceeds the pre-set growing degree days.

The options with growing degree-days are crop specific, since they are obtained from the mean air temperature (climate specific) by considering the base and upper temperature for crop development (crop specific).

Crop data:

By clicking on the **<crop data>** command, AquaCrop displays the base and upper temperature for crop development and the threshold, in growing-degrees per day, below which crop transpiration starts to be affected (crop specific).

Occurrence:

The first occurrence of the Restart is the first day for which the selected criterion holds in the specified time window for the selected year. To avoid the generation of a restart in the early stages of the spring where air temperature might still drop sharply after an early start, AquaCrop offers also the option to select a 2nd or even a 3rd occurrence for the selected criterion.

Rules and Warning messages:

If a Restart cannot be generated within the specified time window for the selected year, the last day of the time window is selected as the Restart day. A warning will appear in a Panel, explaining why the criterion could not be met, and which Restart day was selected (last day of the time window).

When before the end of the time window a 2nd or 3rd occurrence is not yet encountered, AquaCrop selects the last occurrence which was met in the time window. A warning will appear in a Panel, explaining why an earlier occurrence was selected, and which occurrence was finally selected.

- **Generated End of growth based on air temperature**

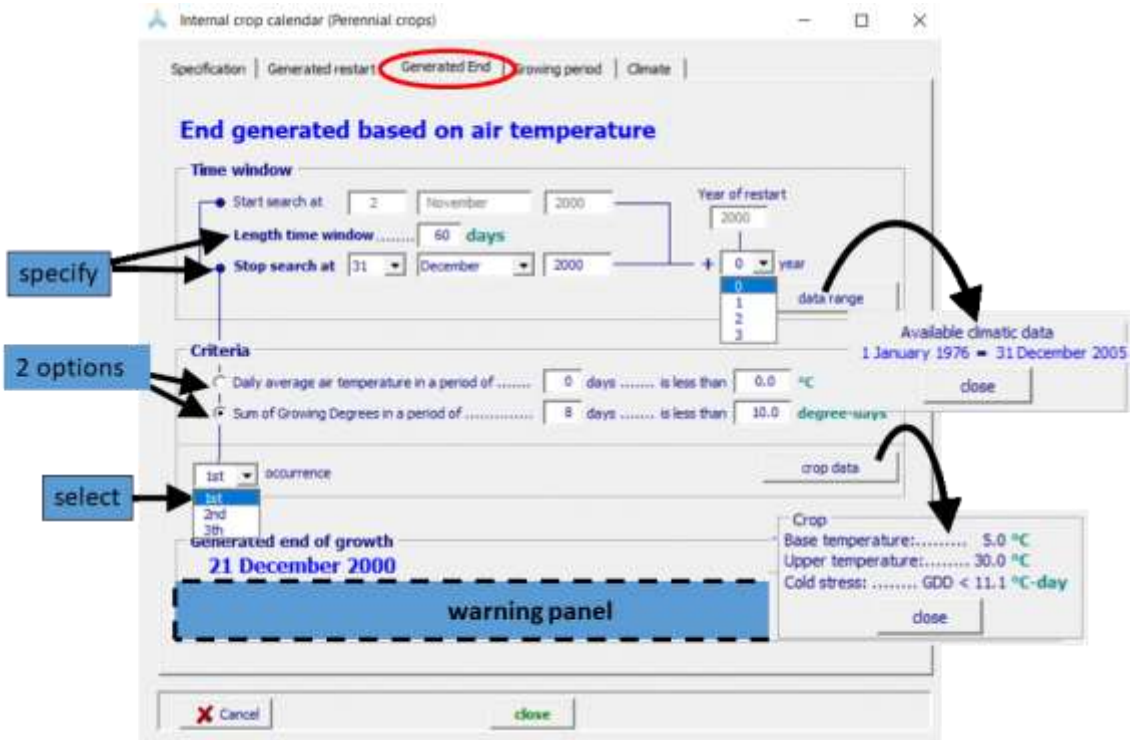


Figure 2.10r3 – The 'Generated End' tabular sheet in which the End of growth is determined by the 1st occurrence when the sum of the growing degrees in a period of 8 days is less than 10 degree-days, counting from 2 November (start of the time window) for the year 2000

<u>Data range:</u>
By clicking on the **<data range>** command, AquaCrop displays the time range for which climatic data is available in the climate file.

<u>Time window:</u>
By selecting one or another Temperature criterion, the end of the growth is determined by appraising the air temperature data specified in the selected Air temperature data file for the selected year. By specifying the last day and the length of a time window at the top of the Menu, only air temperature within the specified window are evaluated. Additionally, extra years can be specified in this panel, if the growing period spans over several years (Fig. 2.10r3).

Air temperature criteria:

The following two criteria are available to determine the End of growth based on air temperature, within the specified time window

- The ***daily average air temperature***, in each day of a given number of successive days, is less than the pre-set average air temperature;
- The ***sum of Growing Degrees in a number of successive days*** is less than the pre-set growing degree days.

The options with growing degree-days are crop specific, since they are obtained from the mean air temperature (climate specific) by considering the base and upper temperature for crop development (crop specific).

Crop data:

By clicking on the **<crop data>** command, AquaCrop displays the base and upper temperature for crop development and the threshold, in growing-degrees per day, below which crop transpiration starts to be affected (crop specific).

Occurrence:

The first occurrence of the End date is the first date for which the selected criterion holds in the specified time window for the selected year. AquaCrop offers also the option to select a 2nd or even a 3rd occurrence for the selected criterion, to avoid a premature ending of the growing period during a cold period before the real end of the season.

Rules and Warning messages:

If an End day cannot be generated within the specified time window for the selected year, the last day of the time window is selected as the End day. A warning will appear in a Panel, explaining why the criterion could not be met, and which End day was selected (last day of the time window).

When before the end of the time window a 2nd or 3rd occurrence is not yet encountered, AquaCrop selects the last occurrence which was met in the time window. A warning will appear in a Panel, explaining why an earlier occurrence was selected, and which occurrence was finally selected.

- **The 'Growing period' tabular sheet**

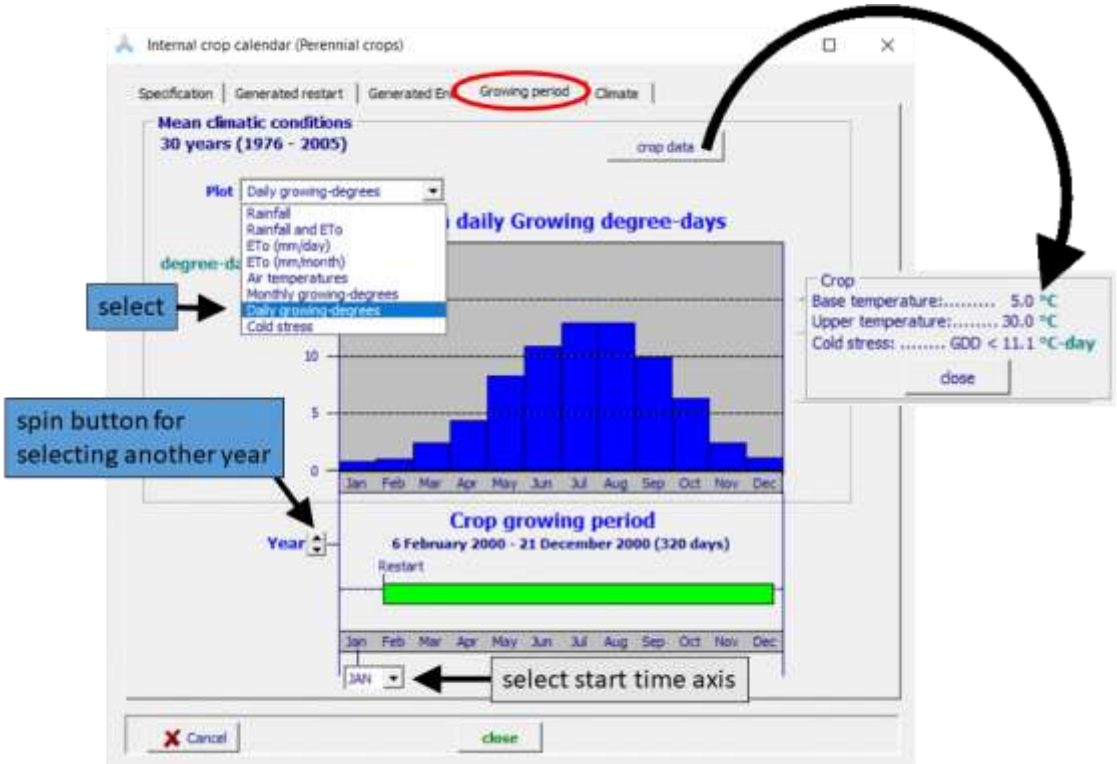


Figure 2.10r4 – The 'Growing period' tabular sheet of the *Internal crop calendar* menu, in which the generated growing period for the selected year, together with selected mean monthly climatic conditions, are plotted

In the 'Growing period' tabular sheet of the ***Internal crop calendar*** menu, the growing period for the selected year is plotted as a green bar on a time axis (Fig. 2.10r4). At the top of the tabular sheet, mean monthly climatic data for the selected climate are plotted. The following plots can be selected:

- Mean monthly rainfall (mm/month)
- Mean monthly rainfall together with the mean monthly ETo (mm/month)
- Mean monthly ETo in mm/day
- Mean monthly ETo in mm/month
- Mean monthly minimum and maximum air temperature (°C)
- Mean monthly growing degrees expressed as a daily average
- Monthly growing-degrees
- Cold stress (%) affecting the crop transpiration

Growing degree-days and cold stress are crop specific, since they are obtained from the mean air temperature (climate specific) by considering the base and upper temperature for crop development and the threshold for cold stress affecting crop transpiration (crop specific).

With the help of the spin button, other years can be selected. With a generated Restart and End of growth, the growing period will stretch or shorten according to the temperature regime of the selected year. The option allows the user to evaluate changes

in the growing period due to the varying weather conditions in the selected year, and when required to strengthen or weaken the threshold values or periods for the selected criterion. As an example, the generated restart and end of growth with the growing degree criterion is listed for the various years of the Brussels data set, in Table 1.

Table 2.10.r – Generated Restart and End of growth, and the corresponding length of the growing period for the various years of the Brussels climatic data set

Restart of growth criterion: 2nd occurrence when the sum of growing-degree days exceeds 20 degree-days in a period of 8 days, in a time window of 60 days starting from 1 January (Fig. 11);

End of growth criterion: 1st occurrence when the sum of growing-degrees days is less than 10 degree-days in a period of 8 days, in a time window of 60 days, ending at 31 December (Fig. 12).

Year	Restart	End	Length (days)		Year	Restart	End	Length (days)
1976	24 Feb	21 Nov	272		1991	27 Feb	16 Nov	263
1977	25 Feb	21 Nov	270		1992	29 Feb	19 Nov	265
1978	27 Feb	1 Dec	278		1993	20 Jan	19 Nov	304
1979	1 Mar	16 Nov	261		1994	1 Mar	21 Dec	296
1980	10 Feb	10 Nov	275		1995	20 Feb	5 Dec	289
1981	1 Mar	13 Nov	258		1996	14 Jan	17 Nov	309
1982	13 Feb	2 Dec	293		1997	1 Mar	26 Nov	271
1983	31 Jan	18 Nov	292		1998	14 Jan	18 Nov	309
1984	29 Feb	10 Dec	286		1999	7 Jan	18 Nov	316
1985	1 Mar	17 Nov	262		2000	6 Feb	21 Dec	320
1986	1 Mar	4 Dec	279		2001	9 Feb	16 Nov	281
1987	1 Mar	10 Nov	255		2002	31 Jan	7 Dec	311
1988	7 Jan	10 Nov	309		2003	1 Mar	10 Dec	285
1989	1 Mar	29 Nov	274		2004	7 Feb	14 Nov	282
1990	9 Feb	10 Nov	275		2005	11 Jan	20 Nov	314

- **The 'Climate' tabular sheet**

Air temperature, rainfall, and ETo data for the selected climate is displayed when selecting the <**Display Climate characteristics**> command key in the 'Climate' tabular sheet of the ***Internal crop calendar*** menu (Fig. 2.10r6).

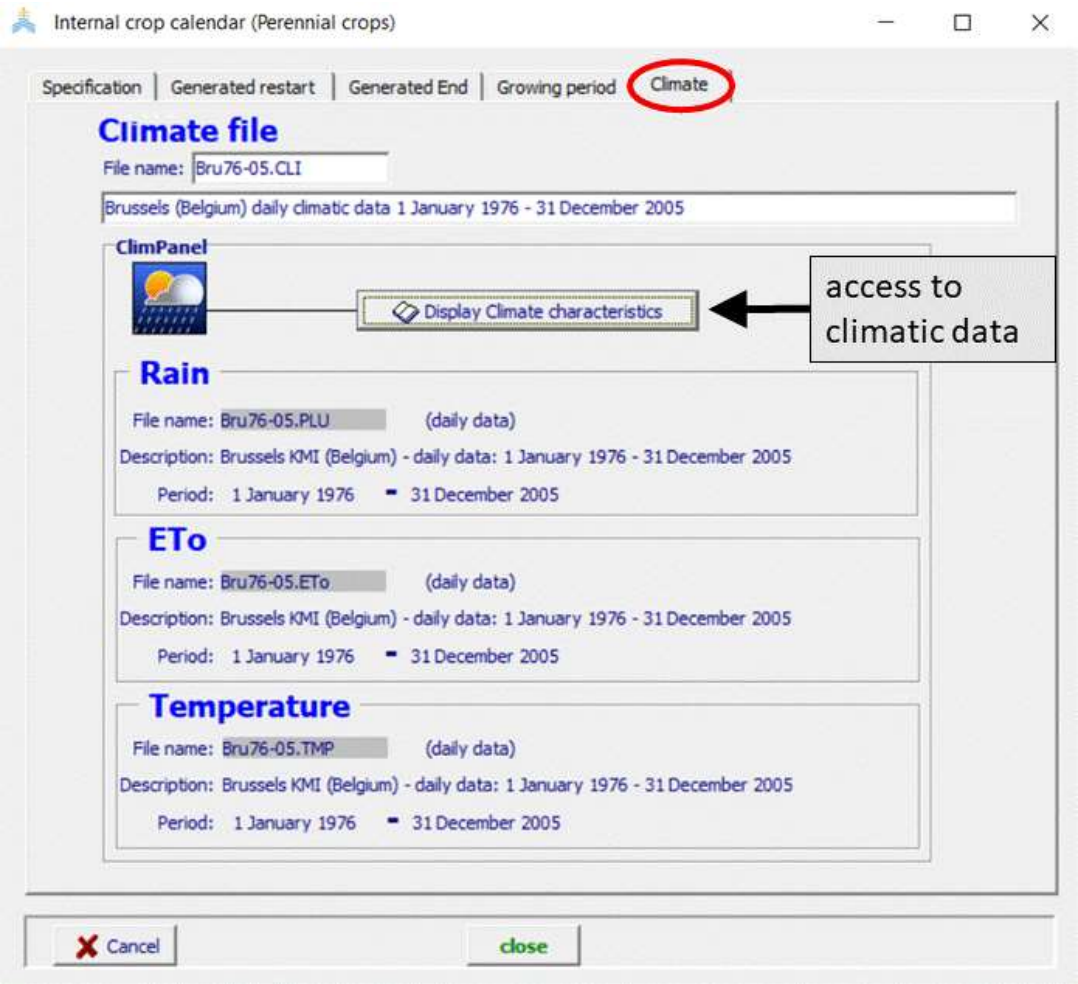


Figure 2.10r5 – The 'Climate' tabular sheet of the *Internal crop calendar* menu, with access to the climatic data for the selected climate

- **Automatic adjustment of growing period to the thermal regime of the year of simulation**

When the Restart and End of growth are generated, the length of the growing period will automatically adjust to the weather conditions for each year of simulation. It considers thereby the rules embedded in the internal crop calendar.

The automatic adjustment consists in stretching or shortening the length of the mid-season in agreement with the generated length of the growing period for the year of simulation (Fig. 2.10r6). Also the start of canopy senesce is adjusted by moving it upwards or downwards in time, respecting thereby the time between senescence and the end of the growing period as specified in the Crop file (in days or growing degree-days). Additionally, the length of the yield formation period is brought in line with the adjusted length of the growing period.

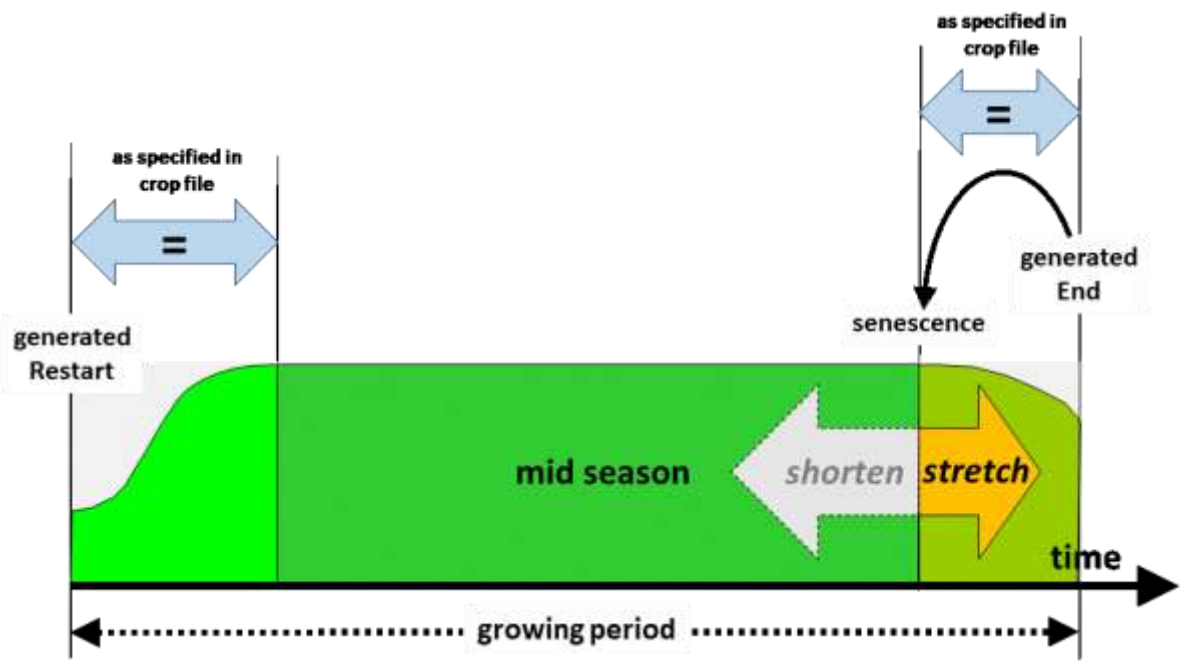


Figure 2.10r6 – Adjustment of the growing period by stretching or shortening the mid-season

2.10.17 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 2.10s – Program settings affecting soil evaporation, crop transpiration, crop development, production and the effect of water and salinity stresses

Symbol	Program parameter	Default
	Soil evaporation	
f_K	▪ Evaporation decline factor for stage II	4
Ke_x	▪ Soil evaporation coefficient for fully wet and non-shaded soil surface	1.10
	Harvest Index	
-	▪ Threshold for green canopy cover below which HI can no longer increase due to inadequate photosynthesis (% cover)	5 %
	Germination	
-	▪ Minimal soil water content required for germination at sowing depth (% TAW)	20 %
	Root zone	
Z_o	▪ Starting depth of the root zone expansion curve (% of minimum effective rooting depth)	70 %
-	▪ Shape factor for the curve describing the effect of water stress (relative transpiration) on root zone expansion	-6
	Senescence	
-	▪ Shape factor (exponent a) for an adjustment factor of Kcb_x, considering the drop in photosynthetic activity of dying crop	1
β	▪ Decrease of p(sen) once canopy senescence is triggered (% of p(sen))	12 %
	Stresses	
-	▪ Aeration stress: Number of days after which deficient aeration is fully effective	3 days
f_{adj}	▪ Water stress: Adjustment factor for the ETo correction of the soil water depletion (p) (fraction of default FAO-adjustment)	1.0
Ztop	***Top soil***	
	▪ Considered thickness of top soil for the estimate of soil water stress in the top of the soil profile	10 cm

2.10.18 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 2.10t – 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

In irrigated agriculture, the planting/sowing date changes little over the years, but in rainfed cropping, crops will only be sown or planted when the top soil is sufficient wet at the start of the rainy season. In a cool climate, crops are typically sown or planted when the weather has warmed up sufficiently.

To determine the likely time of planting in the various years of a simulation run, the onset (a) can be specified directly or (b) a crop calendar file can be loaded in which the onset day is generated based on one or another Rainfall or Air temperature criterion, or can be fixed on a pre-set day.

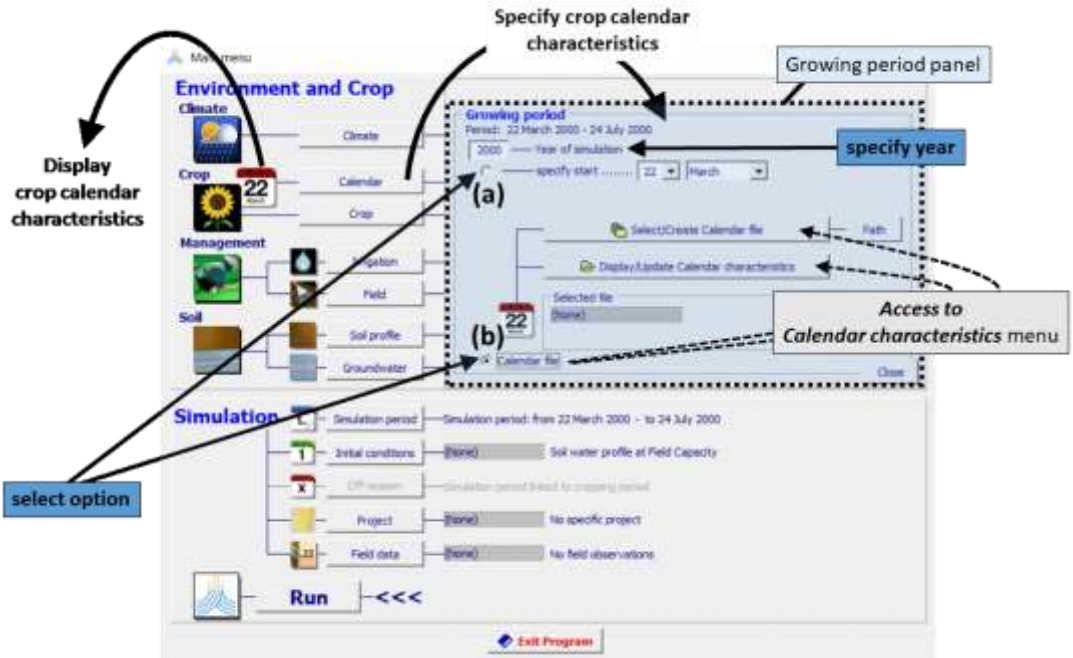


Figure 2.11a – The 'Growing period' panel in the *Main menu*, in which the Year of simulation is specified, and an option is selected (a) to either specify directly the start of the growing period or (b) to select or create a calendar file by which the onset will be generated for a planting/sowing year.

When selecting the <**Calendar**> command in the ***Main menu***, AquaCrop offers the possibility (Fig. 2.11a):

a) to specify directly the day of the observed or planned start of the growing period (in the absence of a crop calendar file), or
b) to select or create a crop calendar file containing a pre-set Onset day or rules for generating an onset based on weather conditions for the selected year.

In the 'Growing period' panel, also the year for the simulation is specified.

Since the information in a crop calendar file is not linked to a specific year, the Onset day automatically adjusts to the weather conditions, each time the year of simulation in the 'Growing period' panel of the ***Main menu*** is changed.

Once the planting/sowing is determined, the length of the growing period of the **annual crops** is given by the time required to reach maturity, which is specified in calendar or growing degree-days in the crop file (Fig. 2.11b). When running a simulation in growing degree-days (GDD), the growing period will be longer in a cold year and shorter in a warm year.

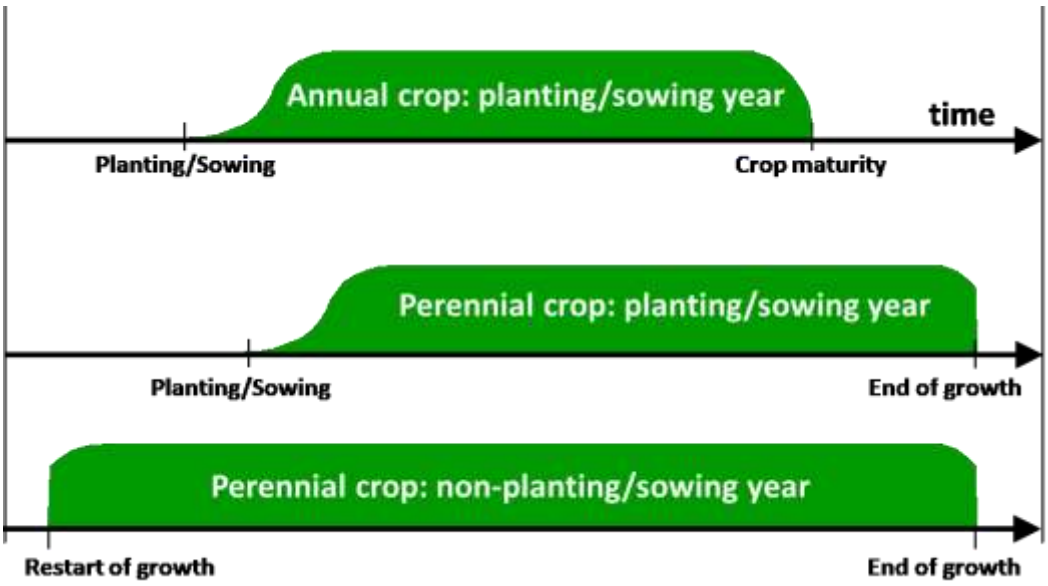


Figure 2.11b – The growing period for annual and perennial crops in two types of years

For **perennial crops**, the observed or planned start of the growing period can also be specified or generated with the help of a calendar file, but only for the planting/sowing year. The restart of growth in a non-planting/sowing year and the end of growth cannot be explicitly specified since they are determined by crop characteristics and weather conditions of the selected year (Fig. 2.11b). Rules embedded in an internal calendar integrated in the crop file specify these dates (see Section 2.10.16 'Internal crop calendar (perennial herbaceous forage crops'). AquaCrop will automatically adjust the restart and end of growth to the thermal regime of the simulation year. The growing period consequently will stretch in a warmer year and shorten in a cooler year.

When a perennial crop file is loaded, AquaCrop adjusts automatically the start and end of the growing period by considering the rules specified in the internal crop calendar and the climatic data for the simulation year. For a seeding/planting year the start of the growing period is either given by a Calendar file or specified as input.

In the ***Main menu***, the user specifies the year number of the lifetime of the perennial crop (Fig. 2.11b/2). Year 1, is the seeding/planting year.

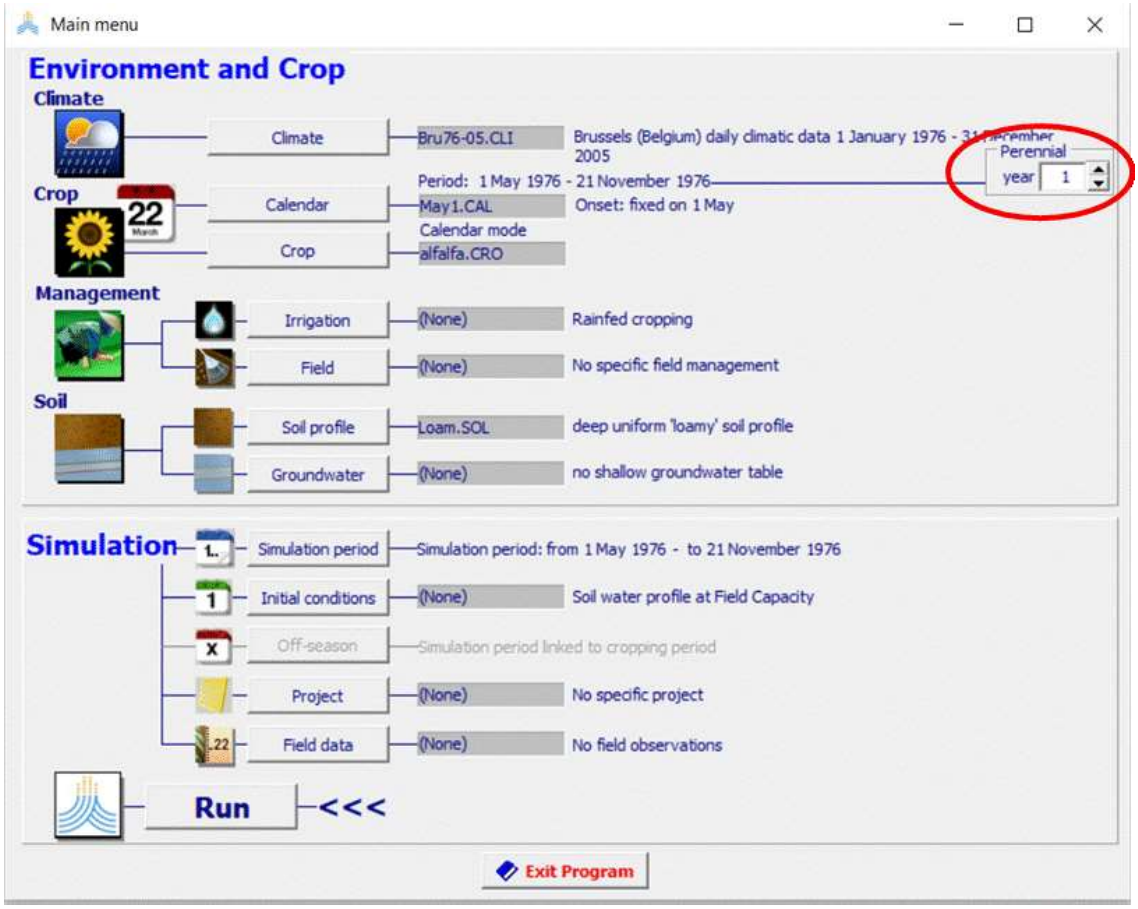


Figure 2.11b/2 – Specification of the year number of the lifetime of the perennial crop in the *Main menu*.

2.11.1 Display of crop calendar characteristics

By clicking on the calendar icon (Fig. 2.11a), the crop calendar characteristics are displayed in the 'calendar' tabular sheet of the ***Display of crop calendar characteristics*** menu (Fig. 2.11c).

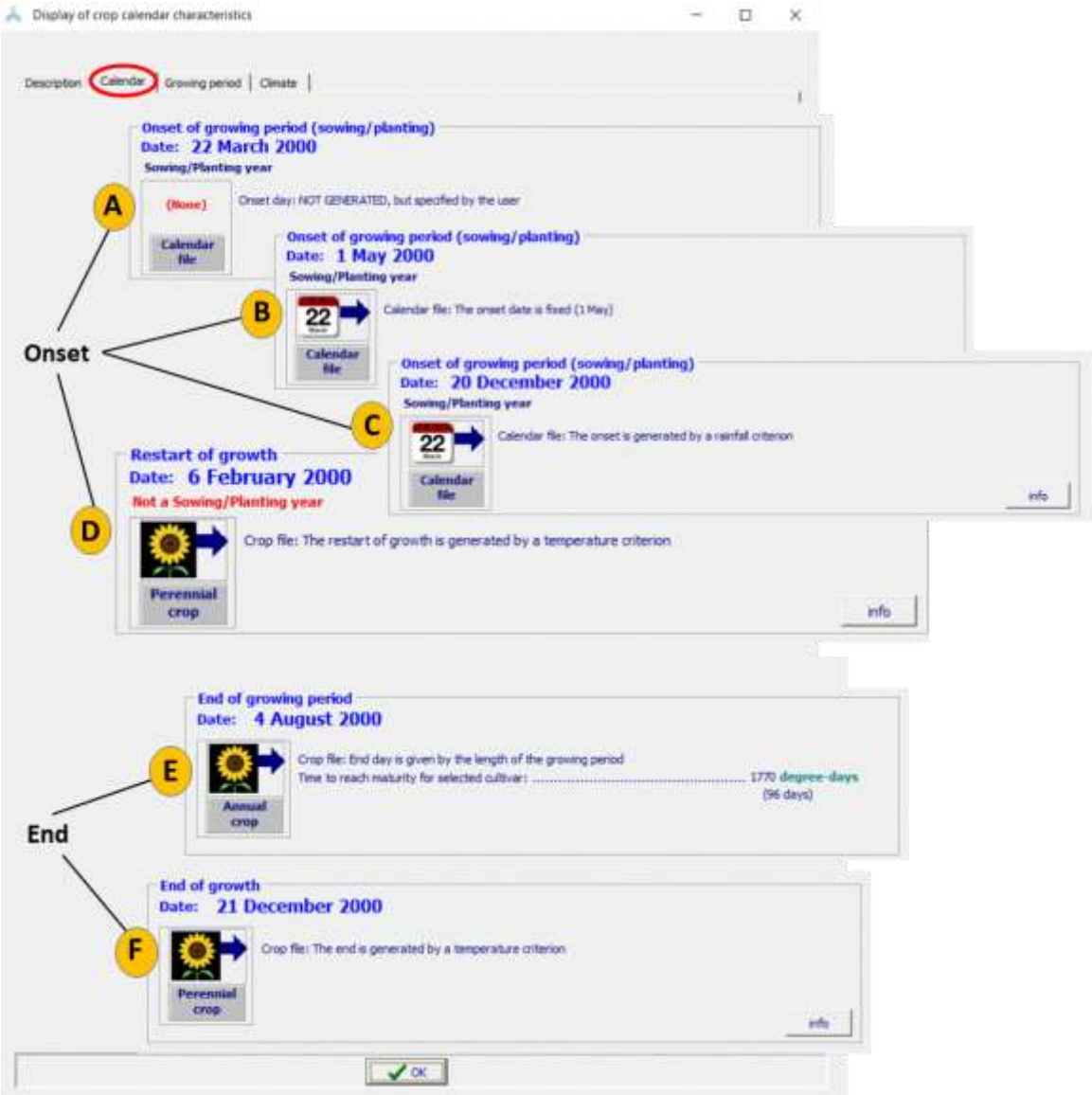


Figure 2.11c – Possible displays for the Onset and End of the growing period in the 'Calendar' tabular sheet of the *Display of crop calendar characteristics* menu, for the simulation year

Possible displays for the Onset and End of the growing period in the 'Calendar' tabular sheet of the *Display of crop calendar characteristics* menu, for the simulation year (Fig. 2.11c) are:

- **Onset for a sowing/planting year (annual or perennial crop):**
  - A. Onset directly specified by the user (no crop calendar file);
  - B. Onset is fixed on a pre-set day specified in the crop calendar file;
  - C. Onset is generated by rules specified in the crop calendar file;

- **Onset for a non-sowing/planting year (perennial crop):**
  - D. Generated restart of growth of a perennial crop (by internal crop calendar integrated in the perennial crop file);

- **End for an annual crop:**
  - E. Given by the time to reach maturity (specified in crop file);

- **End for a perennial crop:**
  - F. Generated end of growth of a perennial crop (by internal crop calendar integrated in the perennial crop file).

In the 'Growing period' tabular sheet of the ***Display of crop calendar characteristics*** menu, the growing period for the selected year is plotted as a green bar on a time axis (Fig. 2.11d).

At the top of the tabular sheet, mean monthly climatic data for the selected climate are plotted. The following plots can be selected:
- Mean monthly rainfall (mm/month)
- Mean monthly rainfall together with the mean monthly ETo (mm/month)
- Mean monthly ETo in mm/day
- Mean monthly ETo in mm/month
- Mean monthly minimum and maximum air temperature (°C)
- Mean monthly growing degrees expressed as a daily average
- Monthly growing-degrees
- Cold stress (%) affecting the crop transpiration

Growing degree-days and cold stress are crop specific, since they are obtained from the mean air temperature (climate specific) by considering the base and upper temperature for crop development and the threshold for cold stress affecting crop transpiration (crop specific).

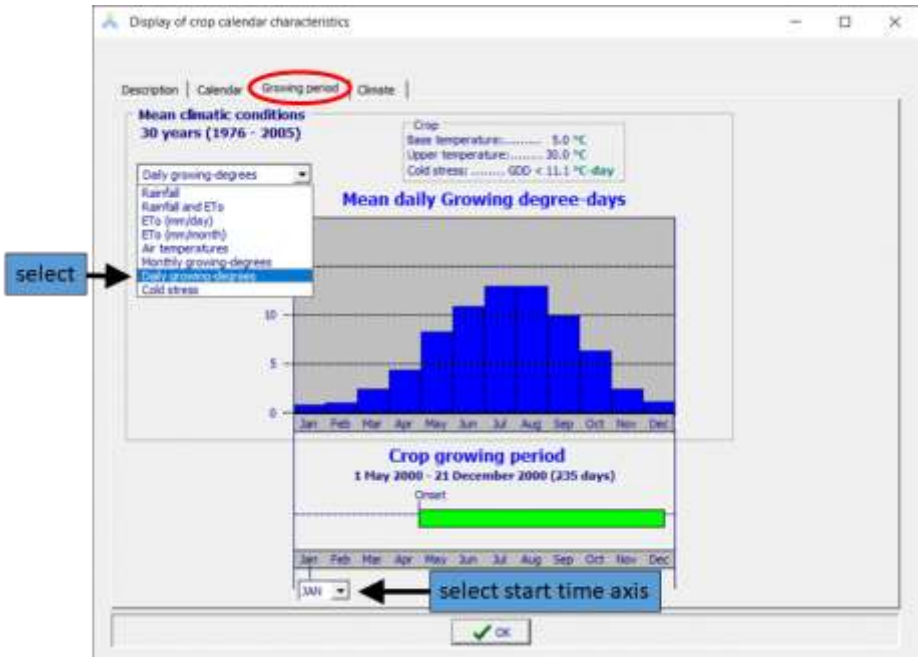


Figure 2.11d –The 'Growing period' tabular sheet of the Display of crop calendar characteristics menu, in which the generated growing period for the selected year, together with selected mean monthly climatic conditions, are plotted

2.11.2 Specifying directly the onset in the Main menu

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.

2.11.3 Crop calendar file

A crop calendar file contains either a pre-set fixed Onset day or information to generate an Onset day by a Rainfall or Air temperature criterion for the year in which the annual/perennial crop is sown/planted. Since the information in a crop calendar file is not linked to a specific year, the generated Onset day will automatically adjust to the weather conditions each time the simulation year in the 'Growing period' panel of the ***Main menu*** is changed.

After selecting or creating a Crop calendar file in the ***Main menu*** (Fig. 2.11a), the calendar characteristics are displayed and can be updated in the ***Crop calendar characteristics*** menu (Fig. 2.11e).

- **Options to determine the onset in a planting/sowing year**

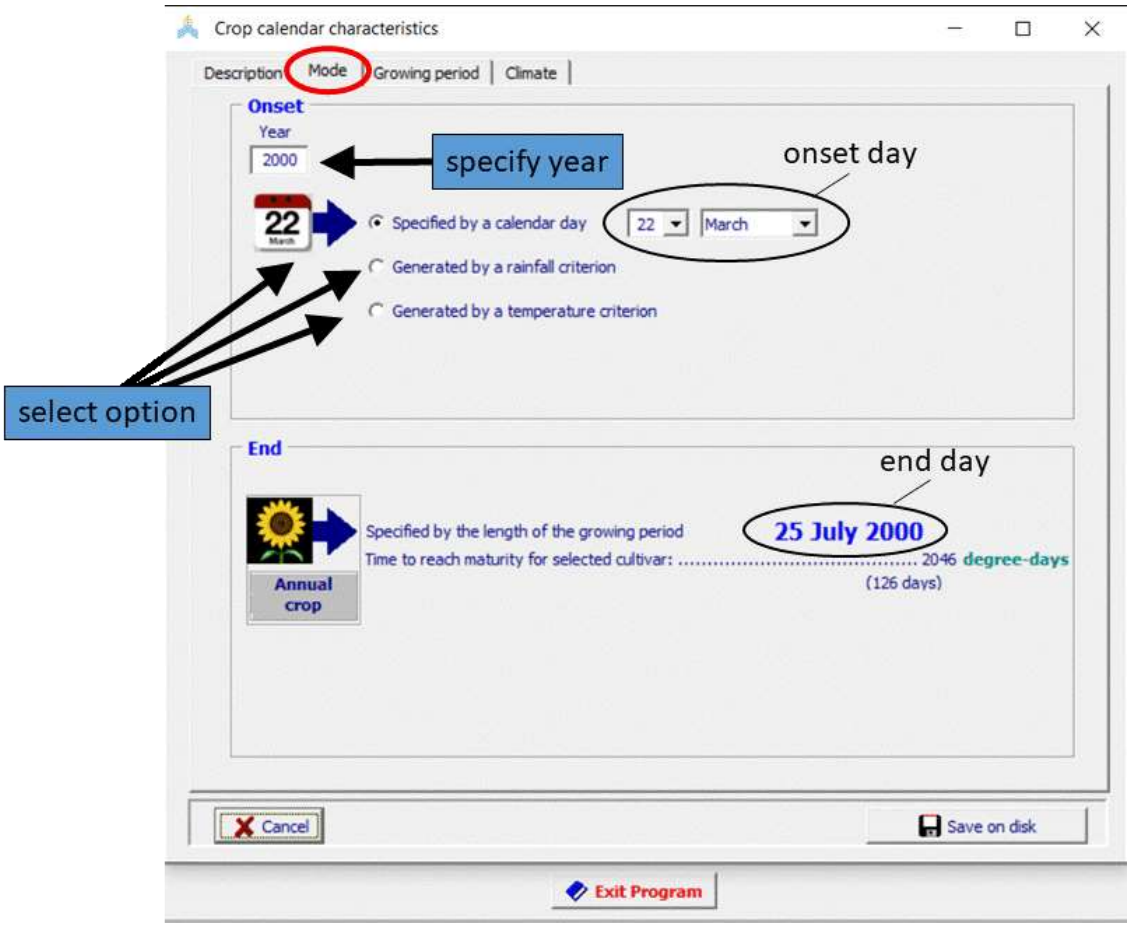


Figure 2.11e – The 'Mode' tabular sheet of the crop calendar characteristics menu, in which a year can be specified, options to specify the Onset can be selected, and the corresponding Onset and End of the growing period for the specified year are displayed.

<u>Year:</u>
A date specified in a crop calendar file consists only of a day and month (e.g. 22 March) and is not linked to a specific year. Also rules to generate an Onset do not change with the selected year.

Nevertheless, a year can be specified in the ***Crop calendar characteristics*** menu., since this allows the user to evaluate changes in the crop calendar due to varying weather conditions in the years. The program generates and displays the corresponding Onset and End of the growing period for the selected year.

The Onset of the growing period:

The options to specify the Onset day are:

- **Specified by a calendar day**: If a pre-set Onset day (Day & Month) is saved in the calendar file, the growing period will always start at the same day in each year of the simulation;
- **Generated by a Rainfall criterion**: This option might be useful for determining a likely sowing or planting date for rainfed crops at the start of the rainy season, since the decision to sow or plant is typically determined by rainfall events;
- **Generated by a Temperature criterion**: This option might be useful for simulations in a cool climate, where crops are typically sown or planted when the air temperature rises above a minimum value.

The two options to generate on onset day are suitable not only for estimating the planting date for current years but also for future years, since climate change is likely to increase the air temperature and alter the rainfall pattern in many regions.

The End day of the growing period:

The end (last day) of the growing period is given by the time to reach crop maturity. Since this is a crop characteristic, AquaCrop obtains the specific length from the crop file, where the time to crop maturity is specified in calendar days or growing degree-days.

- **Onset generated based on rainfall**

In rainfed cropping, sowing or planting is typically determined by rainfall events. By selecting the option 'Generated by a rainfall criterion' in the 'Mode' tabular sheet (Fig. 2.11e), several options based on rainfall can be selected in the 'Rainfall criteria' tabular sheet (Fig. 2.11f).

Generating the onset based on rainfall might be useful not only for estimating the planting dates for current years but also for future years, since climate change is likely to alter the rainfall pattern in many regions.

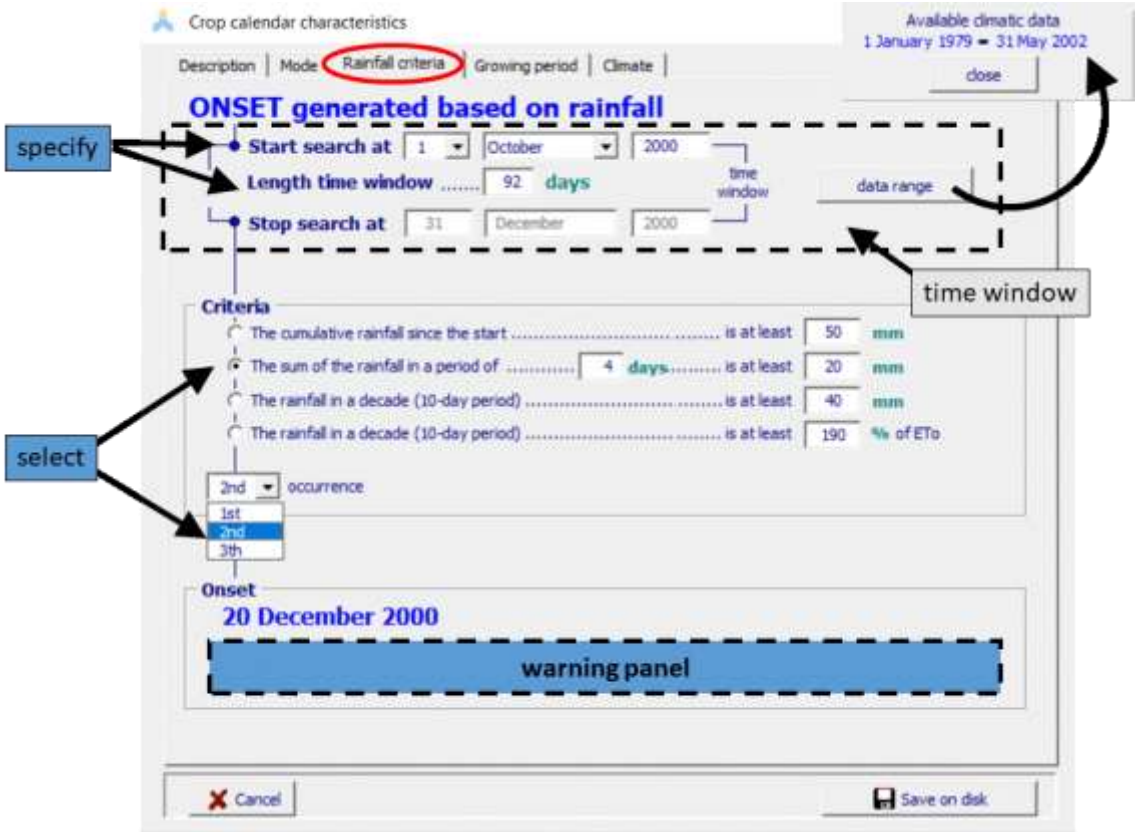


Figure 2.11f – The 'Rainfall criteria' tabular sheet in which the Onset of the growing period is determined by the 2nd occurrence of at least 20 mm of rainfall in a period of 4 successive days, counting from 1 October (start of the time window) for the year 2000

<u>Data range:</u>

By clicking on the **<data range>** command, AquaCrop displays the time range for which climatic data is available in the climate file.

<u>Time window:</u>

By selecting one or another Rainfall criterion, the start of the growing period is determined by appraising the rainfall data specified in the selected Rain data file for the

selected year. By specifying the first day and the length of a time window at the top of the Menu, only rainfall within the specified window is evaluated.

Rainfall criteria:

The following criteria are available to determine the Onset within the specified time window:

- The ***cumulative rainfall*** since the start of the time window is equal to or exceeds the pre-set value;
- The sum of the ***rainfall in a number of successive days*** is equal to or exceeds the pre-set value;
- The ***10-day rainfall*** is equal to or exceeds the pre-set value;
- The ***10-day rainfall exceeds*** the pre-set ***percentage of the 10-day ETo***.

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

Occurrence:

The first occurrence of the Onset is the first day for which the selected criterion holds in the specified time window for the selected year.

When the start of the rainy season is not certain at the first occurrence of the selected criterion, specifying a more stringent criterion might avoid early canopy senescence and a complete crop failure after germination. AquaCrop offers also the option to select the 2nd or even a 3th occurrence, to avoid the selection of a too early onset date after a false start of the rainy season.

Rules and Warning messages:

If an Onset day cannot be generated within the specified time window for the selected year, the last day of the time window is selected as the Onset day. A warning will appear in a Panel, explaining why the criterion could not be met, and which Onset day was selected (last day of the time window).

Farmers often opt for a 2nd or even a 3rd occurrence for the selected criterion to avoid sowing or planting at the early stages of the rainy season when its start is still uncertain. When the rainy season is well on its way, a 1st occurrence might be sufficient to plan sowing or planting. When at the end of the time window the selected 2nd or 3rd occurrence is not yet encountered, AquaCrop selects the last occurrence which was met in the specified time window. This mimics somewhat the behavior of farmers, who are likely to reduce their requirements for planting in the later stages of the rainy season. A warning will appear in a Panel, explaining why an earlier occurrence of the onset was selected, and which occurrence was finally selected.

- **Onset generated based on air temperature**

In cool climates, crops are typical sown or planted when the air temperature rises above a pre-set minimum value. By selecting the Onset option 'Generated by a temperature or ETo criterion' in the 'Mode' tabular sheet (Fig. 2.11e), several options based on air temperature can be selected in the 'Temperature criteria' tabular sheet (Fig. 2.11g).

Generating the onset based on air temperature might be useful not only for estimating the planting dates for current years but also for future years, since climate change is likely to increase the air temperature in many regions.

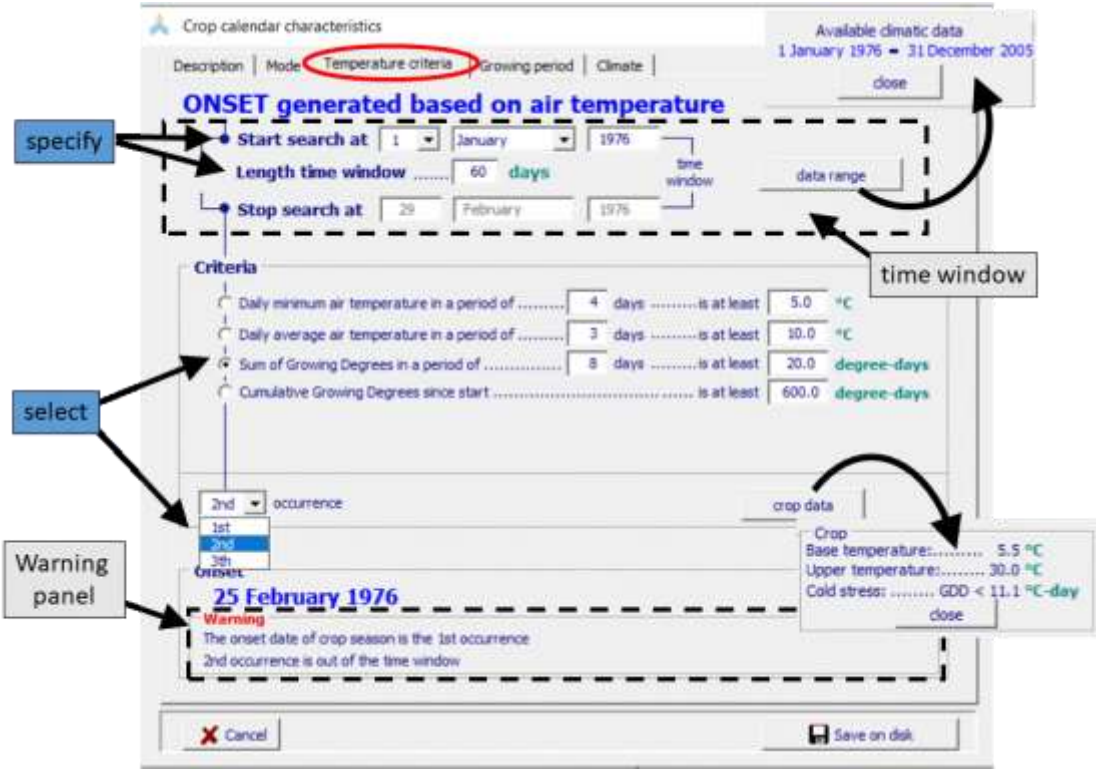


Figure 2.11g – The 'Temperature criteria' tabular sheet in which the Onset of the growing period is determined by the 2nd occurrence when the sum of the growing degrees in a period of 8 days is at least 20 degree-days, counting from 1 January (start of the time window) for the year 2000

<u>Data range:</u>

By clicking on the **<data range>** command, AquaCrop displays the time range for which climatic data is available in the climate file.

<u>Time window:</u>

By selecting one or another Temperature criterion, the start of the growing period is determined by appraising the air temperature data specified in the selected Air temperature data file for the selected year. By specifying the first day and the length of a time window at the top of the Menu, only air temperature within the specified window are evaluated.

Air temperature criteria:

The following criteria are available to determine the Onset based on air temperature, within the specified time window:

- The ***daily minimum air temperature***, in each day of a given number of successive days, is equal to or exceeds the pre-set minimum air temperature;
- The ***daily average air temperature***, in each day of a given number of successive days, is equal to or exceeds the pre-set average air temperature;
- The ***sum of Growing Degrees in a number of successive days*** is equal to or exceeds the pre-set growing degree days;
- The ***cumulative Growing Degrees*** since the start of the time window are equal to or exceed the pre-set growing degree days.

The options with growing degree-days are crop specific, since they are obtained from the mean air temperature (climate specific) by considering the base and upper temperature for crop development (crop specific).

Crop data:

By clicking on the **<crop data>** command, AquaCrop displays the base and upper temperature for crop development and the threshold, expressed in growing-degrees per day, below which crop transpiration starts to be affected (crop specific).

Occurrence:

The first occurrence of the Onset is the first day for which the selected criterion holds in the specified time window for the selected year.

To avoid sowing or planting in the early stages of the spring, where air temperature might still drop sharply after an early start, AquaCrop offers also the option to select a 2nd or even a 3rd occurrence for the selected criterion.

Rules and Warning messages:

If an Onset day cannot be generated within the specified time window for the selected year, the last day of the time window is selected as the Onset day. A warning will appear in a Panel, explaining why the criterion could not be met, and which Onset day was selected (last day of the time window).

When before the end of the time window a 2nd or 3rd occurrence is not yet encountered, AquaCrop selects the last occurrence which was met in the time window. A warning will appear in a Panel, explaining why an earlier occurrence of the onset was selected, and which occurrence was finally selected.

- **The 'Growing period' tabular sheet**

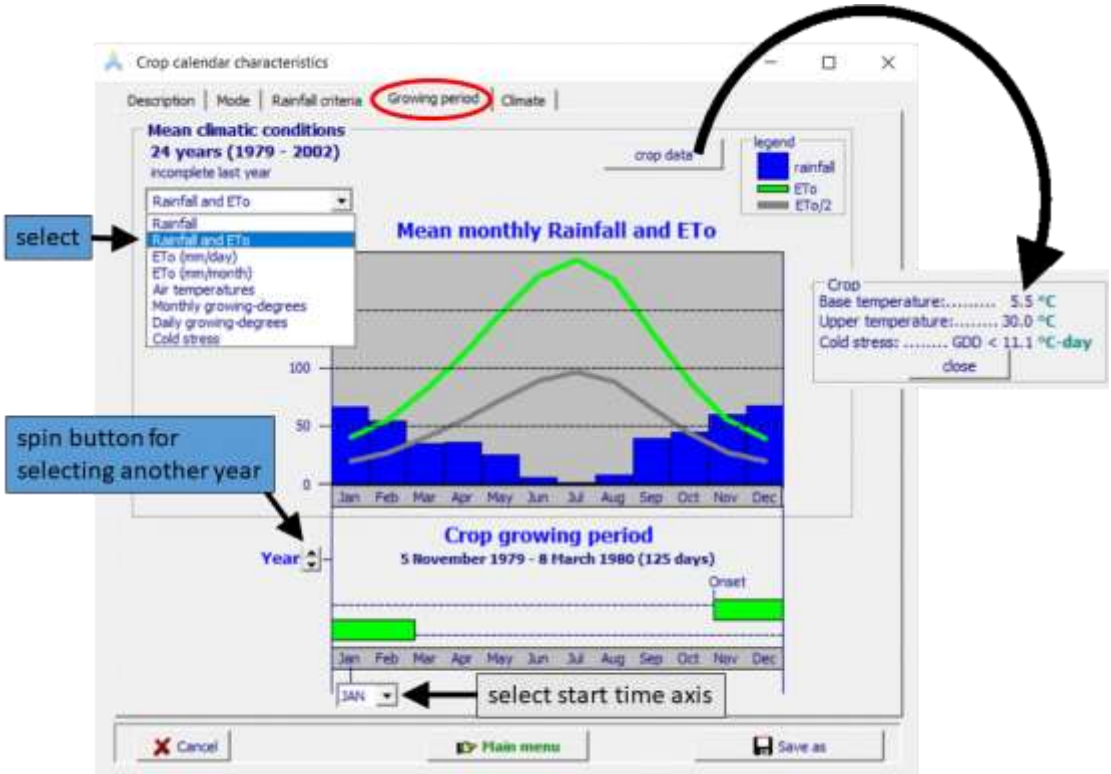


Figure 2.11h – The 'Growing period' tabular sheet of the *Crop calendar characteristics* menu, in which the generated growing period for the selected year, together with selected mean monthly climatic conditions, are plotted

In the 'Growing period' tabular sheet of the ***Crop calendar characteristics*** menu, the growing period for the selected year is plotted as a green bar on a time axis (Fig. 2.11h).

At the top of the tabular sheet, mean monthly climatic data for the selected climate are plotted. The following plots can be selected:

- Mean monthly rainfall (mm/month)
- Mean monthly rainfall together with the mean monthly ETo (mm/month)
- Mean monthly ETo in mm/day
- Mean monthly ETo in mm/month
- Mean monthly minimum and maximum air temperature (°C)
- Mean monthly growing degrees expressed as a daily average
- Monthly growing-degrees
- Cold stress (%) affecting the crop transpiration

Growing degree-days and cold stress are crop specific, since they are obtained from the mean air temperature (climate specific) by considering the base and upper temperature for crop development and the threshold for cold stress affecting crop transpiration (crop specific).

With the help of the spin button, other years can be selected. This allow the user to evaluate changes in the crop calendar due to the varying weather conditions in the selected year, and when required to strengthen or weaken threshold values or periods for the selected criterion. As an example, the onsets generated with a rainfall criterion is listed for the various years of the Tunis data set, in Table 2.11.

Table 2.11 – Variation of the onset generated with a rainfall criterion for the various years of the Tunis climatic data set

Rainfall criterion: 2nd occurrence of 20 mm rainfall in 4 days, in the time window 1 October – 31 December (Fig. 2.11f)

Year	Date	Remark	Year	Date	Remark
1979	5 November	-	1991	24 November	-
1980	20 December	-	1992	10 December	-
1981	7 December	1st occurrence*	1993	26 November	1st occurrence*
1982	30 October	-	1994	31 December	Criterion not met*
1983	2 November	-	1995	4 December	-
1984	4 December	-	1996	27 December	-
1985	9 November	1st occurrence*	1997	15 November	-
1986	30 October	-	1998	29 November	-
1987	31 December	Criterion not met*	1999	28 November	-
1988	23 December	1st occurrence*	2000	20 December	-
1989	27 November	-	2001	31 December	Criterion not met*
1990	13 November	-			

1st occurrence: Before the end of the time window the 2nd occurrence was not yet encountered. The 1st occurrence was automatically selected as the Onset day;

Criterion not met: The Onset day could not be generated within the specified time window for the selected year. The last day of the time window is automatically selected as the Onset day.

- **The 'Climate' tabular sheet**

Air temperature, rainfall, and ETo data for the selected climate is displayed when selecting the <**Display Climate characteristics**> command key in the 'Climate' tabular sheet of the ***Crop calendar characteristics*** menu (Fig. 2.11i).

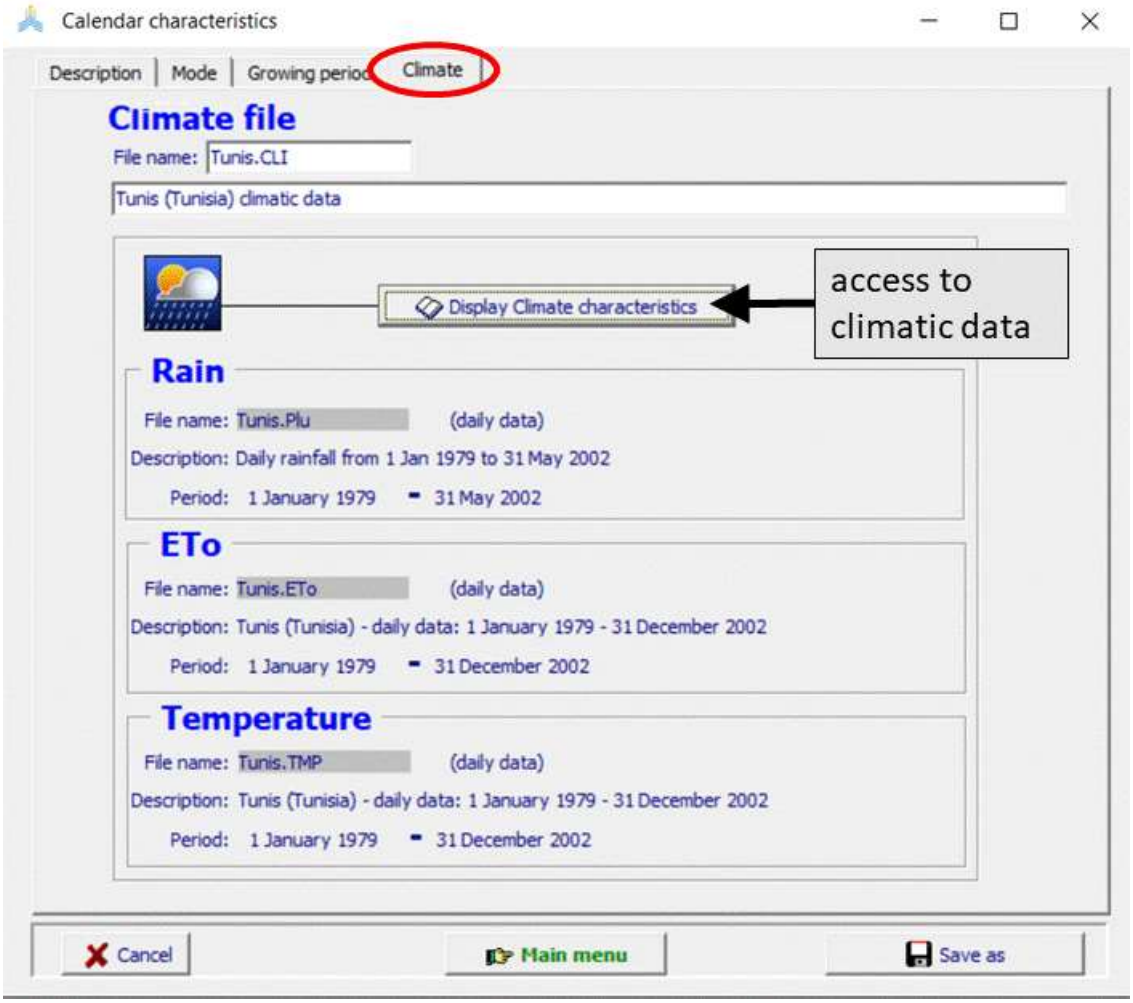


Figure 2.11i – The 'Climate' tabular sheet of the *Crop calendar characteristics* menu, with access to the climatic data for the selected climate

2.11.4 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 2.11b. For the playlist go to FAO AquaCrop website http://www.fao.org/nr/water/aquacrop.html

Table 2.11b – 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 givens 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.

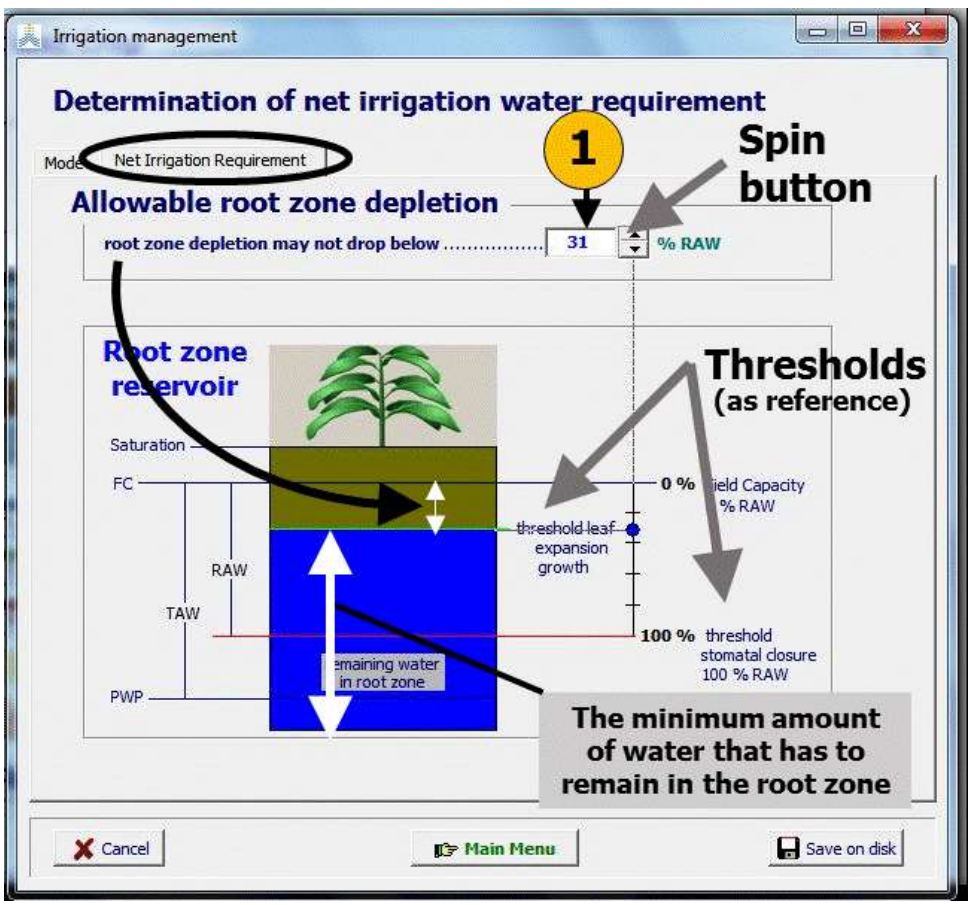


Figure 2.12b – Specified allowable root zone depletion for the determination of the net irrigation requirement in the *Irrigation management* menu

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/a and /b):

- **time of application**: The time is entered as the number of days after a particular reference date. The reference date can be:
    - ***the onset of the growing period***. With this option the irrigation events are not linked to a specific year, but relative to the specified or generated start of the growing period in the year of simulation. If the onset is generated by a temperature or rainfall criterion, the start of the growing period varies with the temperature of rainfall regime of the year, and the irrigation dates will be shifted accordingly (Fig. 2.12c/a);
    - ***a day in a particular year***. This option is useful when the irrigation applications are observed events (Fig. 2.12c/b).

  The number of days after the reference date are 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 (WP_{ET}) 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 WP_{ET} can be improved.

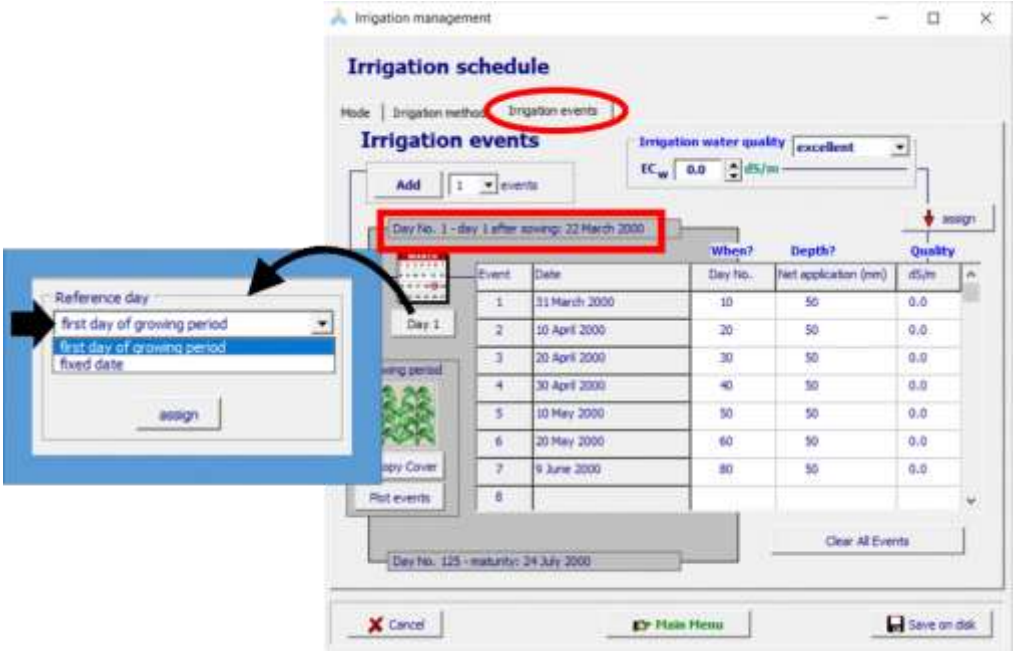


Figure 2.12c/a – Specification of the time, application depth and water quality for irrigation events with reference to the first day of the growing period.

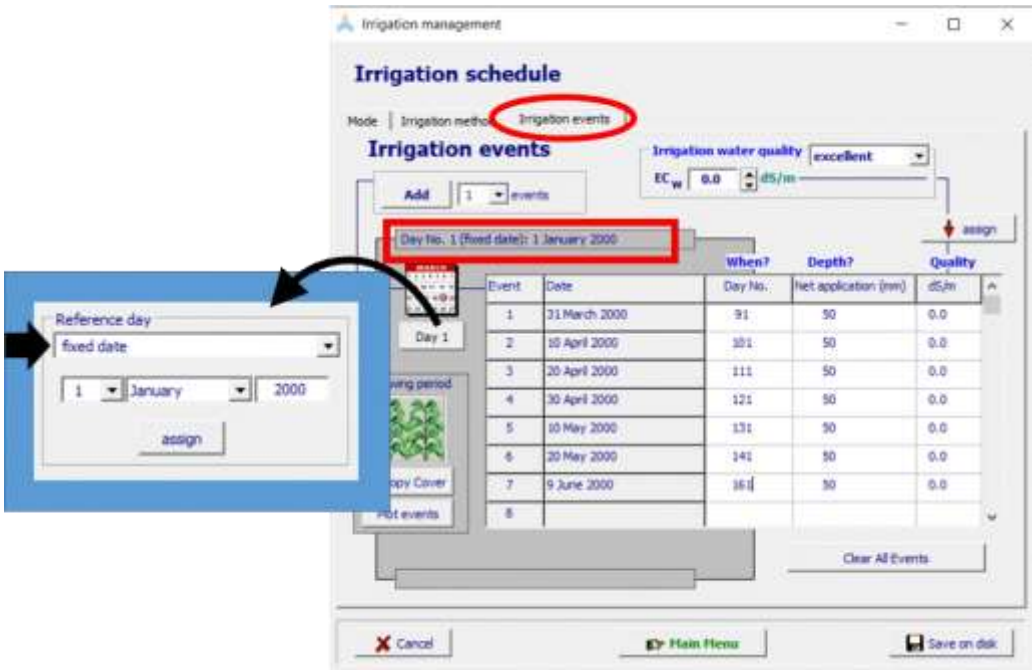


Figure 2.12c/b – Specification of the time, application depth and water quality for irrigation events with reference to a day in a particular year ((1 January 2000).

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.

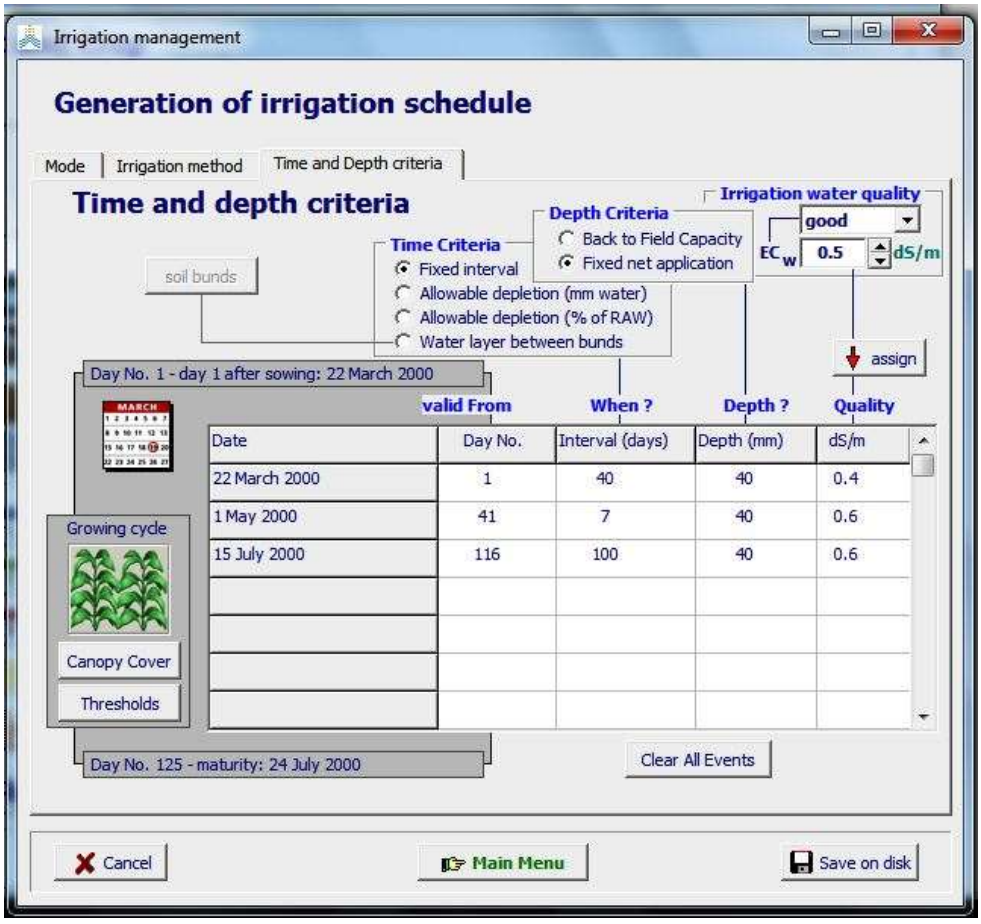


Figure 2.12d – Specifying an irrigation schedule where the fixed irrigation interval (time criterion) varies over the season, while the fixed irrigation application depth (depth criterion) remains constant, and the irrigation water quality deteriorates

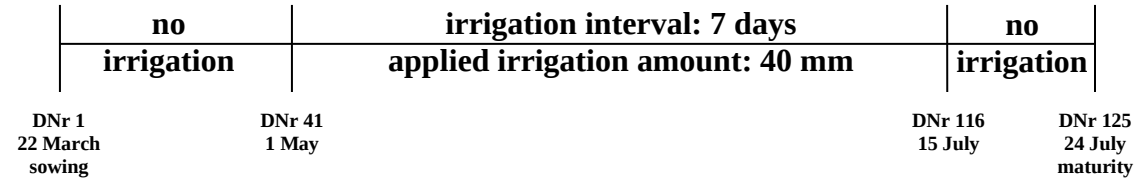


Figure 2.12e – Generated irrigation schedules as defined in Figure 2.12d

Table 2.12a – Time criteria with corresponding parameter

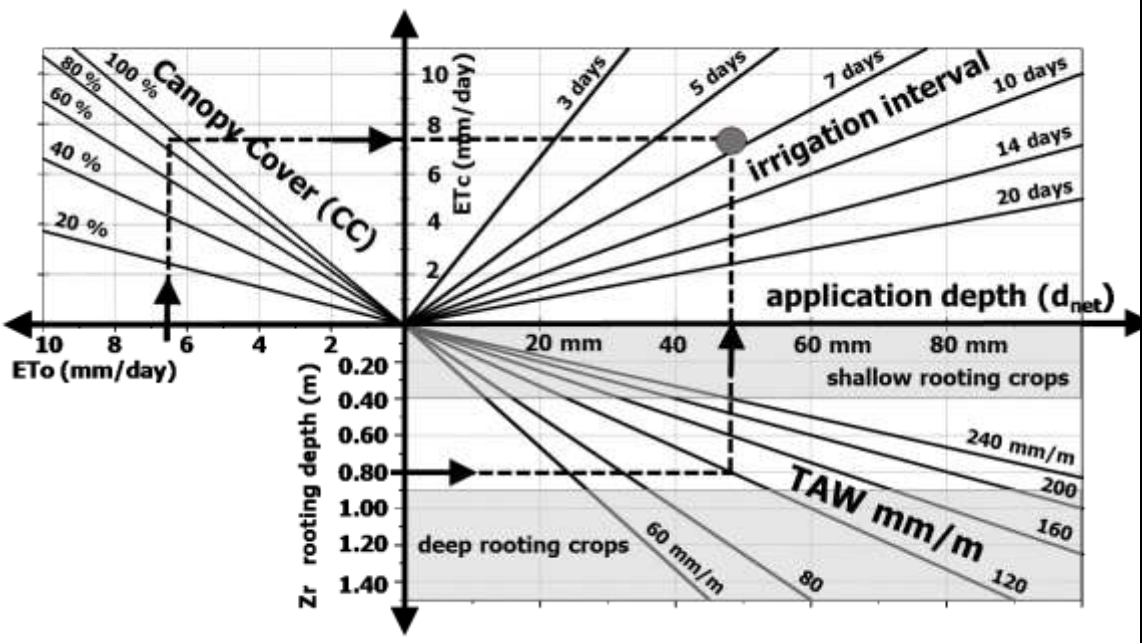
Criterion	Parameter
Fixed interval (days)	Interval between irrigations (for example 10 days). Indicative values are given in Table 2.12c.
Allowable depletion (mm water)	Amount of water that can be depleted from the root zone (the reference is soil water content at field capacity) before an irrigation 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: ▪ 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 (ETo), 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 (Zr) 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 (ETo) of 6.5 mm/day, and a Canopy Cover (CC) of 90%, the crop evapotranspiration (ETc) 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);

ETc = (1.2) CC* ETo [mm/day]; CC* is CC adjusted for micro-advective effects. The value of 1.2 is a representative value for $Kc_{Tr,x}$, 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.

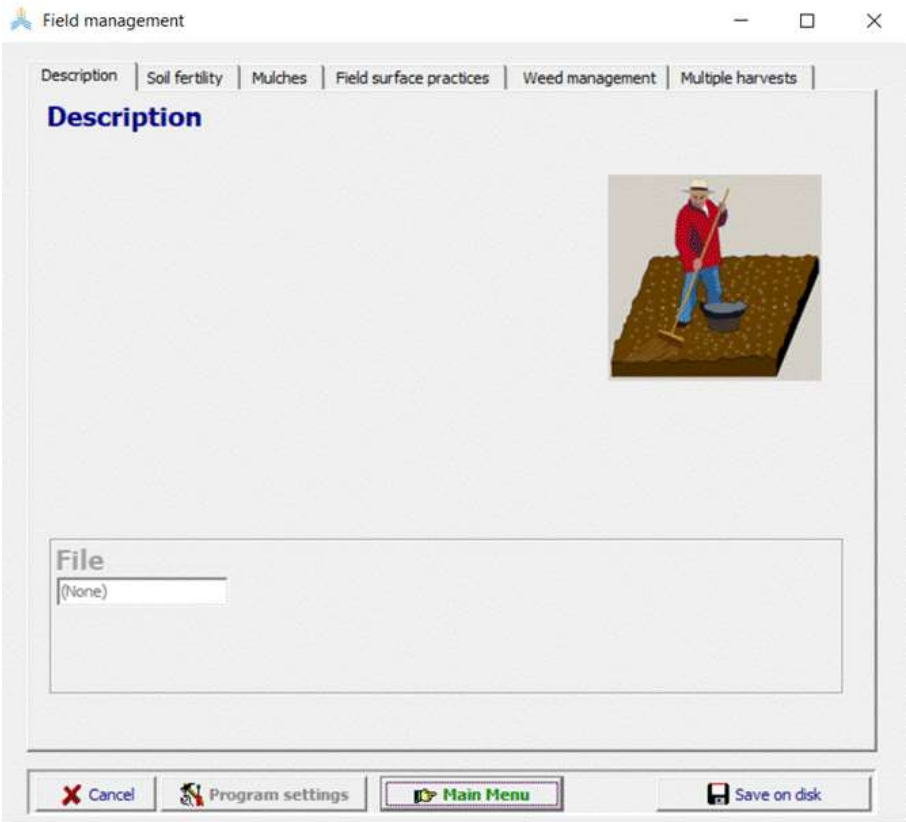


Figure 2.13a – *Field management* menu

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.

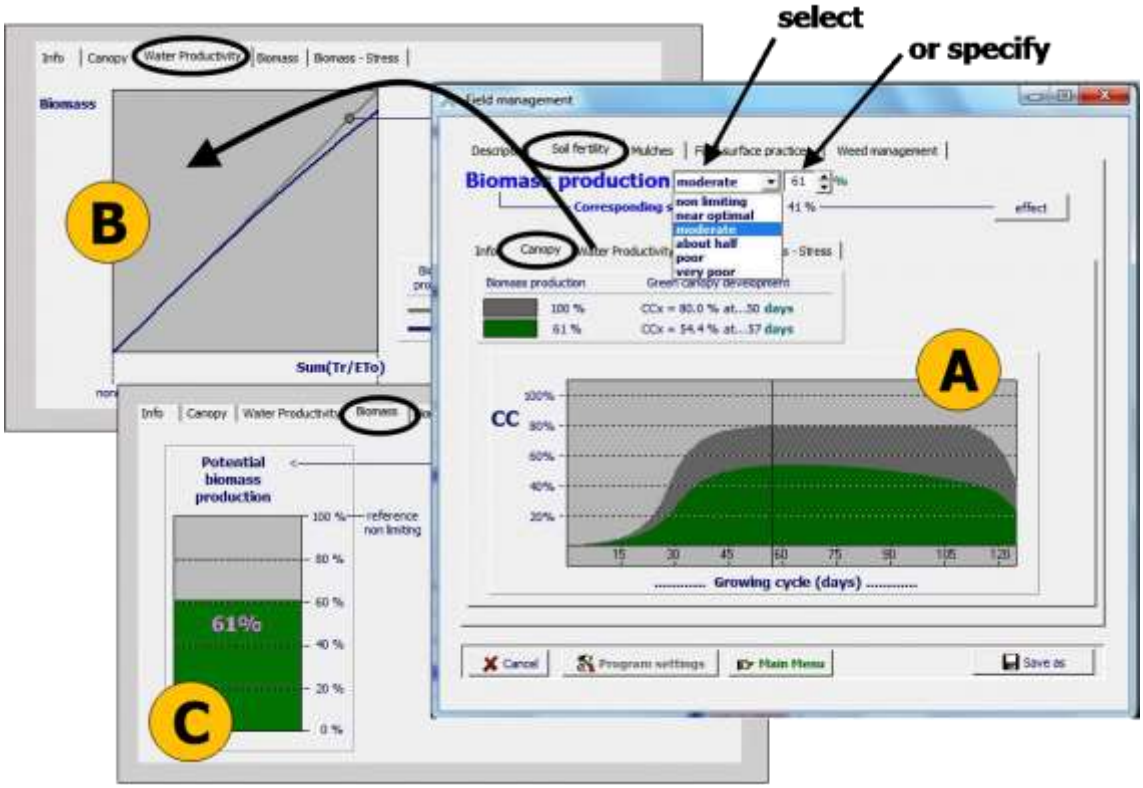


Figure 2.13b – The 'Soil fertility' tabular sheet of the *Field management* menu in which the maximum relative dry aboveground biomass that can be expected in the soil fertility stressed field is specified, and the corresponding effect on (A) canopy cover, (B) water productivity, and (C) potential biomass 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 ($Ks_{exp,f}$, Ks_{WP}, Ks_{CCx}, $f_{CDecline}$).

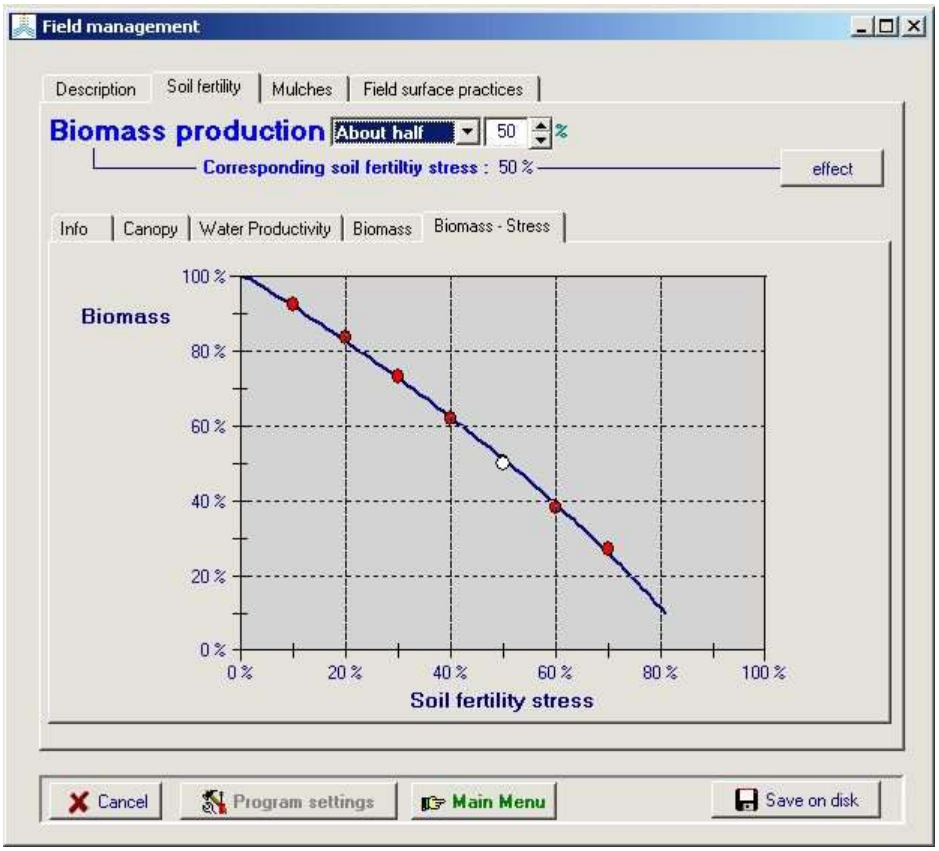


Figure 2.13c - Display of the calibrated Biomass - stress relationship in the *Field management* menu

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.
    - Synthetic plastic mulches, which reduce completely 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, and reduce the soil evaporation by 50%,
    - 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).

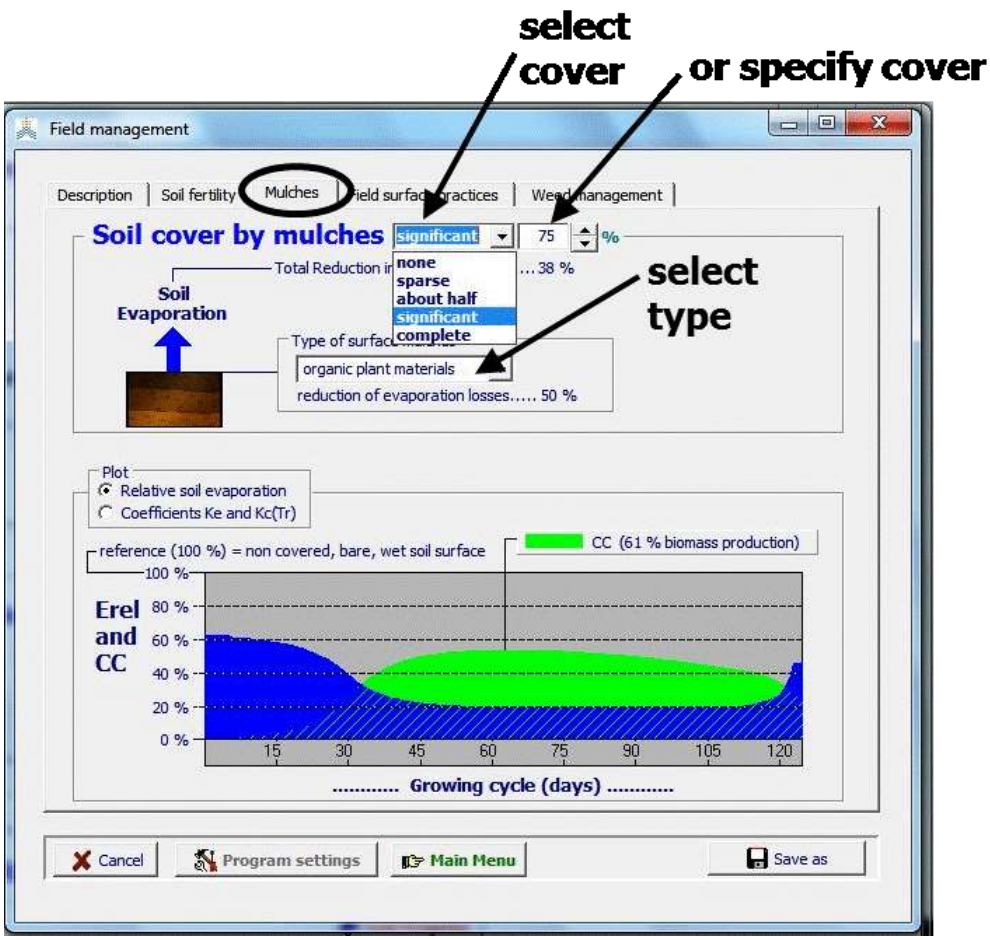


Figure 2.13d – Display of the effect of mulches on soil evaporation

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.

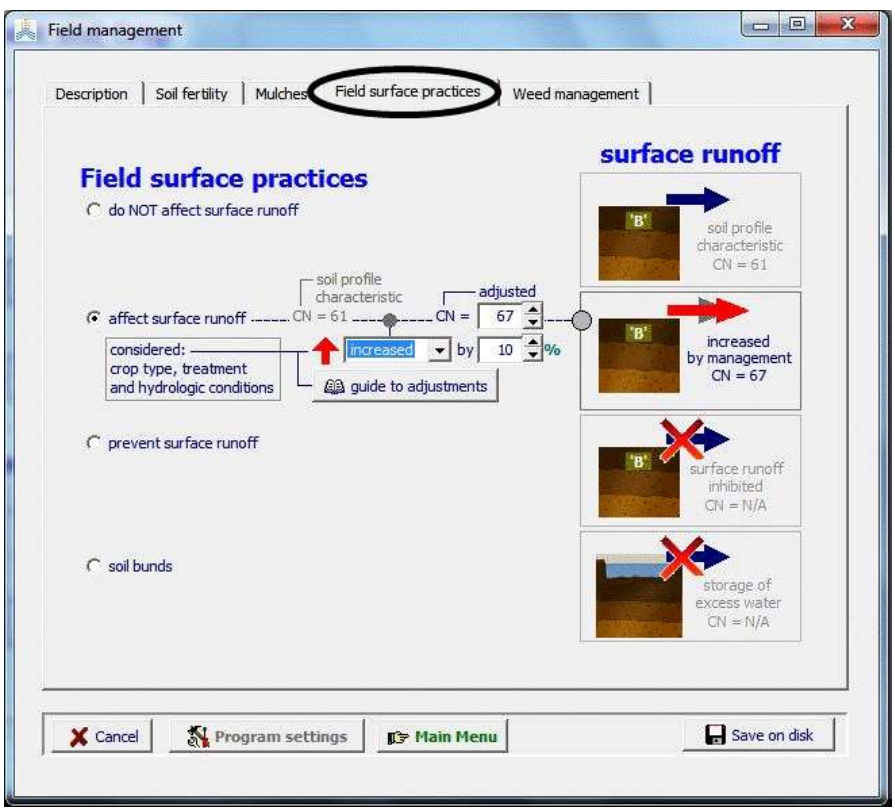


Figure 2.13e – The 'Field surface practices' tabular sheet of the *Field management* menu in which the effect of field surface practice on surface runoff is specified.

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).

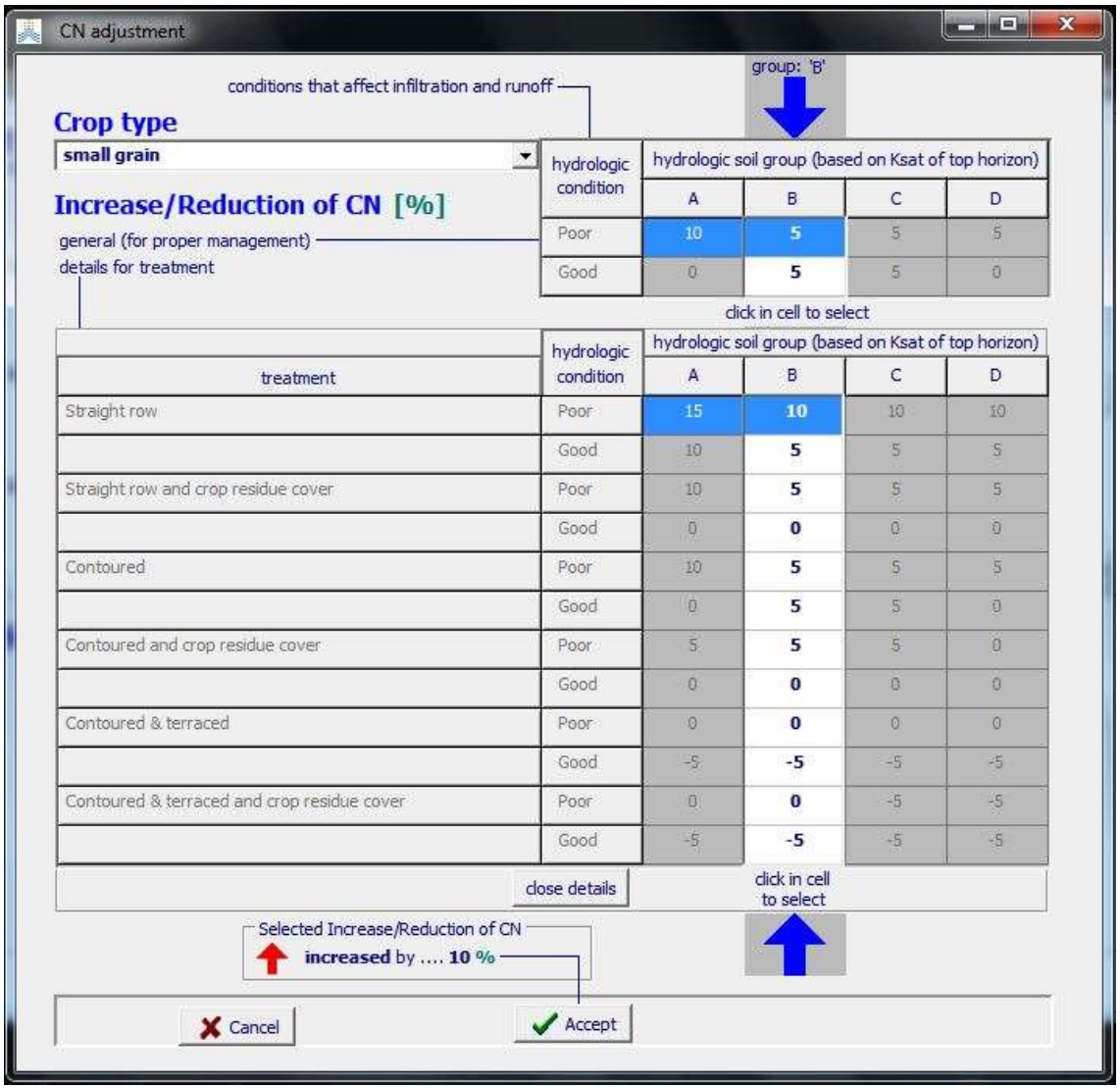


Figure 2.13f – Selection of the percent increase/decrease of the CN based on soil profile characteristics, by considering the crop type, treatment and hydrologic condition in the *CN adjustment* menu.

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	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:

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

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 proofed 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).

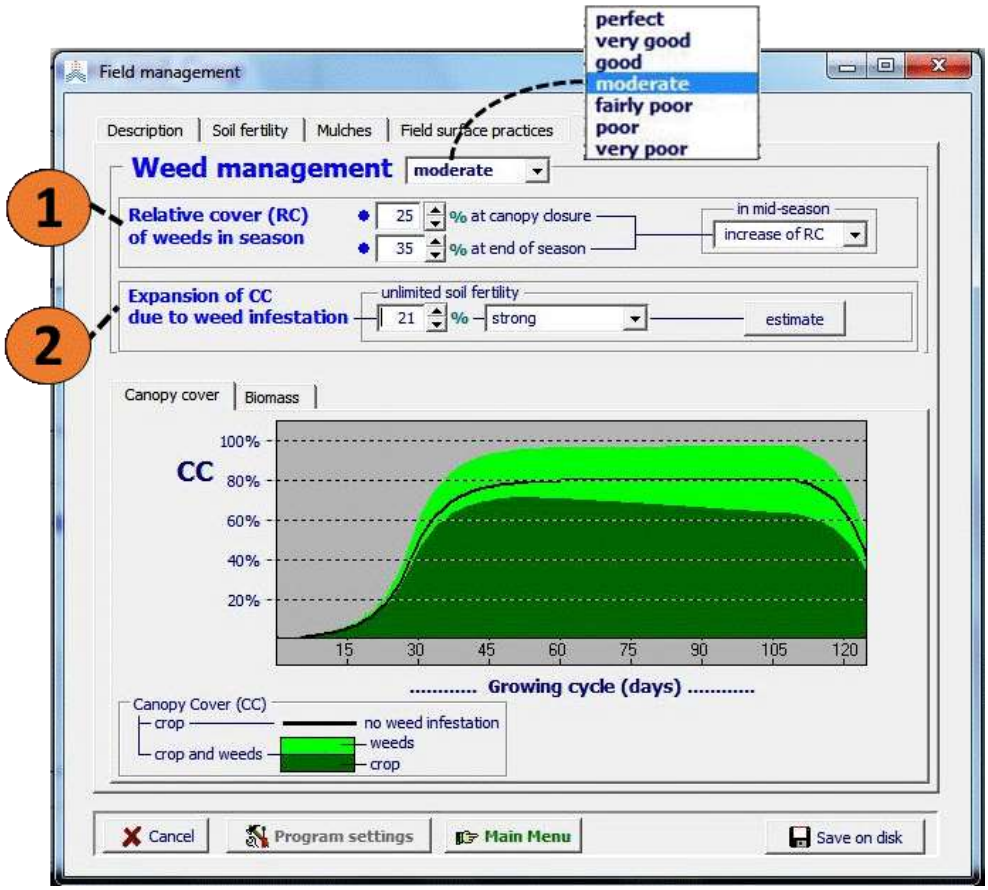


Figure 2.13g – Specification of (1) the Relative cover of weeds (RC) and (2) the expansion of canopy cover (CC) in the 'Weed management' tabular sheet of the *Field management* menu. In the graph the corresponding total canopy cover of crop (dark green) and weeds (light green) in the weed infested field 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 %	≥ 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.

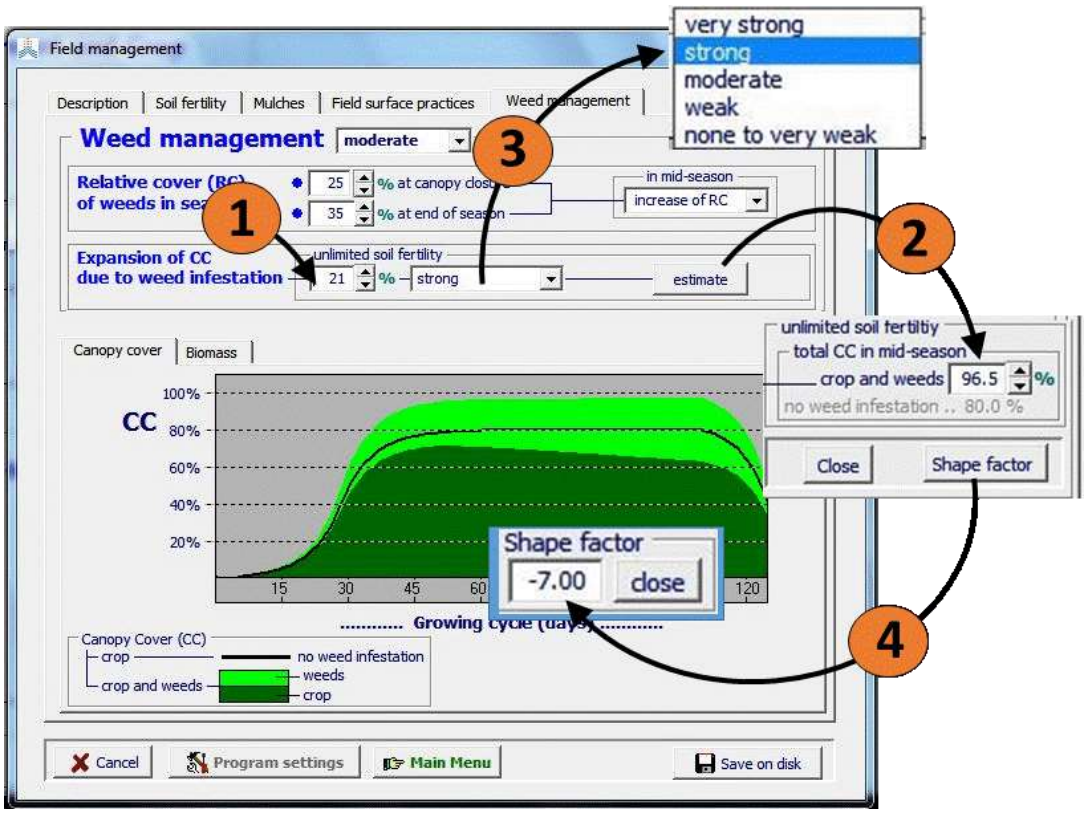


Figure 2.13h – Various ways of specifying the expansion of CC due to weed infestation, (1) by specifying a percent increase, (2) by specifying the total CC at mid-season in a weed infested field, (3) by selecting a class for the expansion of CC, or (4) by specifying a value for the shape factor

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).

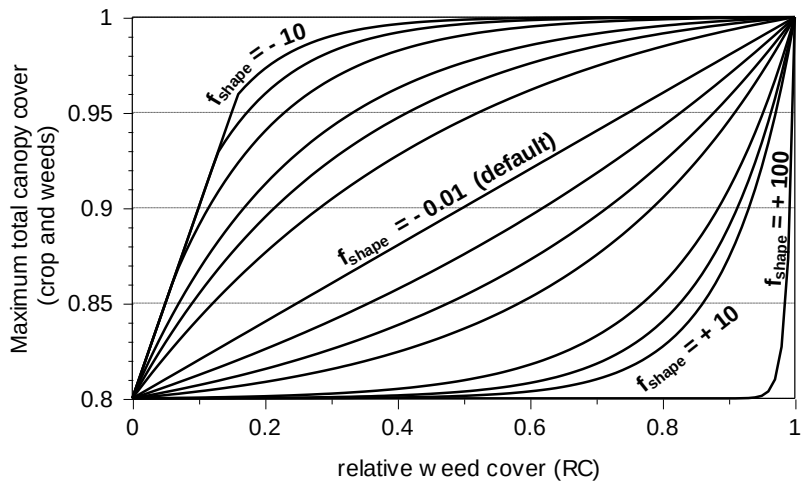


Figure 2.13i – Maximum total canopy cover of weeds and crop at mid-season ($CC_{x,TOT}$) for different relative weed covers (RC) and different shape factors (f_{shape}) for a field that in weed-free conditions would have a CC_x of 0.8

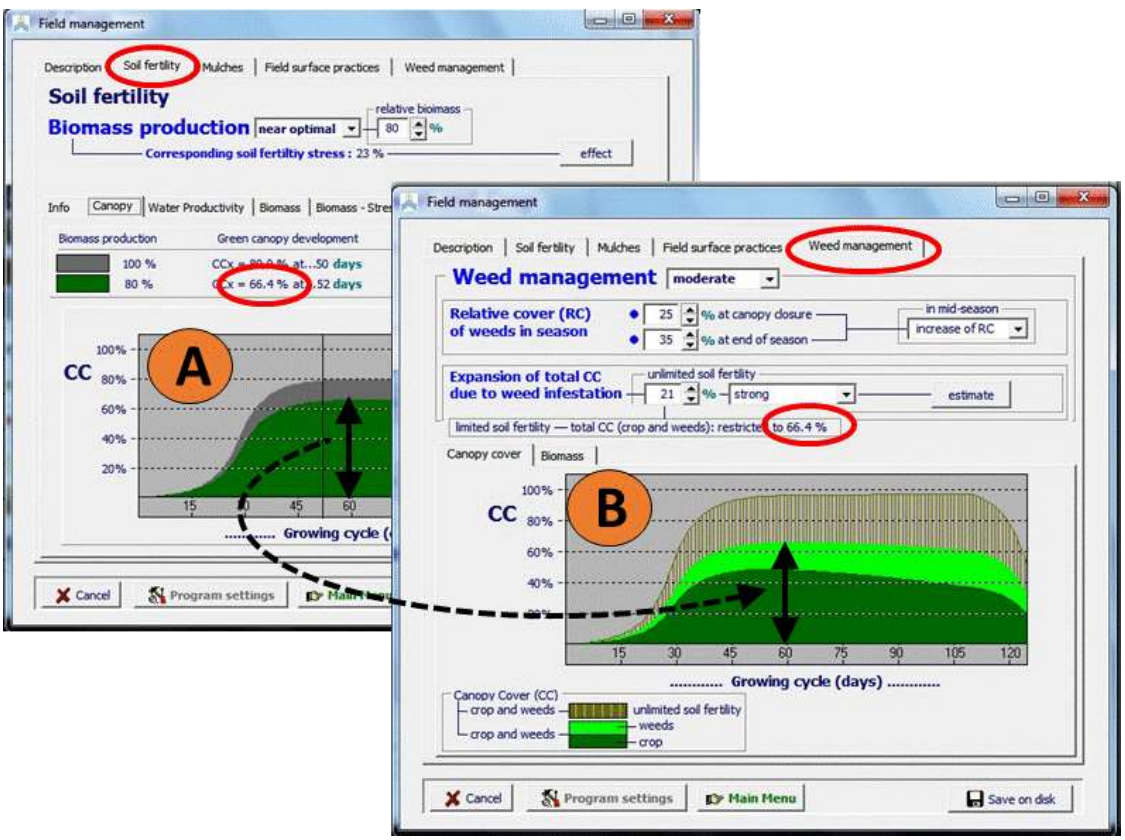


Figure 2.13j – (A) The crop canopy cover that can be reached with limited soil fertility in weed-free conditions and (B) the total canopy cover of crop and weeds that can be reached in a weed infested field with limited soil fertility, as displayed in the *Field management* menu

- **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).

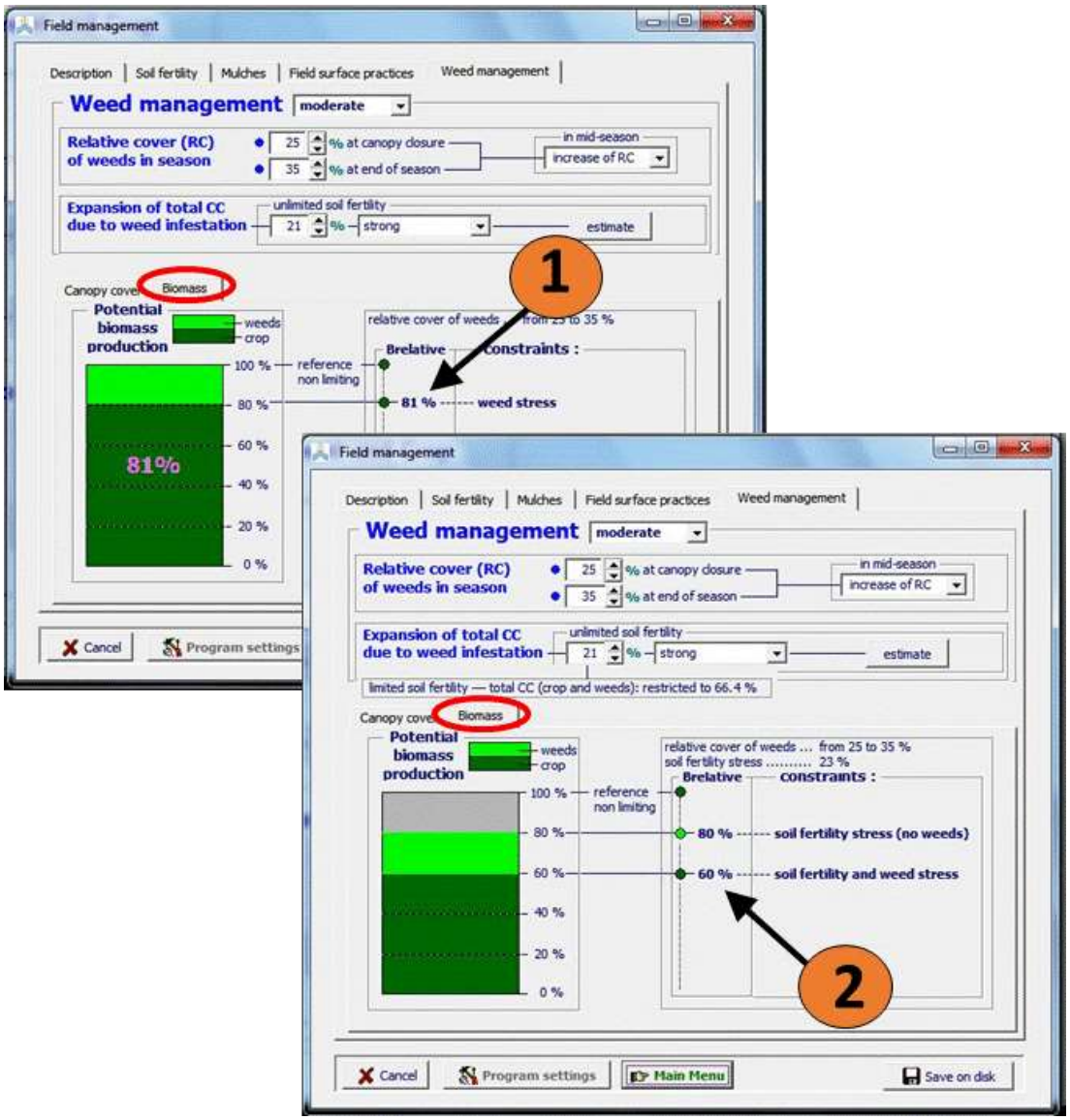


Figure 2.13k – The estimated relative maximum crop biomass production that can be obtained in a weed infested field, (1) without and (2) with soil fertility stress as displayed in the *Field management* menu

- **Effect of self-thinning (perennial herbaceous forage crops)**

In the 'weed management' tab-sheet of the ***field management*** menu, the user specifies the relative cover of the weeds at canopy closure and at the end of the season (Fig. 2.13g). Due to weed infestation the total canopy cover of crop and weeds can become larger than the canopy cover in weed-free conditions.

As a result of natural self-thinning of perennial herbaceous forage crops in the successive seasons, the weed cover might increase as weeds take over the empty spots in the field by unchanged weed management. This correction is automatically applied in AquaCrop when running a simulation. At run time, AquaCrop uses therefore the settings in the 'effect of self-thinning' tab-sheet. In this tab-sheet, the takeover by weeds can be visualized for various takeover classes (from 'fully' to 'hardly to none') and various seasons (Fig. 2.13k/b and /c).

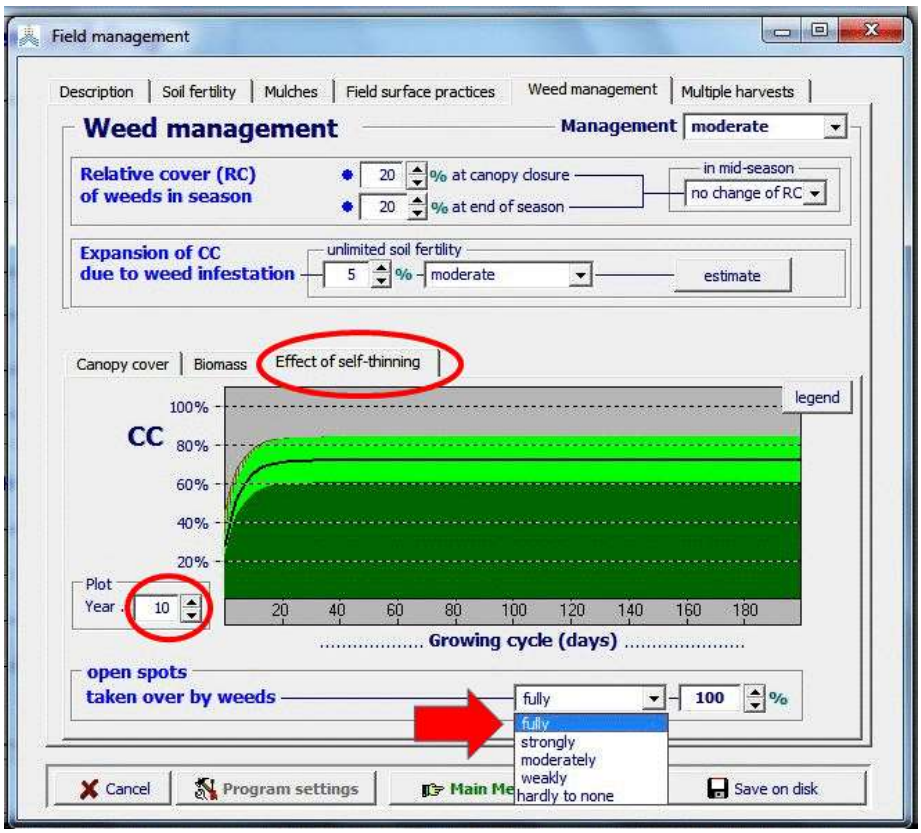


Figure 2.13k/b – Selection of the takeover of open spots in the field by weeds when the crop canopy cover of a perennial herbaceous forage crop decreases as a result of natural self-thinning: fully (100 %) takeover

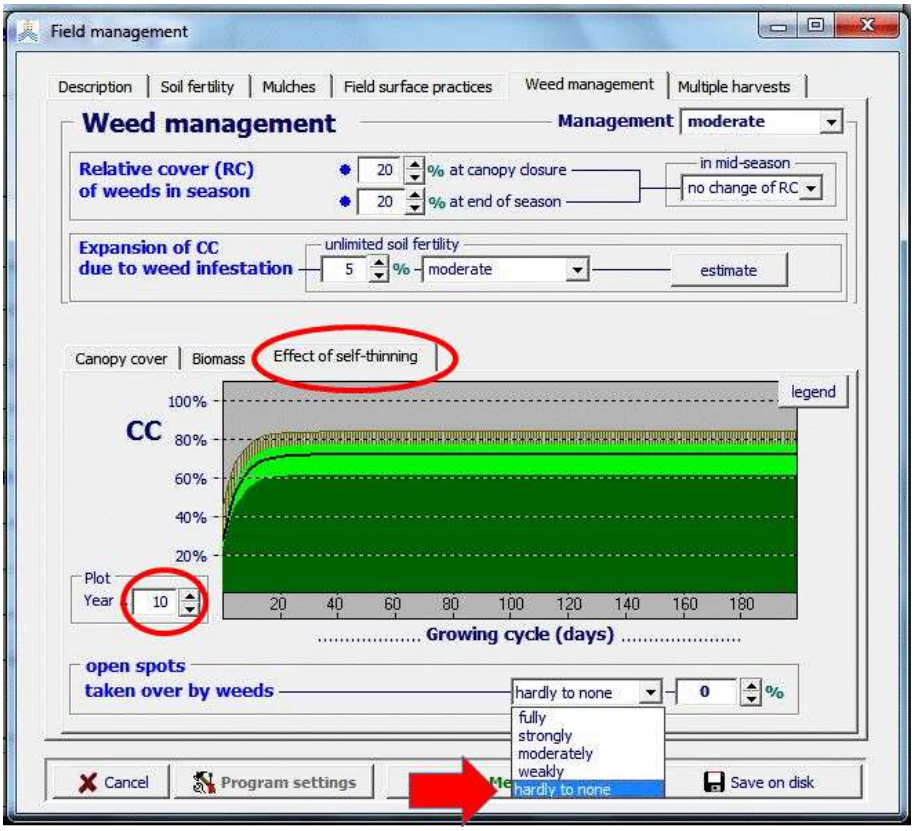


Figure 2.13k/c – Selection of the takeover of open spots in the field by weeds when the crop canopy cover of a perennial herbaceous forage crop decreases as a result of natural self-thinning: hardly to none (0%) takeover

2.13.5 Multiple harvests

In the ***Field management*** menu an extra tab-sheet is available for specifying multiple harvests during the season (Fig. 2.13m1).

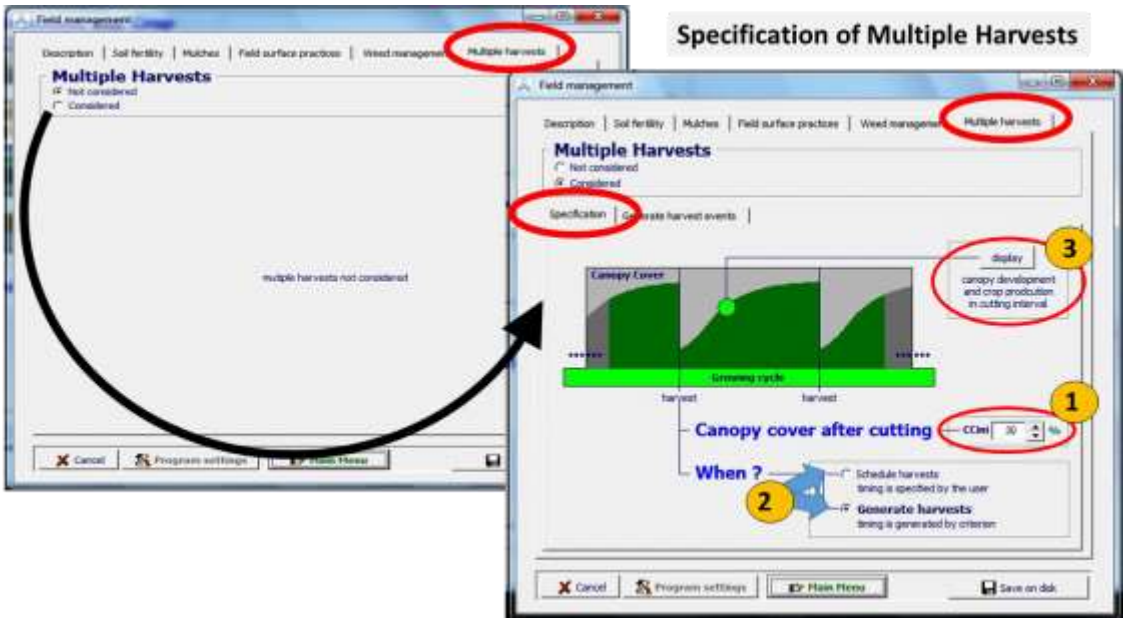


Figure 2.13m1 – Specification of multiple harvests in the *Field management* menu

In the ***Field management*** menu (Fig. 2.13m1), the user specifies:

1. The canopy cover after cutting;
2. The option to specify the timing of harvest;
3. The canopy development and crop production in the cutting interval.

- **The canopy cover after cutting**

The default value for the canopy cover after cutting (CCini) is 30 %. This default value corresponds with indicative values derived from the crop coefficients in FAO Irrigation and Drainage paper Nr 65 (Box 2.13m1):

- Alfalfa Hay = 26 %
- Clover hay, Berseem = 27 %
- Sudan grass hay = 27 %

Box 2.13m1 – Kcb values for forages in FAO Irrigation and Drainage Paper Nr. 56

Table 17 continued.

Crop	$K_{cb\ ini}$[1]	$K_{cb\ mid}$[1]	$K_{cb\ end}$[1]
j. Forages			
Alfalfa Hay – individual cutting periods	0.30[14]	1.15[14]	1.10[14]
– for seed	0.30	0.45	0.45
Bermuda hay – averaged cutting effects	0.50	0.95[15]	0.80
– Spring crop for seed	0.15	0.85	0.60
Clover hay, Berseem – individual cutting periods	0.30[14]	1.10[14]	1.05[14]
Rye Grass hay – averaged cutting effects	0.85	1.00[15]	0.95
Sudan Grass hay (annual) – individual cutting periods	0.30[14]	1.10[14]	1.05[14]
Grazing Pasture - Rotated Grazing	0.30	0.80-1.00	0.80
- Extensive Grazing	0.30	0.70	0.70
Turf grass - cool season[16]	0.85	0.90	0.90
- warm season[16]	0.75	0.80	0.80
k. Sugar cane	0.15	1.20	0.70
l. Tropical Fruits and Trees			
Banana – 1st year	0.15	1.05	0.90
– 2nd year	0.60	1.10	1.05
Cacao	0.90	1.00	1.00
Coffee – bare ground cover	0.80	0.90	0.90
– with weeds	1.00	1.05	1.05
Date Palms	0.80	0.85	0.85
Palm Trees	0.85	0.90	0.90
Pineapple[17] (multiyear crop) – bare soil	0.15	0.25	0.25
– with grass cover	0.30	0.45	0.45
Rubber Trees	0.85	0.90	0.90
Tea – nonshaded	0.90	0.95	0.90
– shaded[18]	1.00	1.10	1.05
m. Grapes and Berries			
Berries (bushes)	0.20	1.00	0.40
Grapes – Table or Raisin	0.15	0.80	0.40
– Wine	0.15	0.65	0.40
Hops	0.15	1.00	0.80

continued...

[14] These K_{cb} coefficients for hay crops represent immediately following cutting; at full cover; and immediately before cutting, respectively. The growing season is described as a series of individual cutting periods.

[15] This $K_{cb\ mid}$ coefficient for bermuda and ryegrass hay crops is an overall average $K_{cb\ mid}$ coefficient that averages K_{cb} for both before and following cuttings. It is applied to the period following the first development period until the beginning of the last late season period of the growing season.

[16] Cool season grass varieties include dense stands of bluegrass, ryegrass, and fescue. Warm season varieties include bermuda grass and St. Augustine grass. The 0.90 values for cool season grass represent a 0.06 to 0.08 m mowing height under general turf conditions. Where careful water management is practiced and rapid growth is not required, K_{cb}'s for turf can be reduced by 0.10.

[17] The pineapple plant has very low transpiration because it closes its stomates during the day and opens them during the night. Therefore, the majority of ET_c from pineapple is evaporation from the soil.

[18] Includes the water requirements of the shade trees.

Estimate of CC after cutting = 100 x Kcb_{ini} / Kcb_{mid}

- Alfalfa Hay = 100 x (0.30/1.15) = 26 %
- Clover hay, Berseem = 100 x (0.30/1.10) = 27 %
- Sudan grass hay = 100 x (0.30/1.10) = 27 %

- **The timing of the harvest events**

To specify the time of the multiple harvests, the user has the option:

- To specify the individual harvest events (Fig. 2.13m2 and 2.13m3)
- To generate harvests events with one or another criterion (Fig. 2.13m4).

<u>Specify the individual harvest events:</u>

Specify the time of the multiple harvests, by **specifying the harvest at specific days after a particular reference date**. The reference date can be:

- ***the first day of the growing period*** (Fig. 2.13m2). With this option the cuttings are not linked to a specific year, but relative to the specified or generated start of the growing period in the year of simulation. If the onset is generated by a temperature criterion, the start of the growing period varies with the temperature regime of the year, and the dates of harvests will be shifted accordingly.
- ***a day in a particular year*** (Fig. 2.13m3). This option is useful, when the harvest dates are observed events.

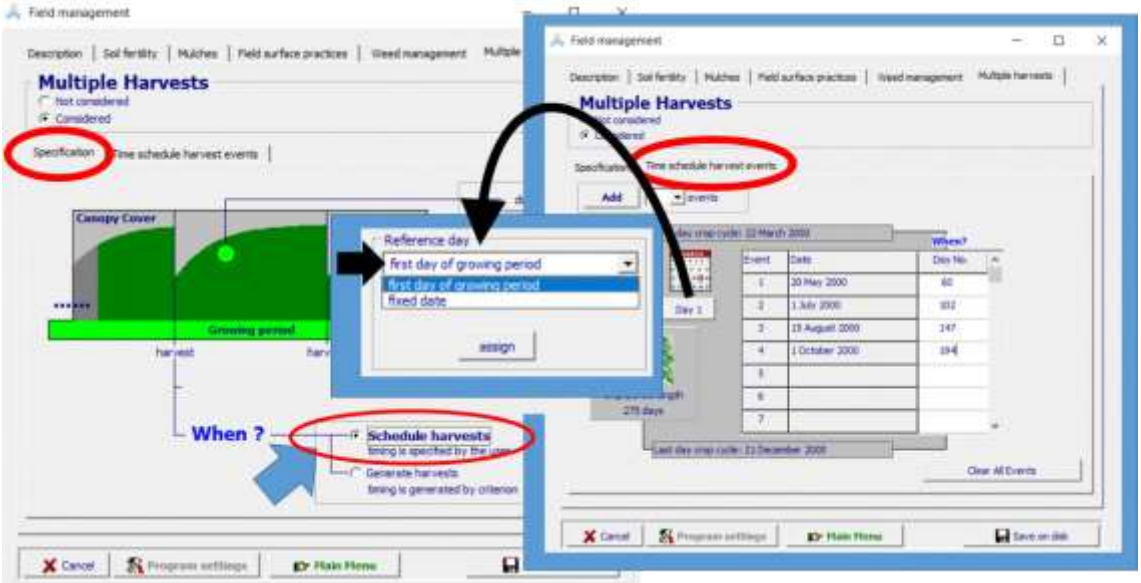


Figure 2.13m2 – Specifying the multiple harvest calendar with reference to the first day of the growing period

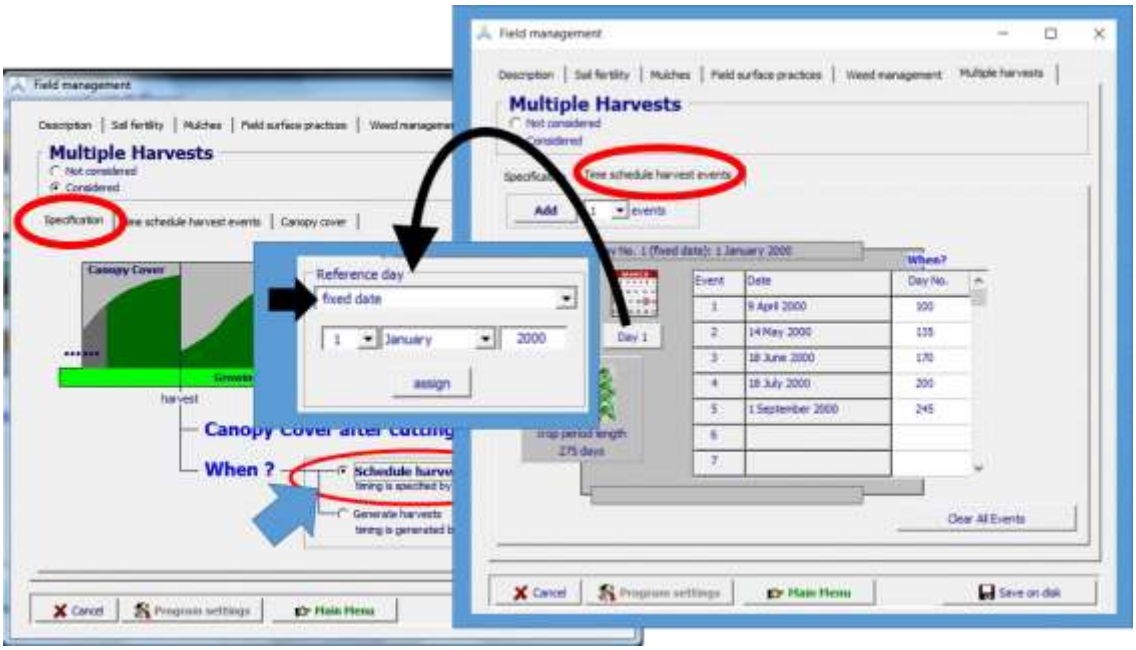


Figure 2.13m3 – Specifying the multiple harvest calendar with reference to a day in a particular year

<u>Generate harvest events:</u>

Specify the time of the multiple harvests, by **generating harvests events with one or another criterion** (Fig. 2.13m4):

The criteria that can be selected to generate a harvest at run time are (Fig. 2.13m4):

- Fixed interval in days;
- Fixed interval in GDD;
- Mass (ton/ha) of dry above ground biomass produced;
- Mass (ton/ha) of dry yield produced;
- Mass (ton/ha) of fresh yield produced.

When generating multiple harvests (Fig. 2.13m4), the user can:

- alter the threshold of the criterion (days, GDD or ton/ha) when the season advances;
- specify the period before which no harvest can take place;
- specify the length of the harvesting period. The harvest period does not necessarily stretch to the end of crop cycle, in order to avoid cuttings during the period in which assimilates are transferred to the root system;
- specify if at the last day of the season, the crop is completely harvest (when the crop will be replanted in the next season).

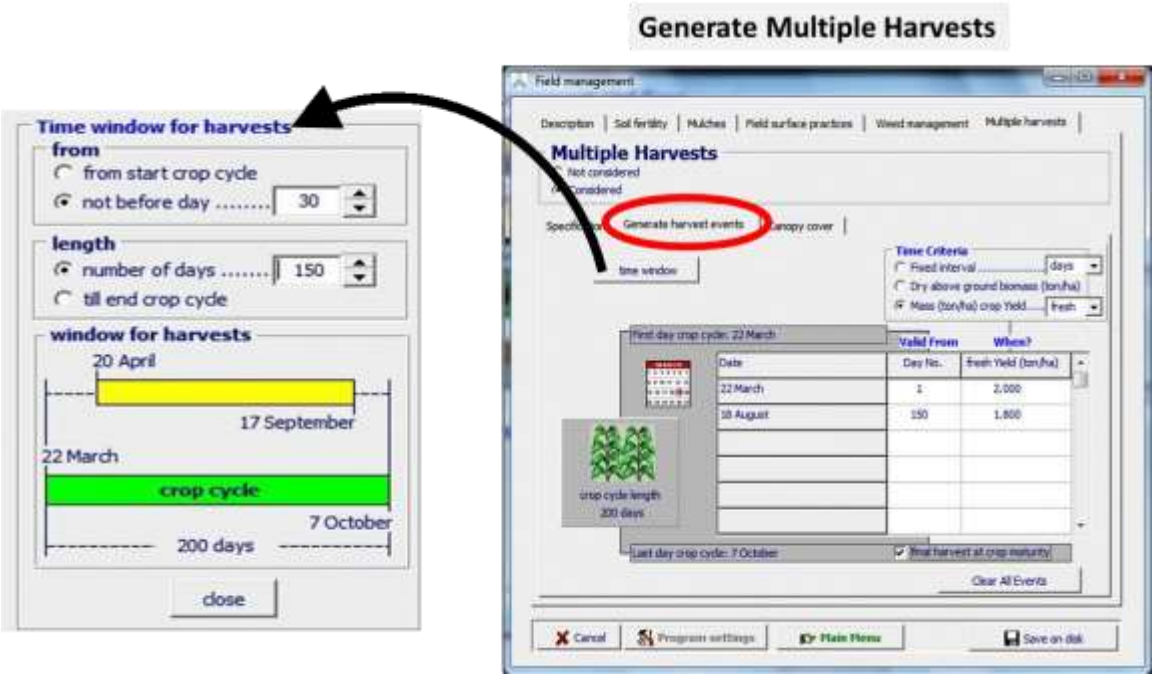


Figure 2.13m4 – Selection of the criterion and specification of its threshold for generating multiple harvests (right), and specification of the time window in which the crop can be harvested (left)

- **Canopy development and crop production in the cutting interval**

By clicking on the **<display>** button in the Multiple Harvests tab-sheet, the crop development and production is displayed in the ***Canopy development and crop production in cutting interval*** menu (Fig. 2.13m5 and 2.13m6).

In the ***Canopy development and crop production in cutting interval*** menu the user can:

- adjust the Canopy cover (percentage) after cutting (CCini);
- specify the length of the cutting interval (days);
- and specify the air temperature in the cutting interval by selecting the month in the middle of the cutting interval.

For the selected CCini and period of the cutting interval (length and central month), AquaCrop obtains the average air temperature and the growing degree days from the mean monthly air temperatures for the selected climate. By clicking on the **<plot>** button in the Climate panel, the mean monthly maximum and minimum air temperatures are displayed (Fig. 2.13m6).

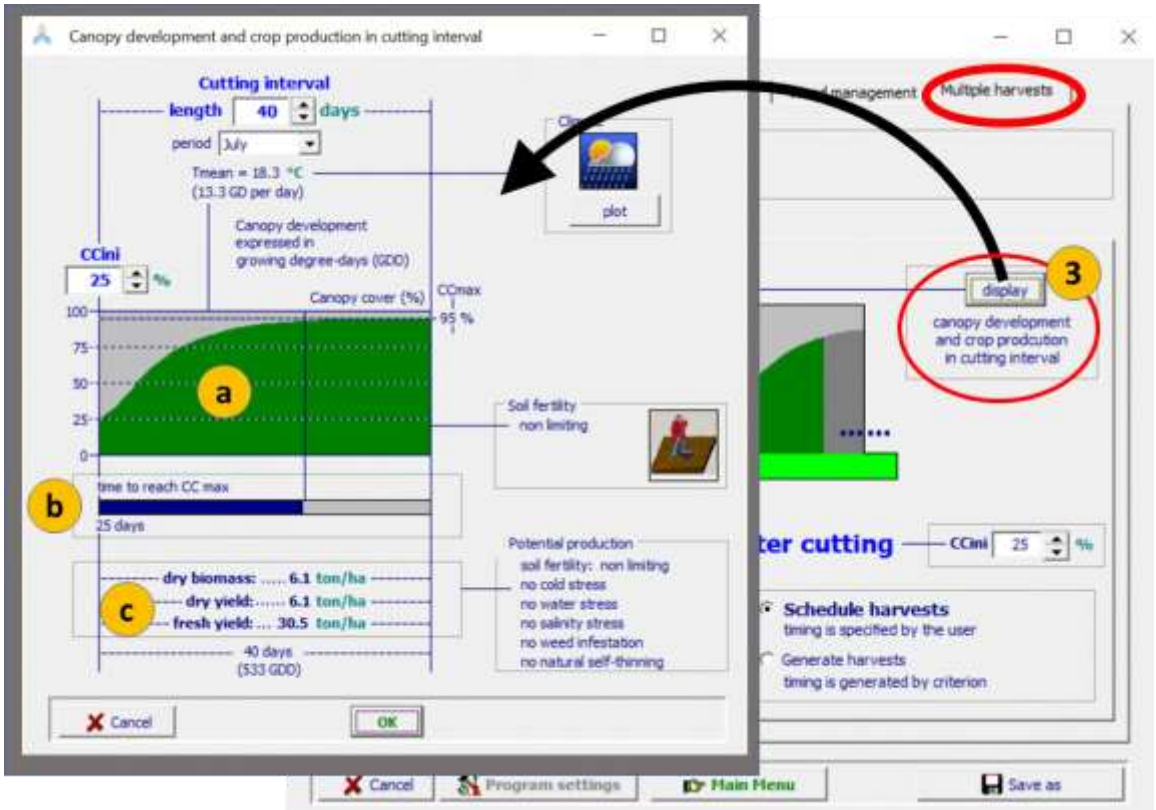


Figure 2.13m5 – The canopy development and estimated production in the absence of any stress in a 40 day cutting interval in the period of July, as displayed in the *Canopy development and crop production in cutting interval* menu

In the ***Canopy development and crop production in cutting interval*** menu, AquaCrop displays (Fig. 2.13m5 and 2.13m6):

a. the canopy development;
b. the time to reach maximum canopy cover;
c. the production in the absence of water stress, salinity stress, and weed infestation.

The (a) canopy development, (b) the time to reach maximum canopy cover, and (c) the estimated dry biomass and yield, might be valuable information to fine-tune the values of CCini if field observations are available. The estimate of the crop production, assumes that no water or salinity stress, and weed infestation affects crop production. However, cold stress (linked with the climatic conditions and the selection of the period of the cutting interval), and the soil fertility level specified in the ***Field management*** menu, are considered in the estimates of the displayed crop production (Fig. 2.13m6).

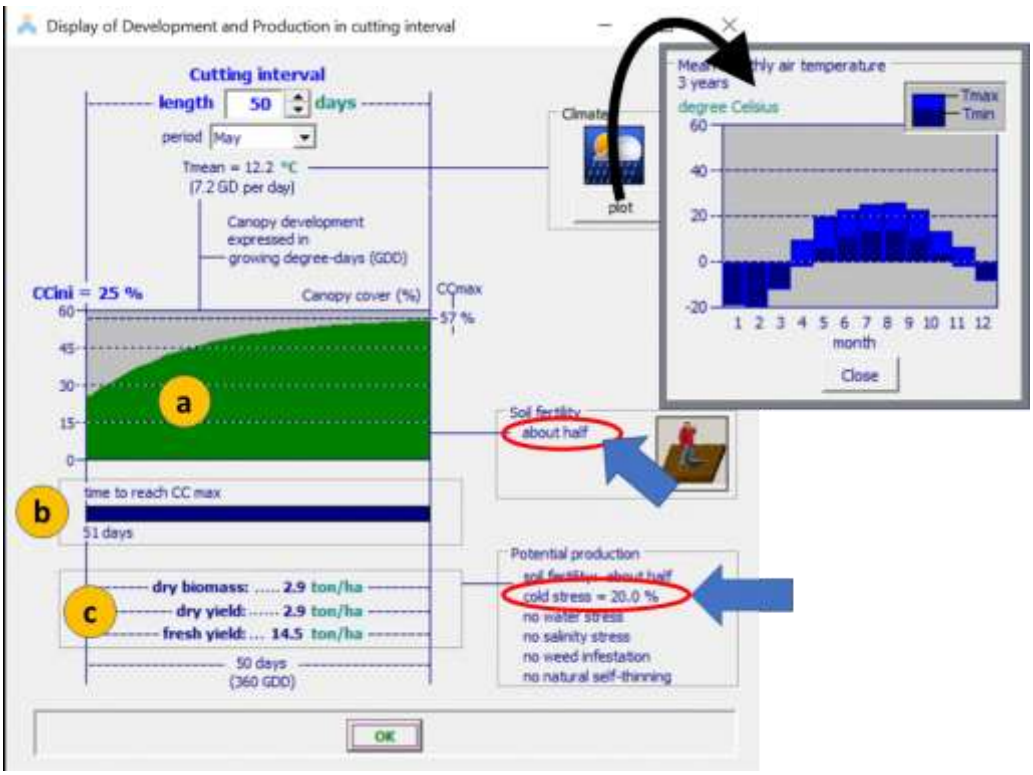


Figure 2.13m6 – The estimated crop production for soil fertility and cold stress as displayed in the Canopy development and crop production in cutting interval menu

Box 2.13m2 – Simulation of regrowth when running a simulation

Simulation of regrowth at run time:

- **Development of Canopy Cover (CC):** By considering the CCini from the input in the ***Field management*** menu, the development of the canopy cover (CC) after each cutting is simulated. Soil water, soil fertility, soil salinity stress may slow down the canopy development during the season;
- **Crop transpiration:** By considering ETo, the simulated CC adjusted for micro-advective effects (CC*), the crop transpiration coefficient for maximum canopy cover ($Kc_{Tr,x}$) and the possible stresses (cold stress, closure of stomata as a result of water and/or salinity stress) AquaCrop simulates crop transpiration;
- **Soil evaporation** is simulated by considering (1-CC*) and ETo;
- **Soil water balance:** By considering the simulated crop transpiration and soil evaporation the soil water balance is adjusted each day;
- **Biomass and crop Yield**: From the simulated crop transpiration, the daily production of biomass (by considering WP*), the transfer of assimilates to above or below-ground organs, and crop Yield (by considering HI), is obtained.

2.13.6 Program settings

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

Table 2.13n – 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

2.13.7 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 2.13p. For the playlist go to FAO AquaCrop website http://www.fao.org/nr/water/aquacrop.html

Table 2.13p – 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).

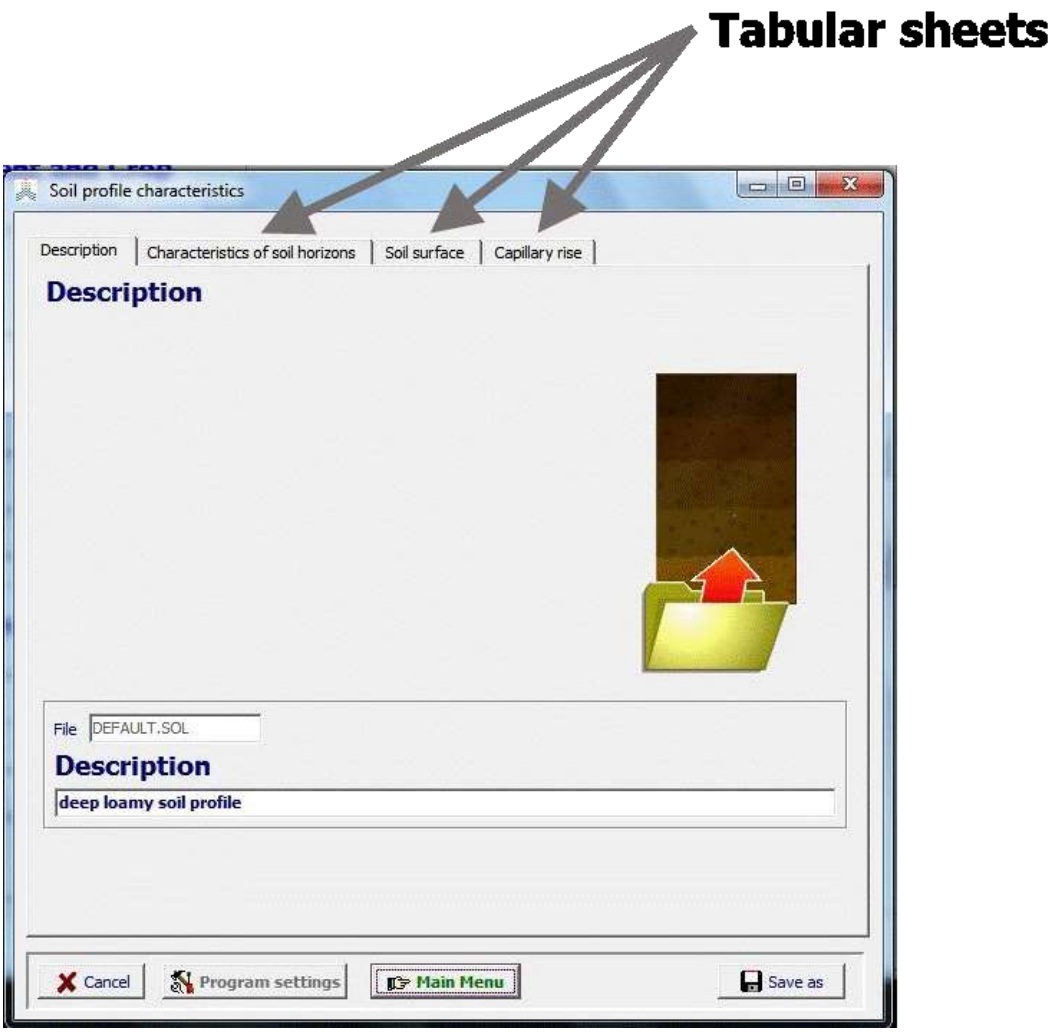


Figure 2.14a – The *Soil profile characteristics* menu with its tabular sheets: 'Description' (displayed), 'Characteristics of soil horizons', 'Soil surface', and 'Capillary rise'

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.

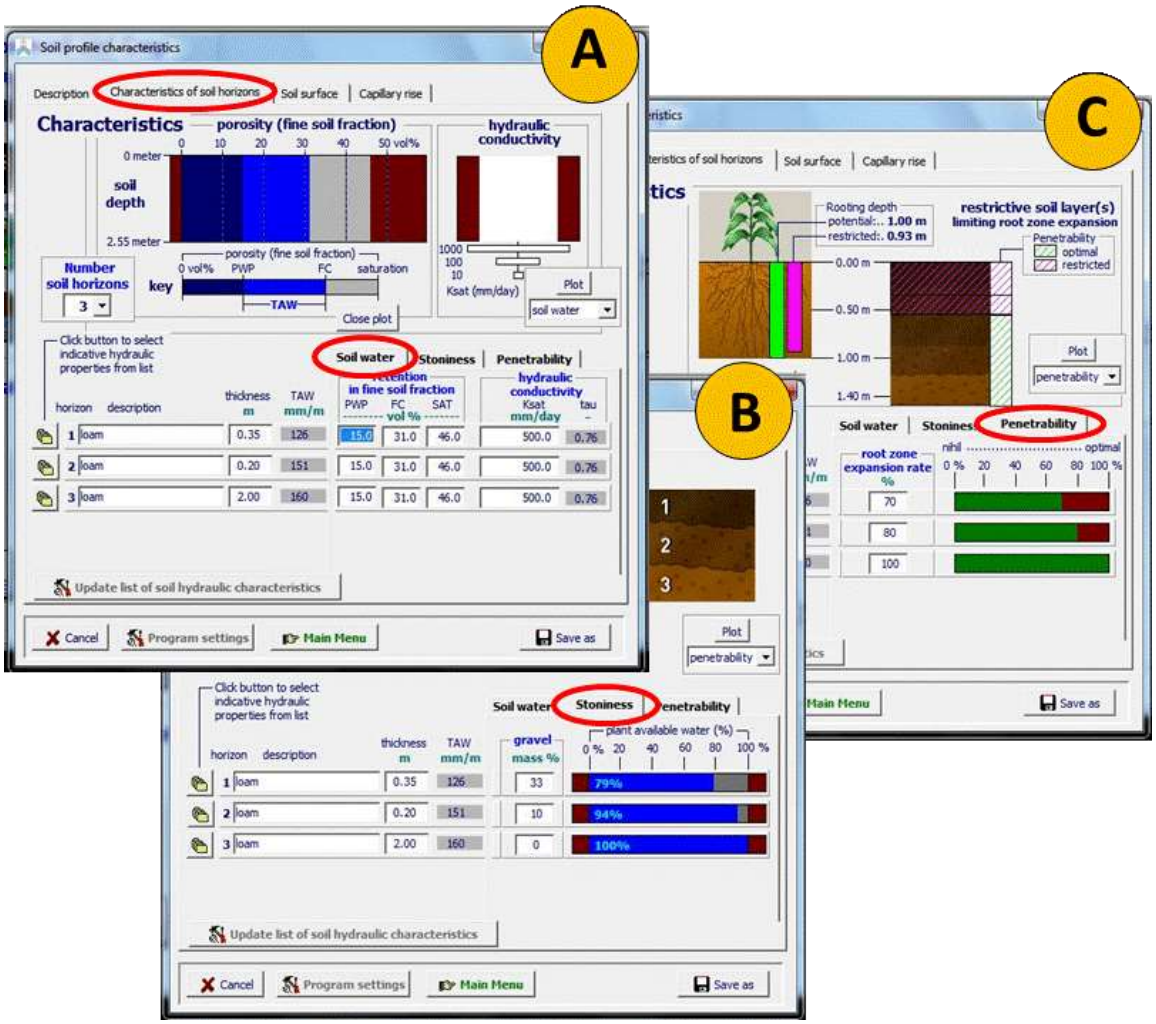


Figure 2.14b – Specification of physical characteristics of the various soil horizons in the (A) 'Soil water', (B) 'Stoniness' and (C) 'Penetrability' tab-sheet in the *Soil profile characteristics* menu.

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 ($Mass\%_{gravel}$):

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

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

- 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 $Mg.m^{-3}$	Bulk densities that may affect root growth $Mg.m^{-3}$	Bulk densities that restrict root growth $Mg.m^{-3}$
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 (Ksat) 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 Ksat, 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 Ksat. 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 Ksat, 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.

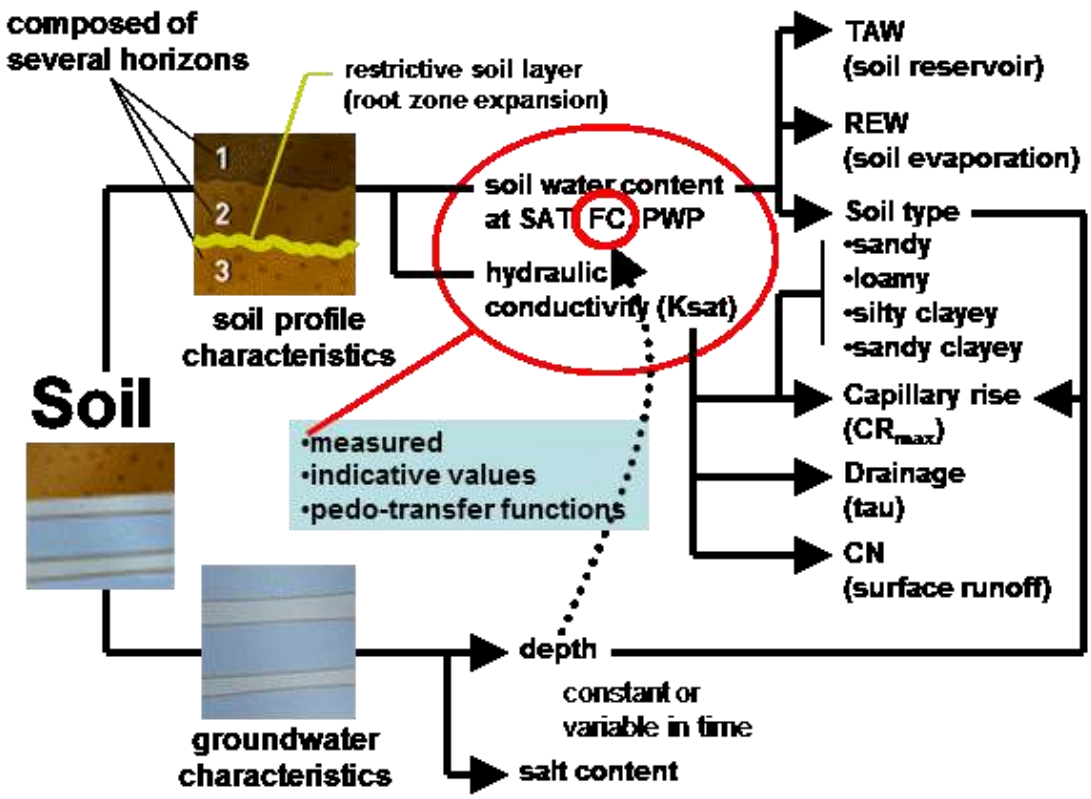


Figure 2.14c – Soil physical and groundwater table characteristics

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.

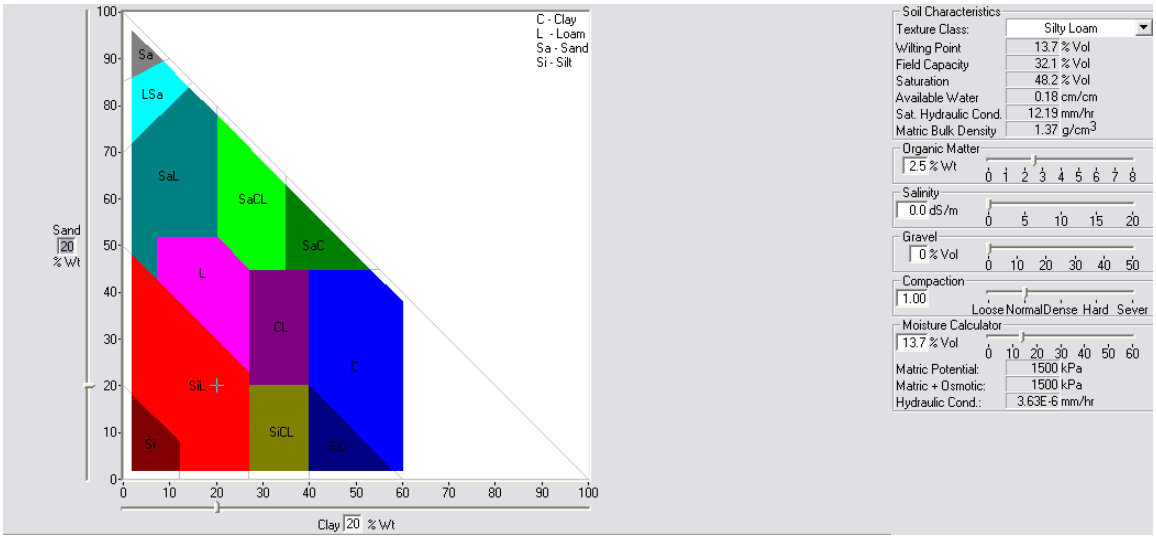
The user can make use of indicative values provided by AquaCrop for various soil textural classes (Tab. 2.14c), or import locally determined or derived data from soil texture with the help of pedo-transfer functions (Box 2.14). The values presented in Table 2.14c are derived with the help of pedo-transfer functions are only indicative values. The default values for the hydraulic conductivity at saturation (Ksat) 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 (Ksat) 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



Calculator developed by the USDA Agricultural Research Service in cooperation with the Washington State University (Keith E. Saxton: ksaxton@wsu.edu) available at Internet: http://http//hydrolab.arsusda.gov/soilwater/Index.htm

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.

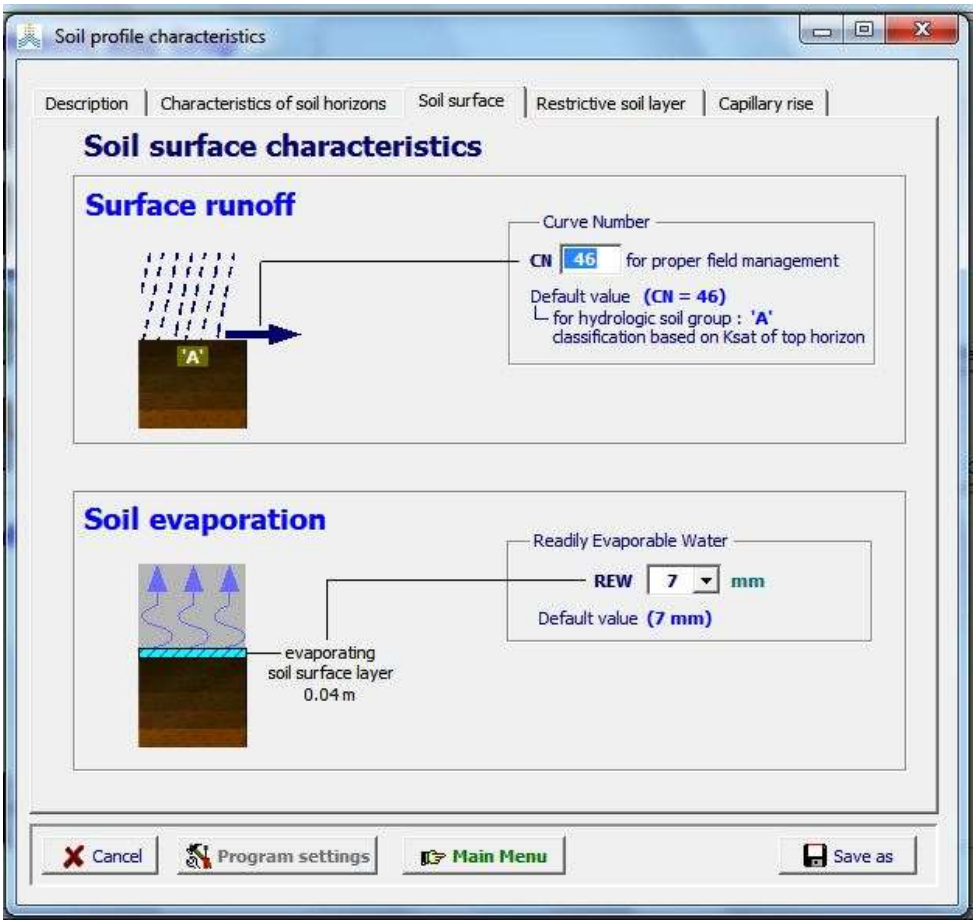


Figure 2.14d – Characteristics of the soil surface layer

Table 2.14d – Hydrologic soil groups, the corresponding range for the saturated hydraulic conductivity (Ksat) 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).

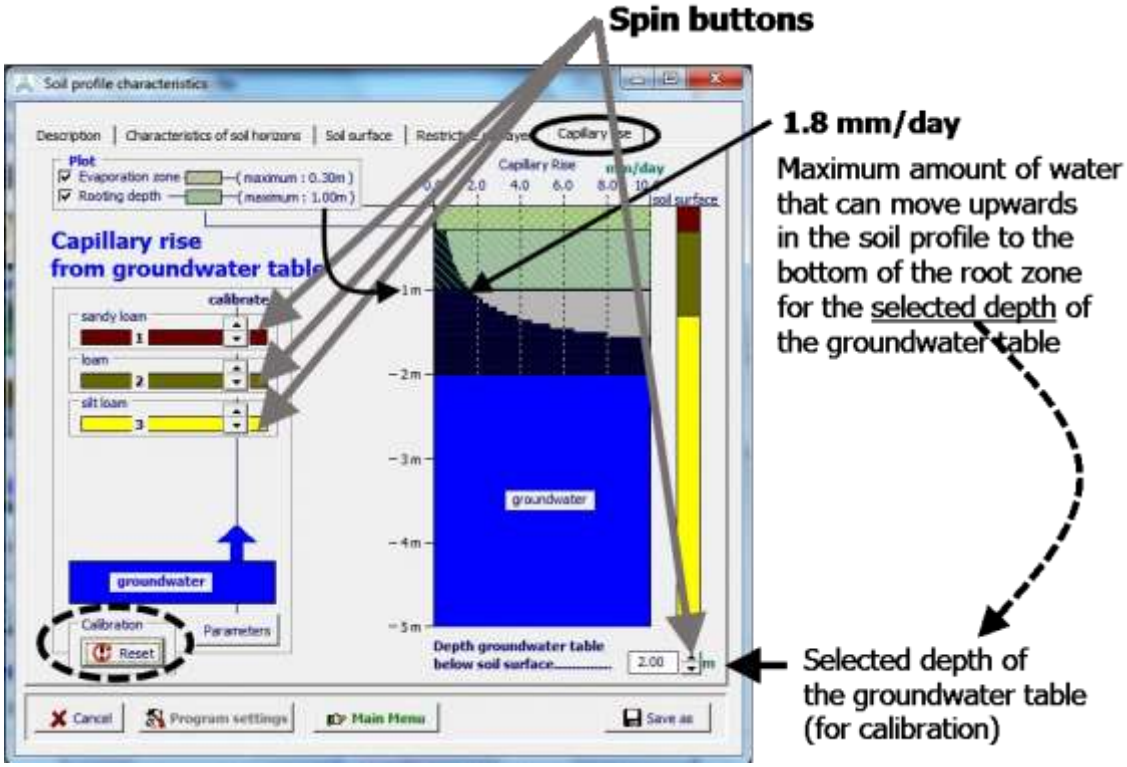


Figure 2.14e – The 'Capillary rise' tabular sheet of the *Soil profile characteristics* menu in which the maximum amount of water that can be transported upwards to the bottom of the root zone (for the specified crop), can be calibrated with the help of spin buttons, for a selected groundwater table 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	
	▪ 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	
	▪ Salt diffusion factor (expressing the capacity of salt diffusion in the soil matrix ▪ Salt solubility	20 % 100 g/litre
	Capillary rise	
	▪ 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.

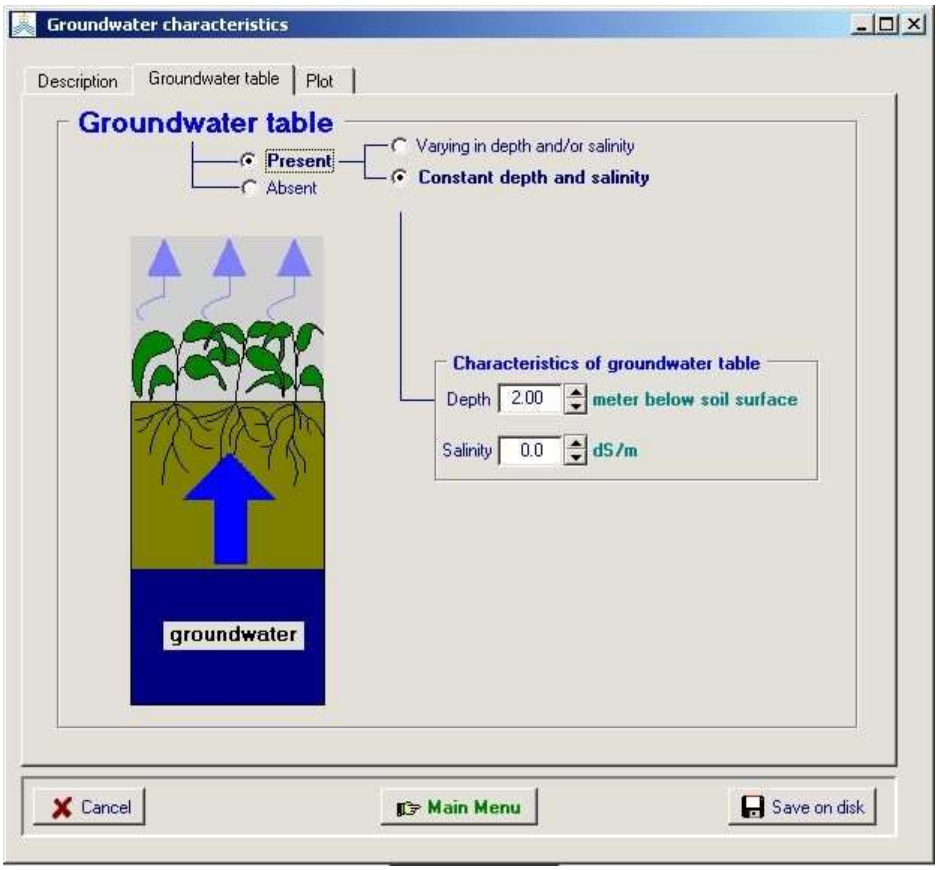


Figure 2.15a – Specifying the constant characteristics of a groundwater table in the Groundwater table tab sheet of the ***Groundwater characteristics*** menu.

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).

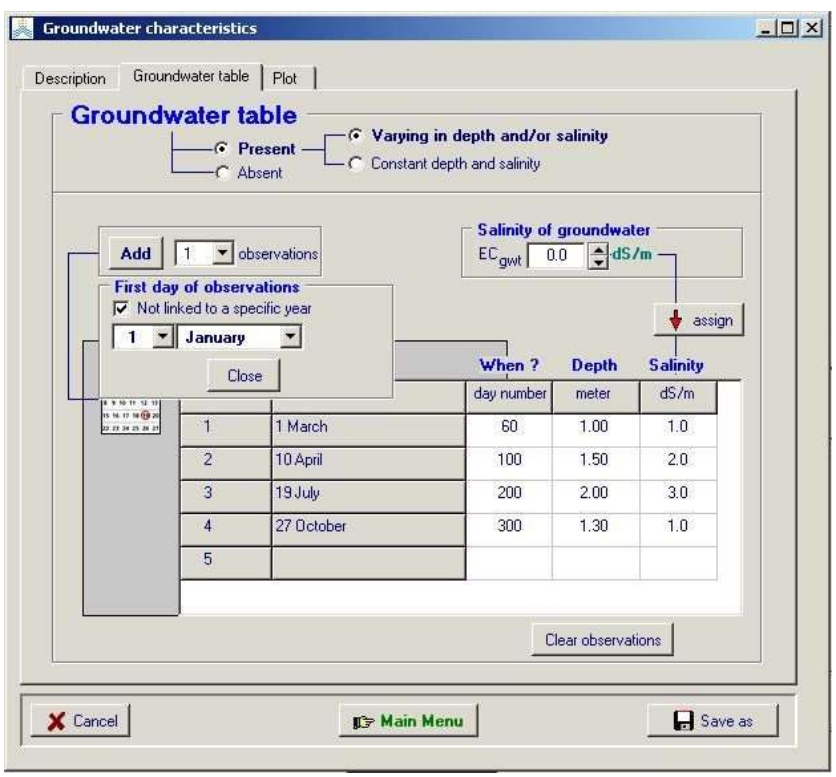


Figure 2.15b – Specifying the variable characteristics of a groundwater table not linked to a specific year in the ***Groundwater characteristics*** menu

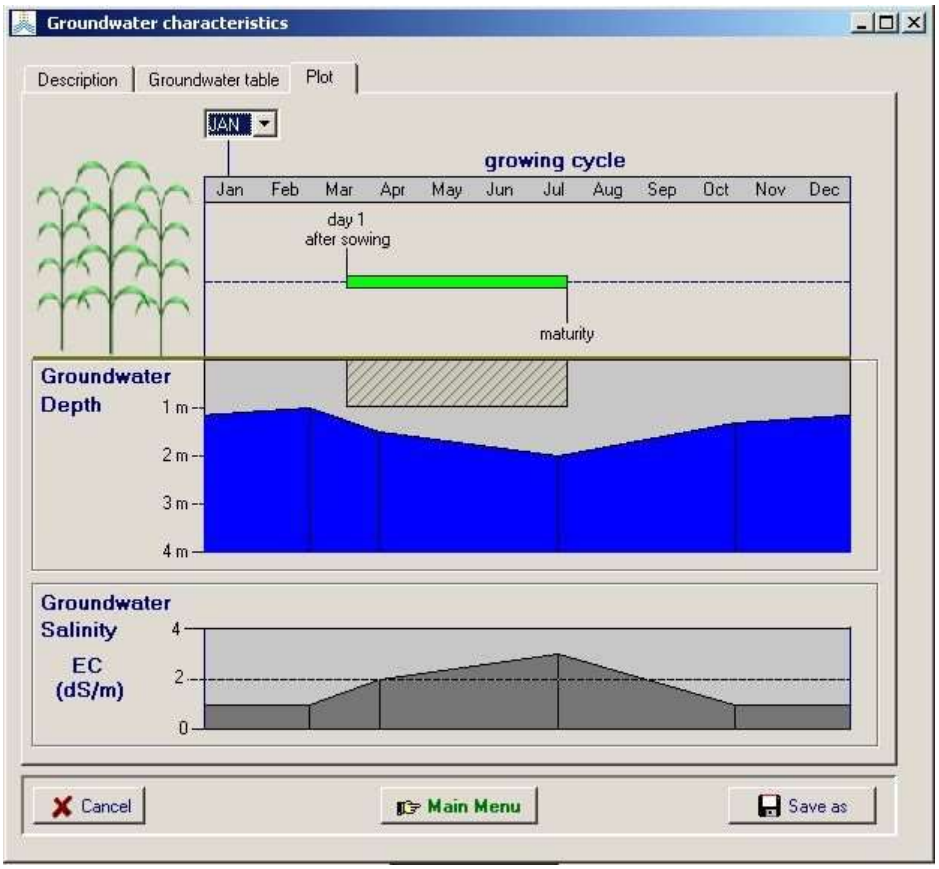


Figure 2.15c – Graphical display of the variable characteristics of a groundwater table not linked to a specific year in the ***Groundwater characteristics*** menu.

- **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.

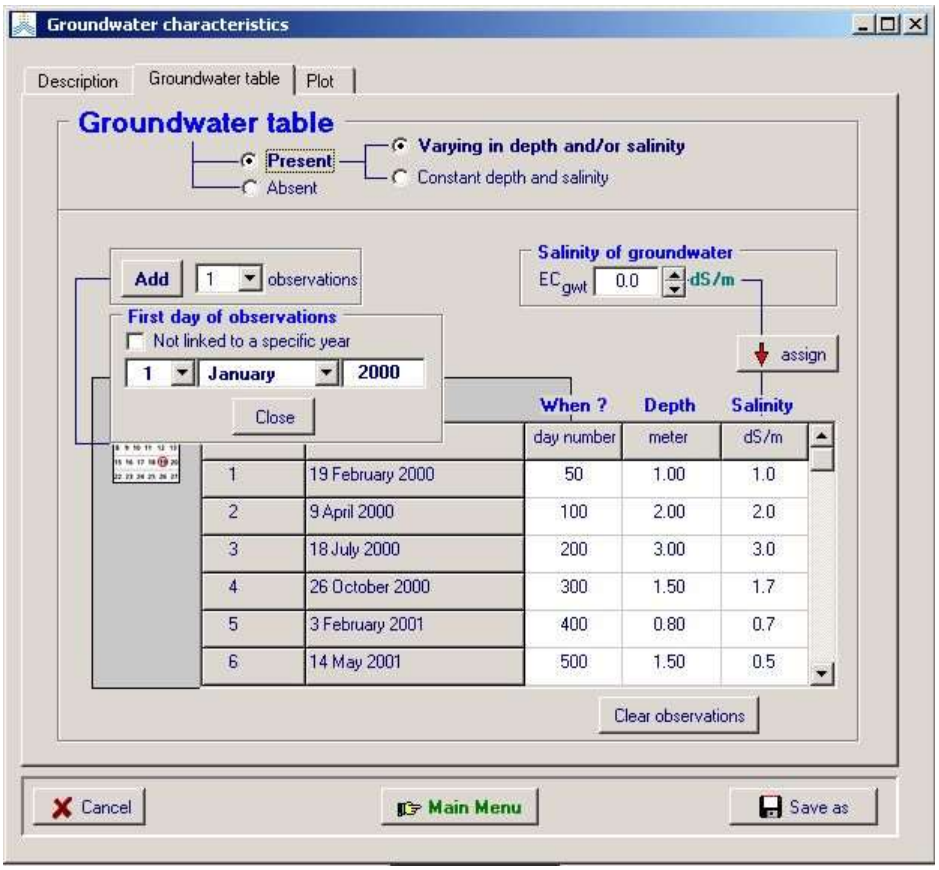
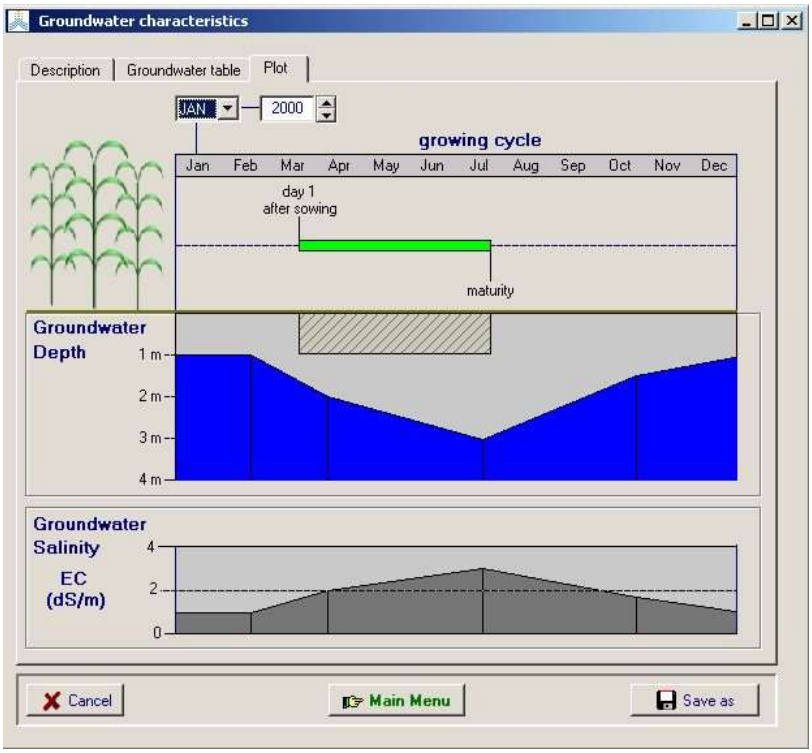


Figure 2.15d – Specifying the variable characteristics of a groundwater table linked to a specific year in the ***Groundwater characteristics*** menu.



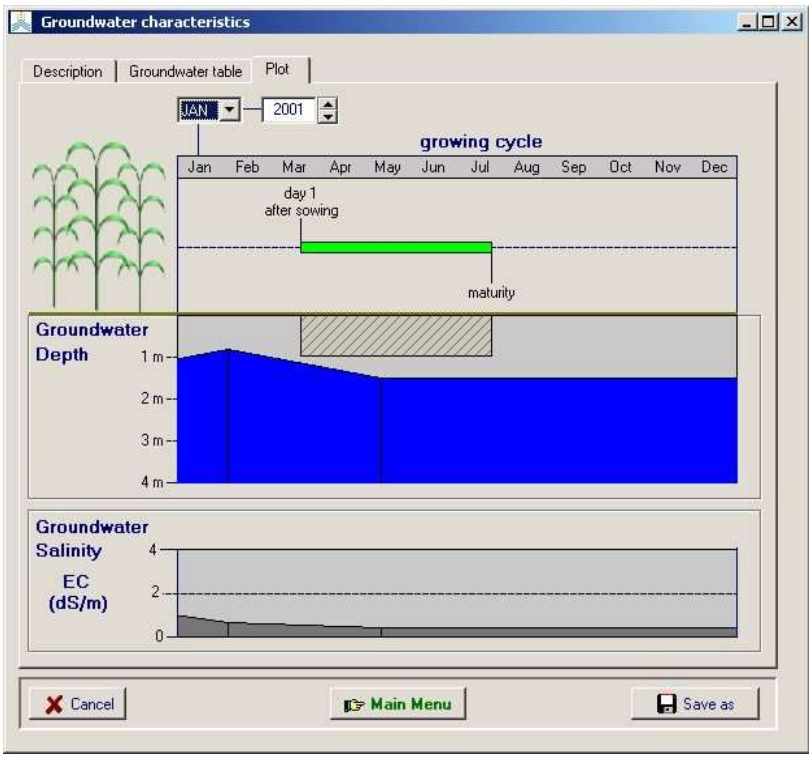


Figure 2.15e – Graphical display of the variable characteristics of a groundwater table linked to specific years (2000 and 2001) in the ***Groundwater characteristics*** menu

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.

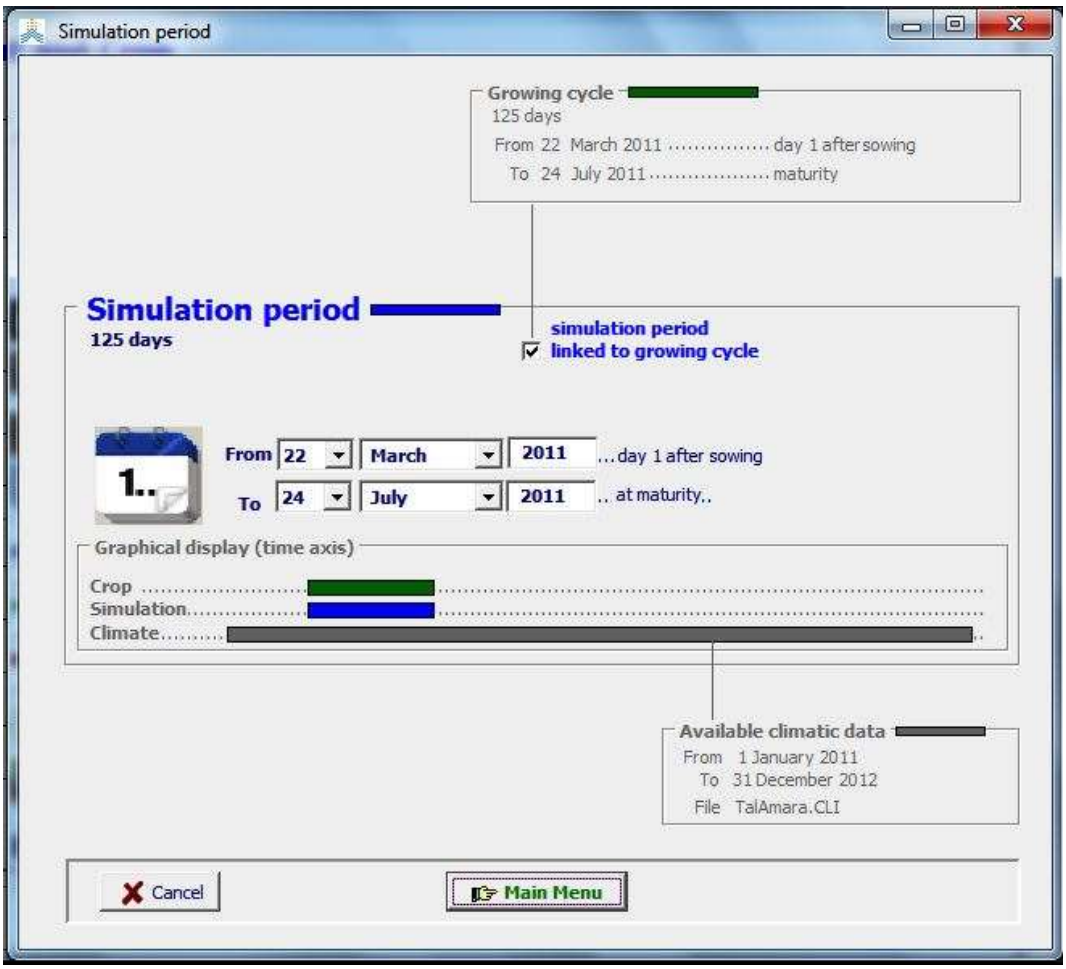


Figure 2.16a – Specification of the simulation period in the *Simulation period* menu (linked to the growing cycle)

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

No longer supported

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

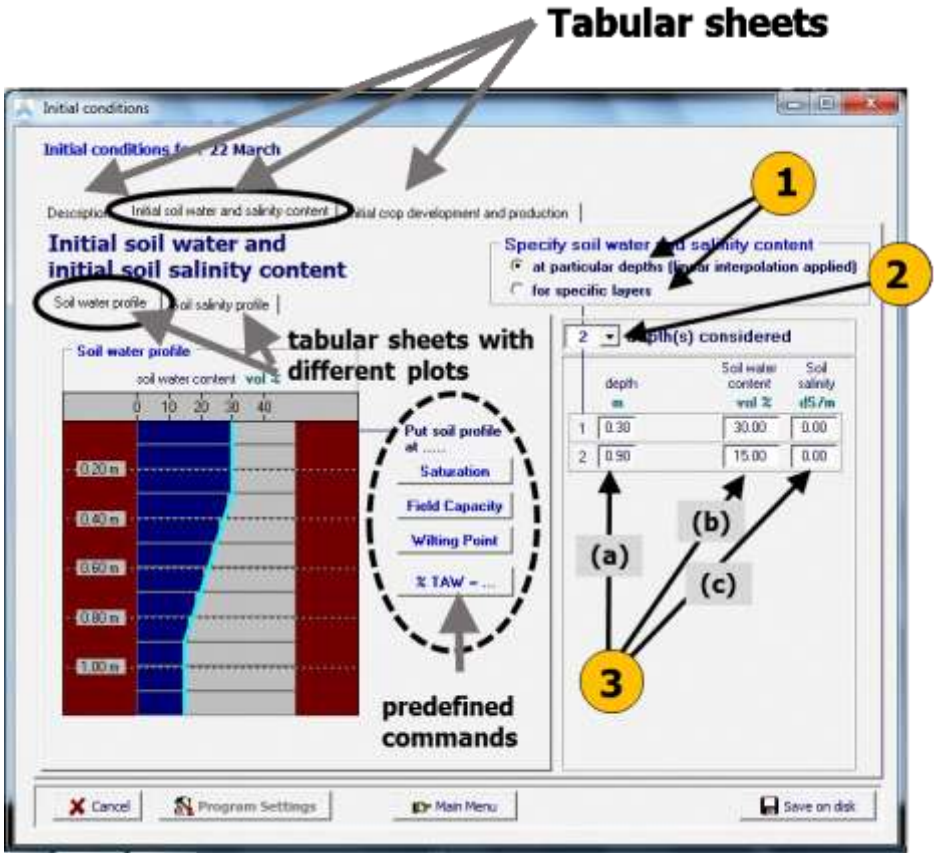


Figure 2.17a – The *Initial conditions* menu with its tabular sheets: 'Description', 'Initial soil water and salinity content' (displayed), and 'Initial crop development and production'.

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 $\theta_{initial}$ 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).

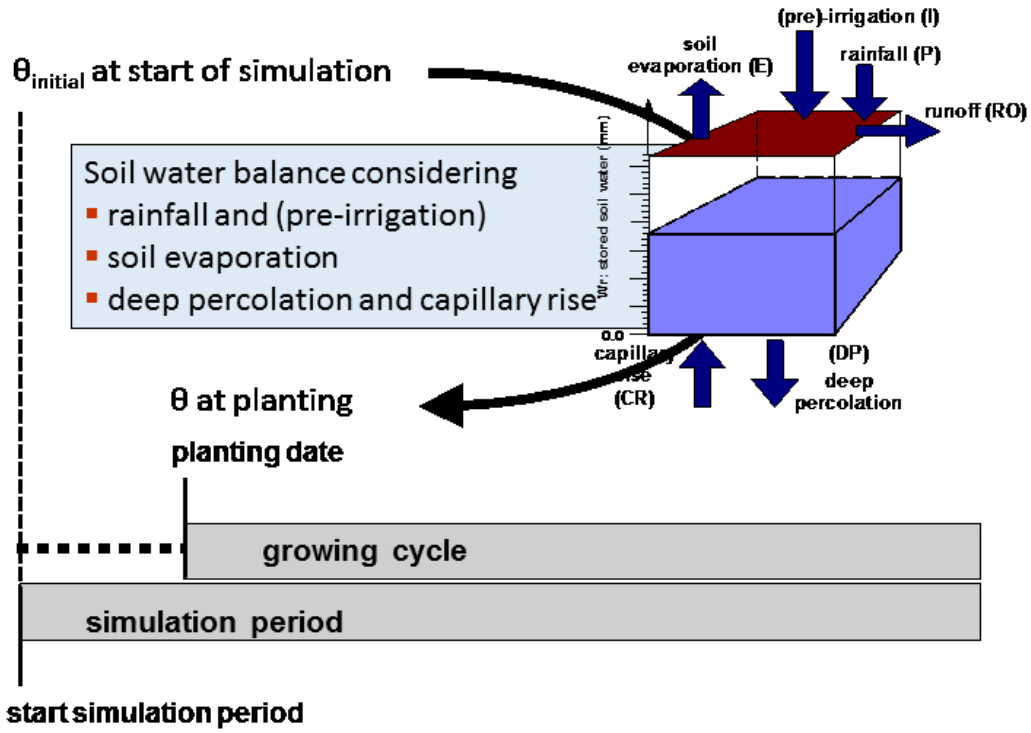


Figure 2.17b – Determination of the soil water content at planting by considering the weather conditions between the start of the simulation and the sowing/planting date

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).

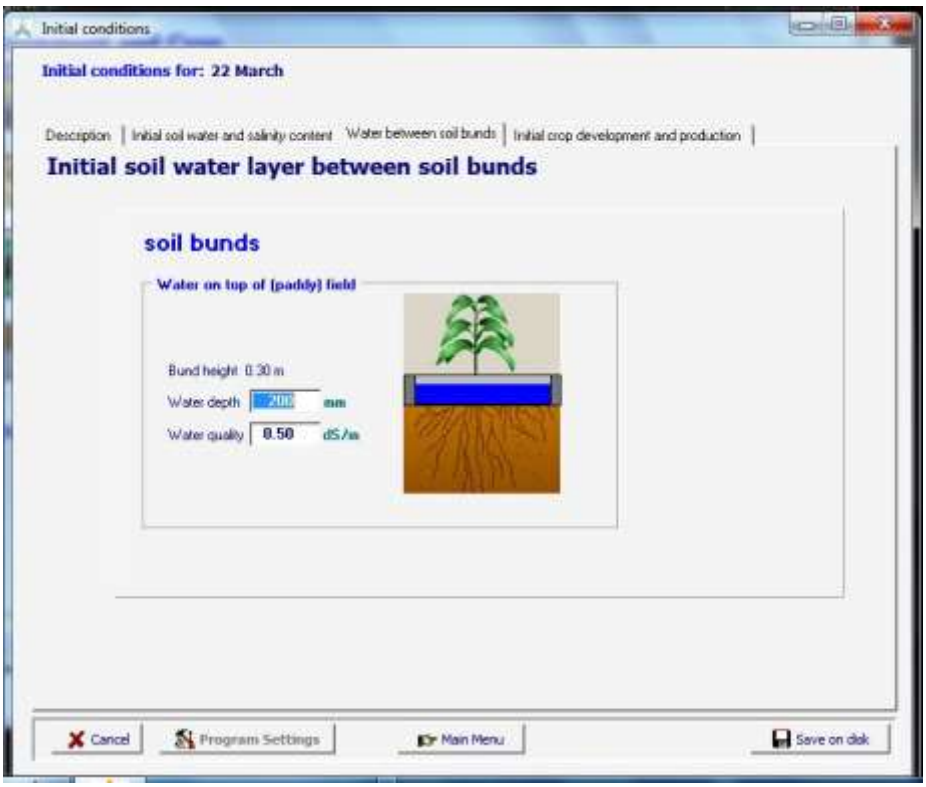


Figure 2.17c – Specification of the depth and quality of the water between soil bunds at the start of the simulation period in the *Initial conditions* menu when soil bunds are present

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 necessary 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.

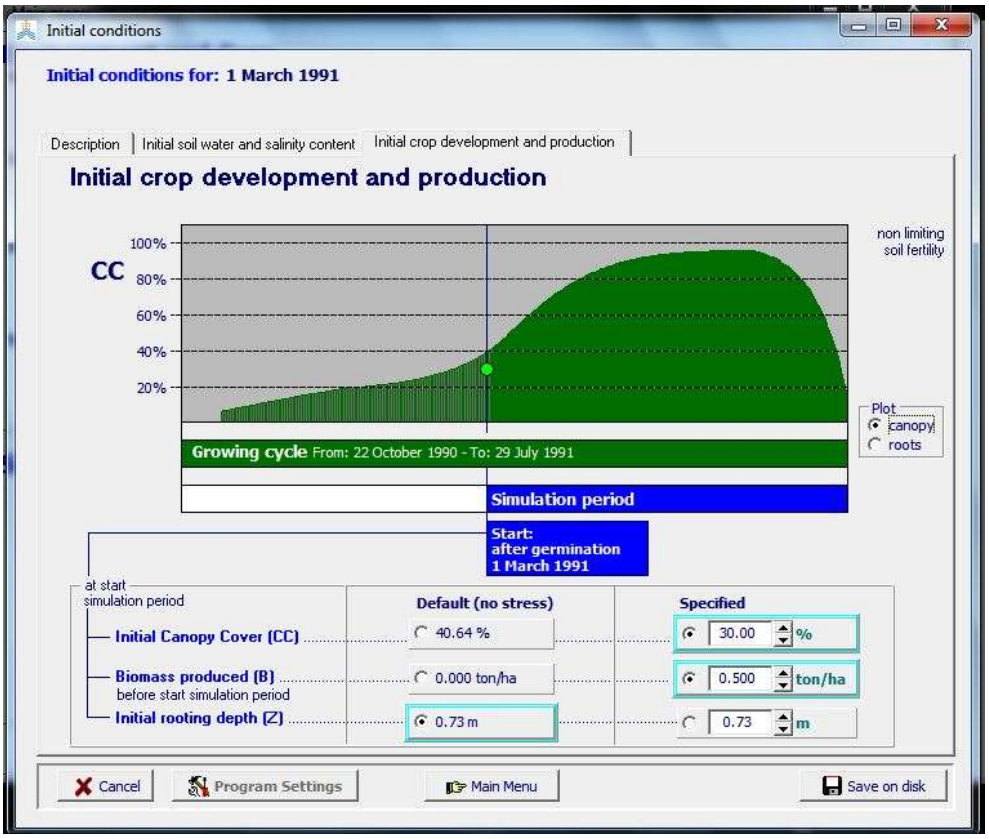


Figure 2.17d – Specification of the green Canopy Cover (CC) and produced Biomass (B) at the start of the simulation period in the *Initial conditions* Menu for a simulation period which starts after germination

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).

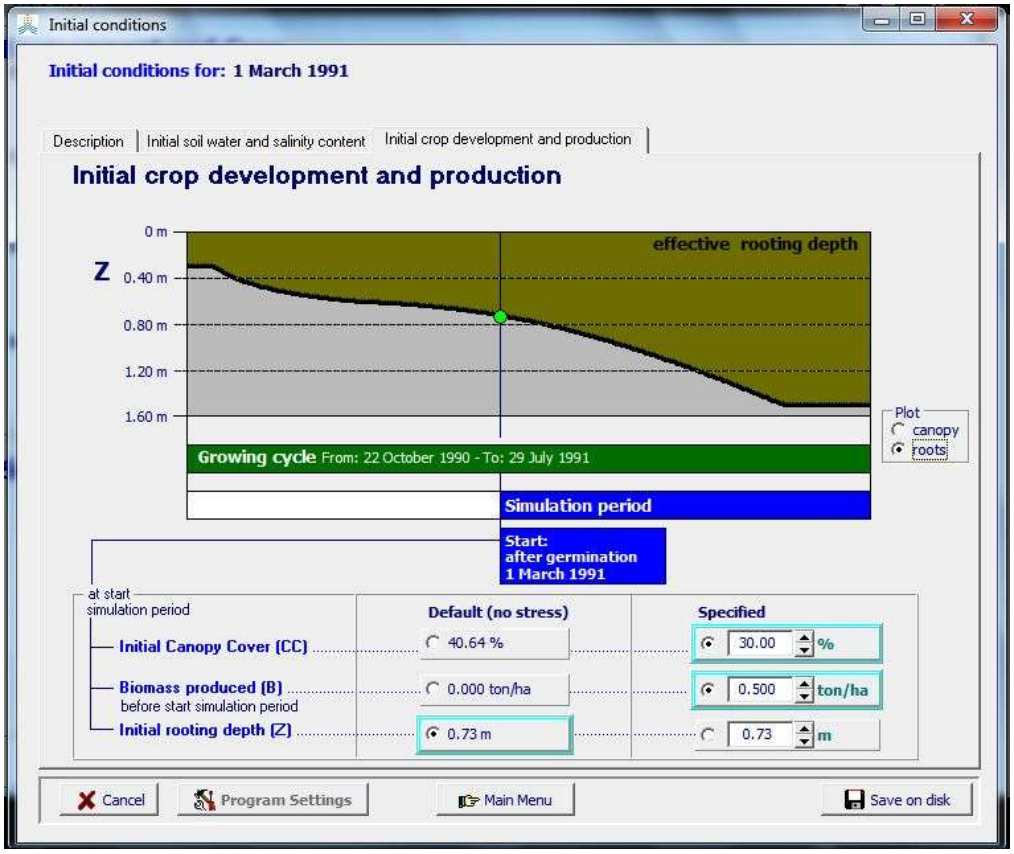


Figure 2.17e – Specification of the rooting depth (Z) at the start of the simulation period in the *Initial conditions* Menu for a simulation period which starts after germination

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.

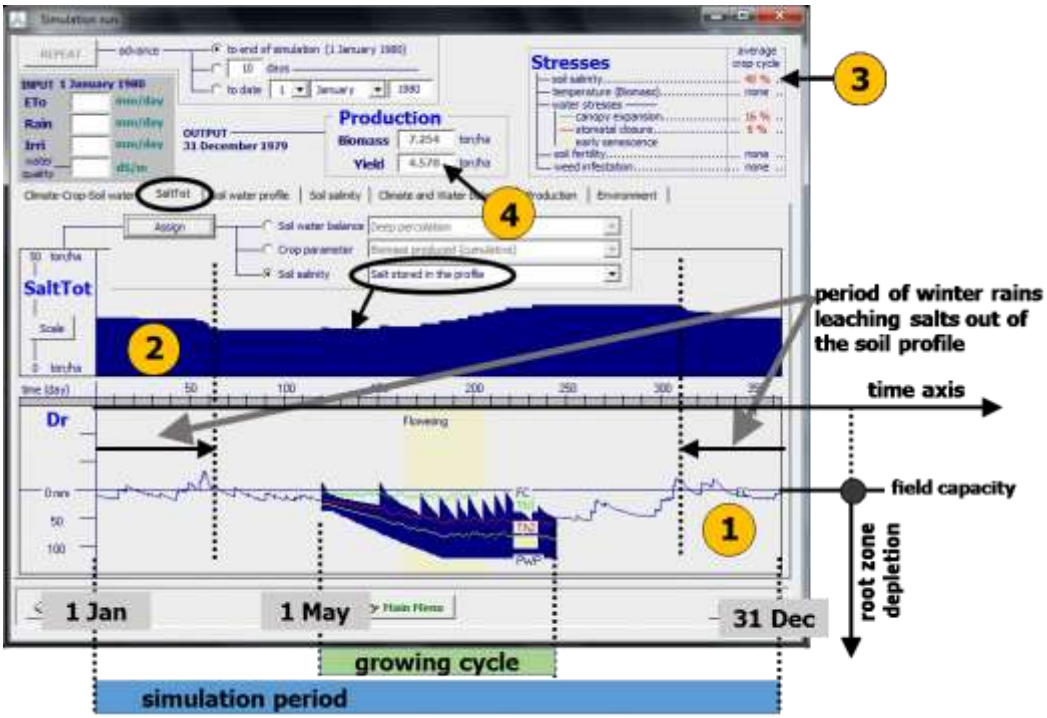


Figure 2.17f – Display, in the *Simulation run* menu, of (1) root zone depletion, (2) salt stored in the soil profile, (3) soil salinity stress and (4) crop yield, as a result of irrigating with water of poor quality and the leaching effect of winter rains in the off-season. Runs were repeated for a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

2.17.5 Hot starts within the growing cycle

No longer supported

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).

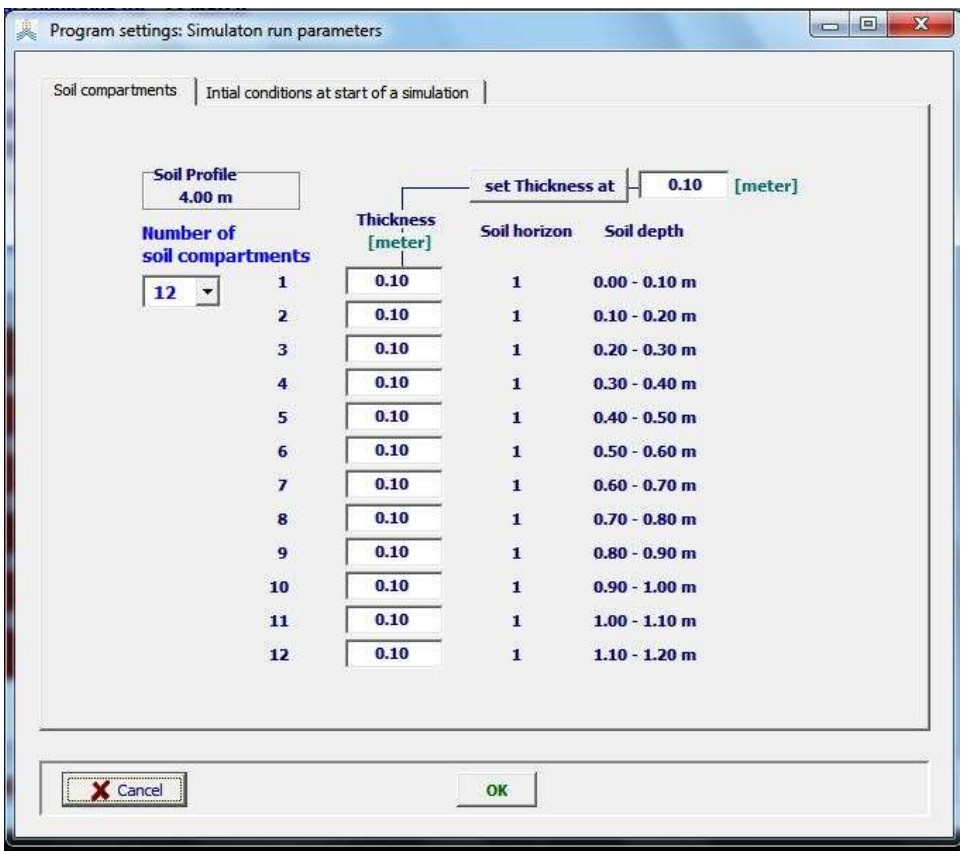


Figure 2.17j – Specification of the number and thickness of the soil compartments in the *Program settings: Simulation run parameters* menu

- **Initial conditions at start of a simulation**

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.

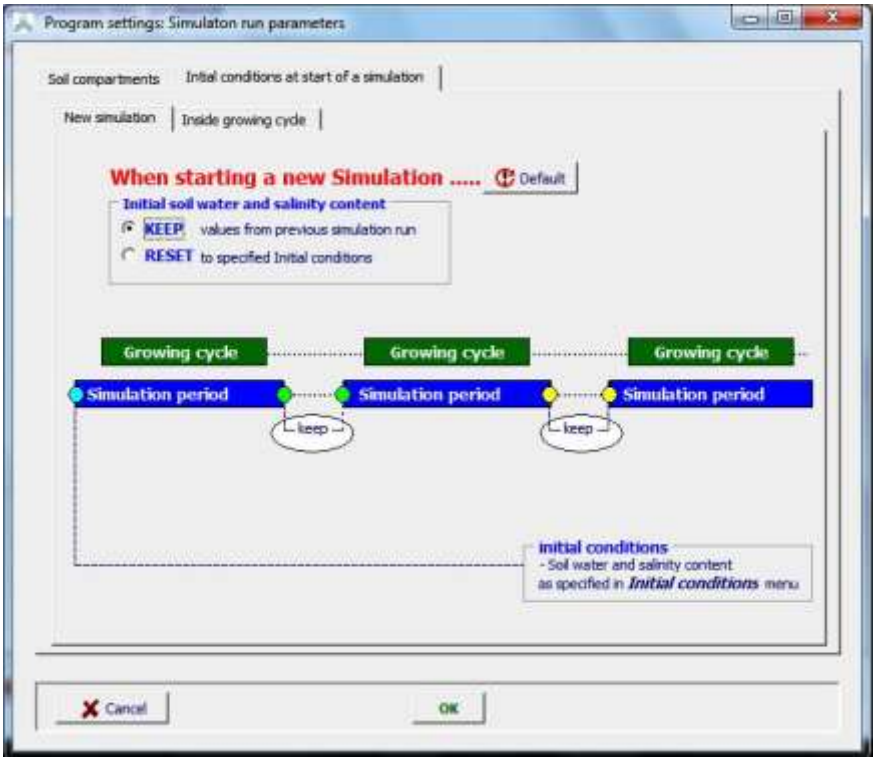


Figure 2.17k – Specification of the program parameter for the initial soil water and soil salinity content in the *Program settings: Simulation run parameters* menu

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**>).

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.

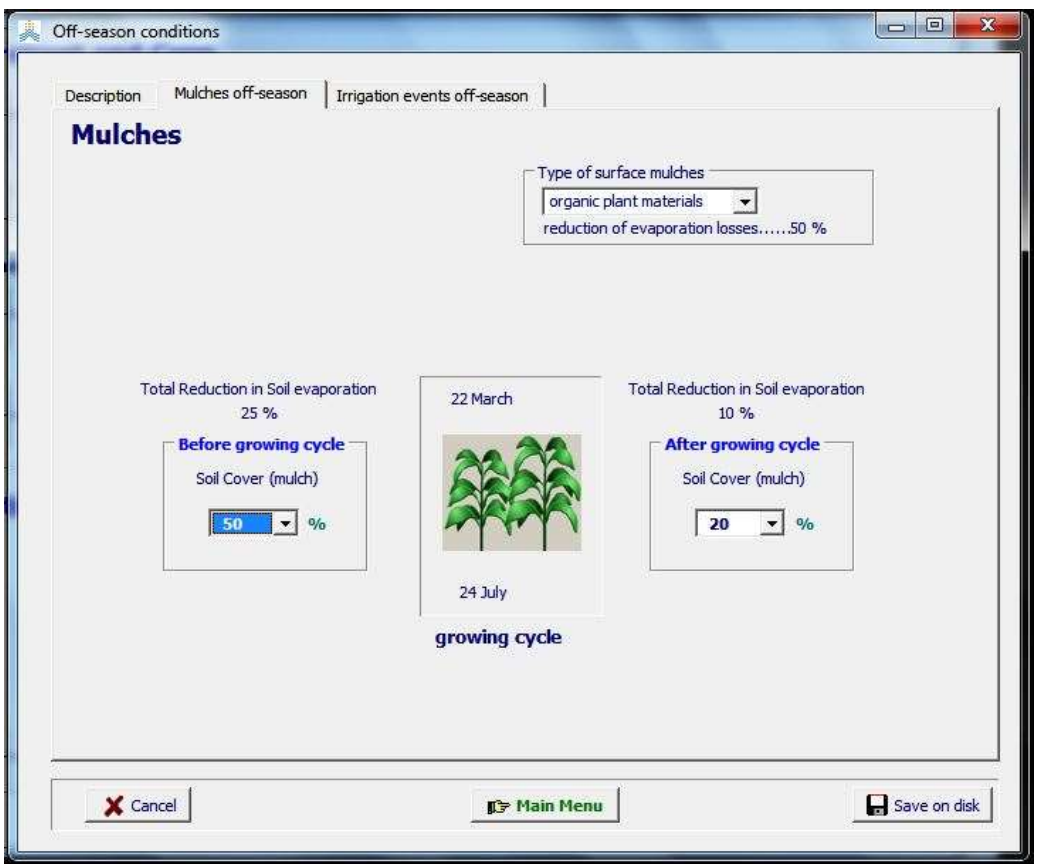


Figure 2.18a – Specification of mulches in the *Off-season conditions* menu

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.

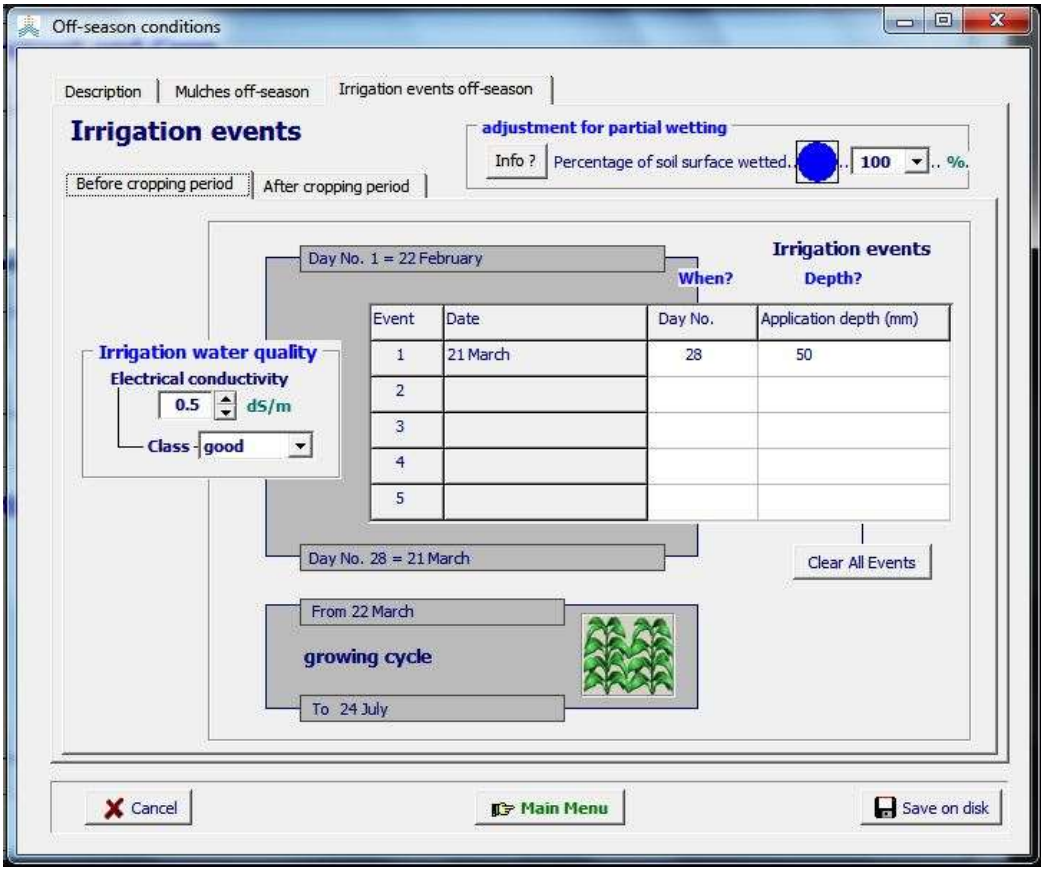


Figure 2.18b – Specification of a pre-irrigation in the *Off-season conditions* menu

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 select in the Main menu the sowing date or crop calendar, the simulation period and the appropriate environmental, initial and off-season files (Project file is 'None').

The user can also create or load a project file containing all the required information for a simulation run. In the ***Select project file*** menu, the user can select a project from the list of available projects (section 2.19.2) or find the access to the ***Create project*** menu (section 2.19.3). Once a project file is loaded, its characteristics can be displayed in the ***Display of project characteristics*** menu (section 2.19.5) and adjusted in the ***Project characteristic*** menu (section 2.19.6).

NOTE:

The structure of project files and available options differ from the structure and options in previous AquaCrop versions. As such project files of previous AquaCrop versions can no longer be loaded in Versions 7.0. However, all other files (climate, crop, soil, management, ...) of previous AquaCrop versions can still be loaded when creating a new project in AquaCrop Version 7.0.

2.19.1 Project types

Distinction is made between projects containing the required information for a single simulation run (Single run project with 'PRO' as filename extension) and projects consisting of a set of successive runs, the so called multiple run projects with 'PRM' as filename extension. When running 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 simulations for a number of successive years, for a particular field or irrigation management. The structure of the project file is given in Section 2.19.7.

The settings for the program parameters are saved in another text file which has the same file name as the project, but with the filename extension 'PP1' (for single run projects) and 'PPn' (for multiple run projects). The structure of the program parameters file is given in Section 2.19.7.

2.19.2 Selecting a project and program parameter file

- **Project**

By selecting the **<Project>** command and subsequently 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 one of the available project files can be selected (Fig. 2.19a).

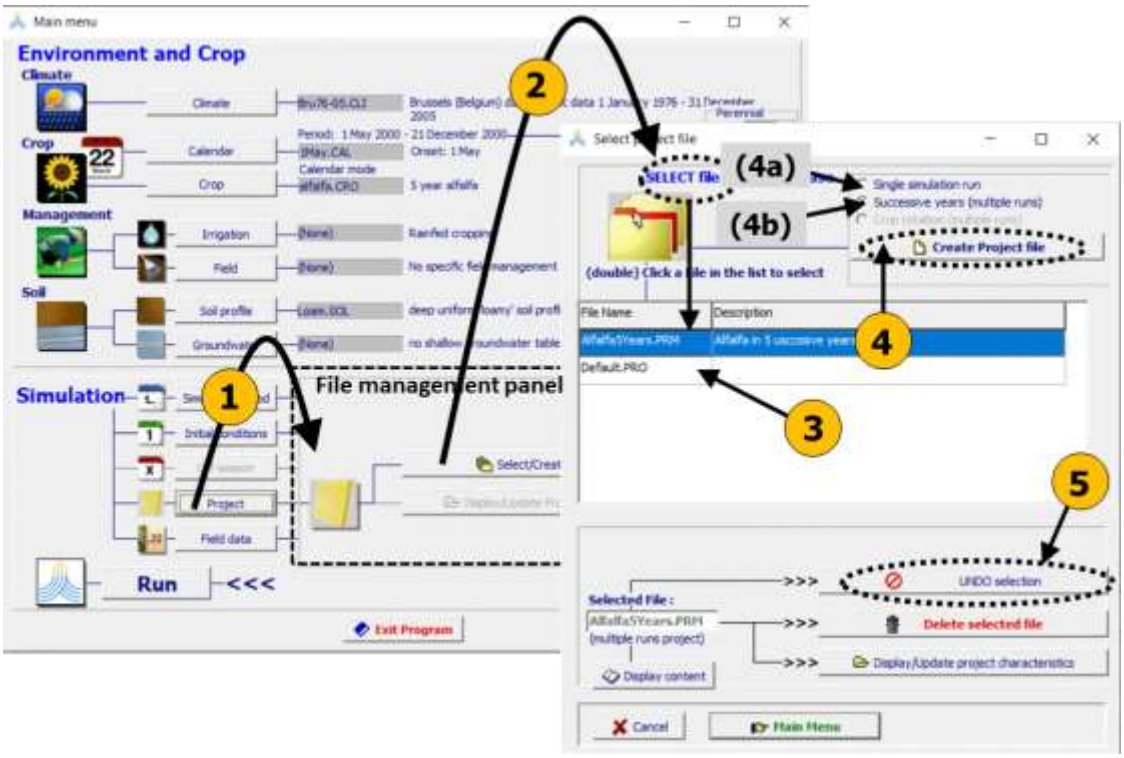


Figure 2.19a – By selecting (1) the <Project> command and subsequently (2) the <Select/Create Project file> command in the file management panel of the *Main menu*, the user gets access to the *Select project file* menu, in which (3) one of the available project files can be selected, (4) the <Create project file> command can be selected and its type can be specified: '4a' (Single simulation run), or '4b' (Successive years (multiple runs)), and (5) the project selection can be undone.

- **Program parameters**

When loading a project (files with extension PRO or PRM), AquaCrop also load the corresponding file with the Program Parameters (file with the same name, but with filename extension PP1 or PPn). In absence of a program parameter file, the project will run with the default settings for the program parameters (Table 2.19a).

Table 2.19a – Default setting for program parameters

Settings for crop program parameters (12 parameters)	
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) in which soil water depletion has to be determined
Settings for field program parameters (1 parameter)	
30	Depth [cm] of soil profile affected by water extraction by soil evaporation
Settings for soil parameters (5 parameters)	
0.30	Considered depth (m) of soil profile for calculation of mean soil water content for CN adjustment
1	Adjustment of CN to Antecedent Moisture Class (1 = Adjusted)
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
Settings for temperature program parameters (3 parameters)	
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

Settings for 10-day or monthly rain program parameters (4 parameters)	
1	Procedure to estimate daily rainfall (when input is 10-day/monthly rainfall) (1 = USDA-SCS procedure)
70	Percentage of 10-day or monthly rainfall which is effective (when Procedure (option 2) is a fixed percentage)
2	Number of showers in a decade for run-off estimate (when input is 10-day/monthly rainfall)
5	Parameter for reduction of soil evaporation (when input is 10-day/monthly rainfall)

- **Undo project selection**

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), and
- all program parameters are rest to their default value

2.19.3 Creating a project

Creating a project becomes straight forward, when before launching the creation, the files containing the characteristics of the crop, calendar, environment (climate, management, and soils), initial conditions and field data for the specific run are already selected in the ***Main menu***. This is however not required since the user can still select other files in the ***Create project*** 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 option 4):

a) Single simulation run;
b) Successive years (multiple runs).

After selecting the **<Create project file>** command, the ***Create project*** menu is displayed (Fig. 2.19b, c, d, and e).

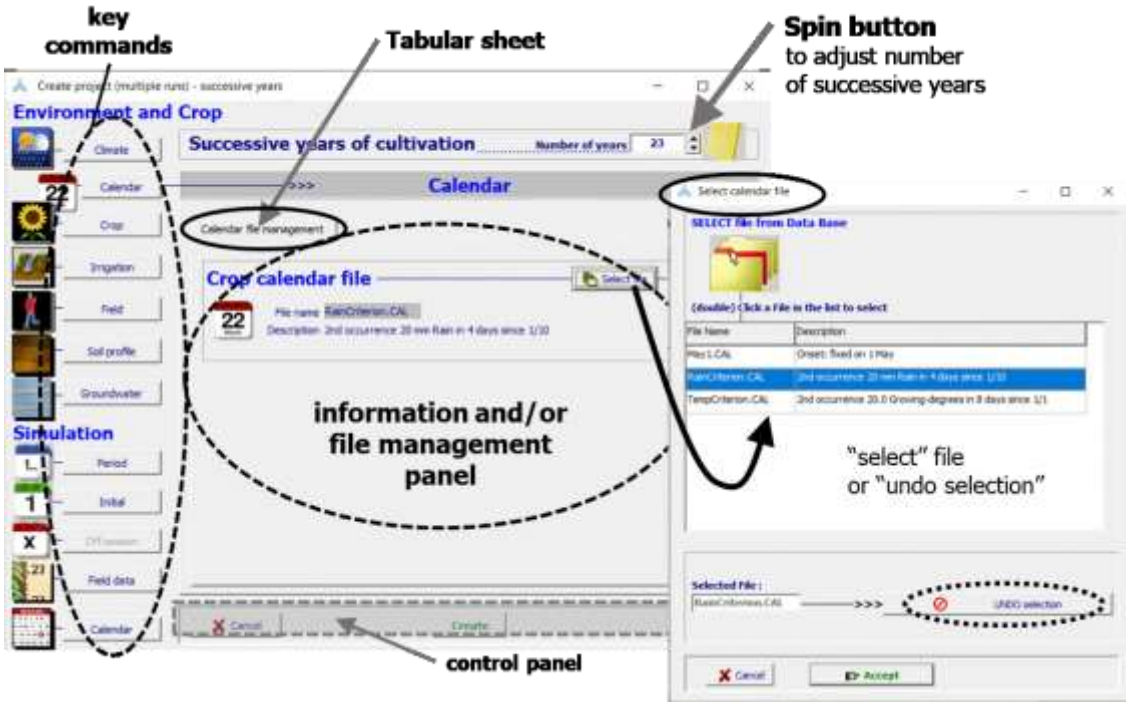


Figure 2.19b – The key commands in the *Create project* menu, with which information and/or file management panels can be displayed for file management and specification of required data

- **Number of successive years**

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 successive simulation runs) can be altered (Fig. 2.19b).

- **Information and File management panels**

By selecting one of the key commands at the left side of the ***Create project*** menu, a corresponding information and/or file management panel is displayed with indication of the selected file and required information if relevant (Fig. 2.19b). Another file can be selected or the selection can be undone in the ***Select file*** menu when selecting the **<Select file>** command (Fig. 2.19b). If no file is selected (File name is '(None)'), default conditions are considered (see 2.3 Default settings at start).

The data specified in the information and/or file management panel differ depending on the selected key command.

Climate

The name and description of the enveloping climate file and corresponding rainfall, ETo, air temperature and CO2 file are displayed, together with plots of the climatic data stored in the files.

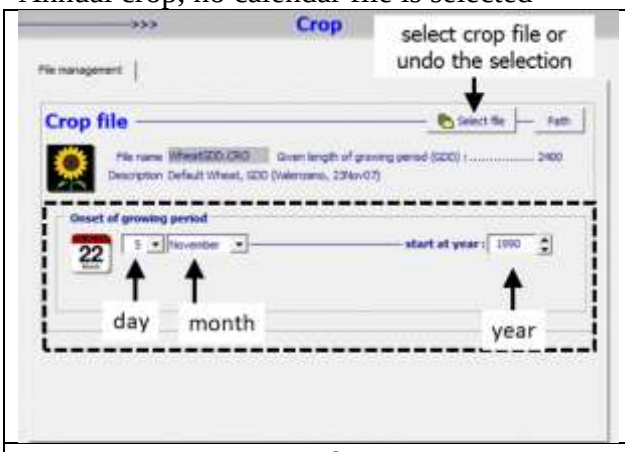
Calendar

The name and description of the selected crop calendar file are displayed (Fig. 2.19b);

Crop

The name and description of the selected crop file, with specification of the sowing/planting date, or the way it is determined, are displayed. The information differs if a calendar file is selected or not and if an annual or perennial crop is selected (Fig. 2.19c).

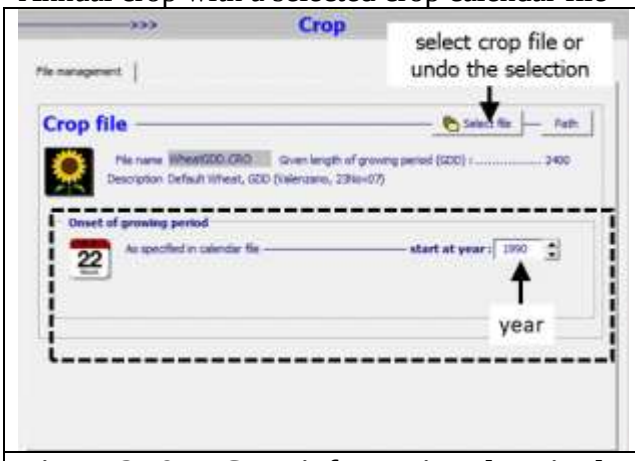
- Annual crop, no calendar file is selected



Specify:
- Day,
- Month, and
- Year (single project), or first Year of the series of successive years (multiple project)

Figure 2.19c – Crop information sheet in the *Create project* menu, in which the Onset of the growing period is specified and a crop file can be selected or the selection can be undone: Annual crops without a calendar file

- Annual crop with a selected crop calendar file



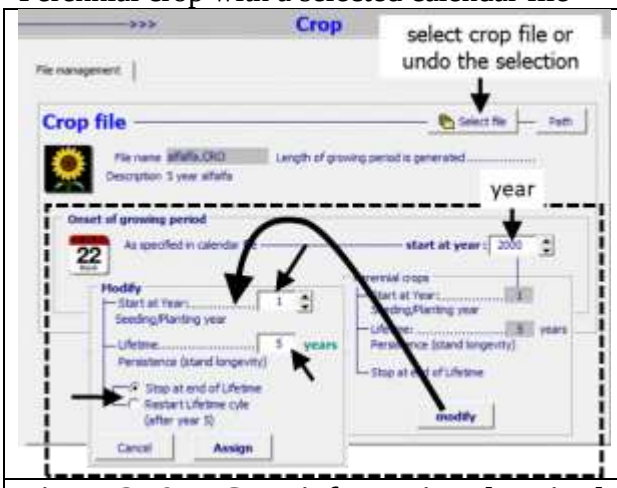
Specify:

- Year (single project), or first Year of the series of successive years (multiple project)

The year is the seeding/planting year of the annual crop

Figure 2.19c – Crop information sheet in the *Create project* menu, in which the Onset of the growing period is specified and a crop file can be selected or the selection can be undone: Annual crops with a calendar file

- Perennial crop with a selected calendar file



Specify:

- First year of the series of successive years;
- If the first year is, or is not, a Seeding/planting year;
- The lifetime (stand longevity) in number of years;
- If the series of successive runs has to stop or restart at end of the lifetime cycle

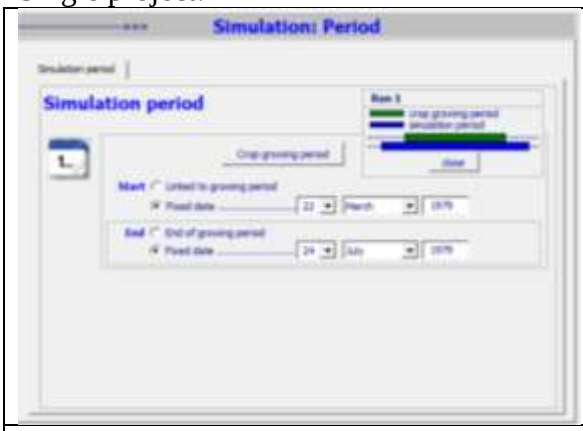
Figure 2.19c – Crop information sheet in the *Create project* menu, in which the Onset of the growing period is specified and a crop file can be selected or the selection can be undone: Perennial crops with a calendar file

<u>Irrigation</u>
The name and description of the selected irrigation management file are displayed;
<u>Field</u>
The name and description of the selected field management file are displayed;
<u>Soil profile</u>
The name and description of the selected soil profile file are displayed;
<u>Groundwater</u>
The name and description of the selected groundwater table file are displayed;

Simulation Period

The information differs between a single and multiple project (Fig. 2.19d).

- Single project:

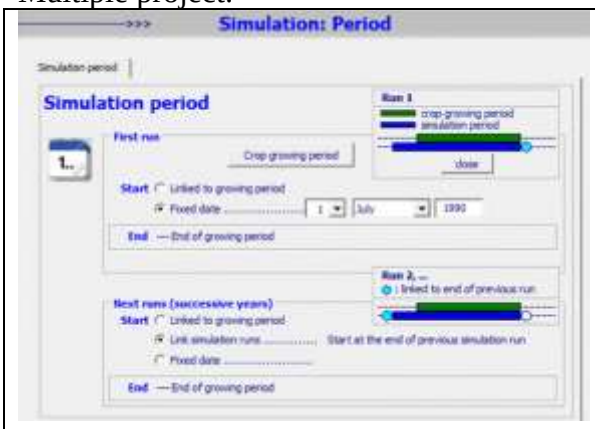


The start and end of the simulation period can be:

- linked to the growing cycle;
- specified on a fixed date.

Figure 2.19d – Simulation period information sheet in the *Create project* menu, in which the simulation period is specified: Single project

- Multiple project:



- The start of the simulation period of the first run can be:
  - A. linked to the growing cycle;
  - B. start at a specific date.
- The start of the simulation period for the next runs (successive years) can be:
  - C. linked to the growing cycle;
  - D. start at a specific date for each year;
  - E. 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');
- The end of the simulation runs corresponds always with the end of the growing period.

Figure 2.19d – Simulation period information sheet in the *Create project* menu, in which the simulation period is specified: Multiple project

Initial

The name and description of the selected file with the initial conditions are displayed;

Off-season
The name and description of the selected file with the off-season conditions are displayed;
Field data
The name and description of the selected file with Field data are displayed;
Calendar
Graphical and numerical display with the start, end and length of the growing cycle and simulation period in various tabular sheets (Fig. 2.19e).

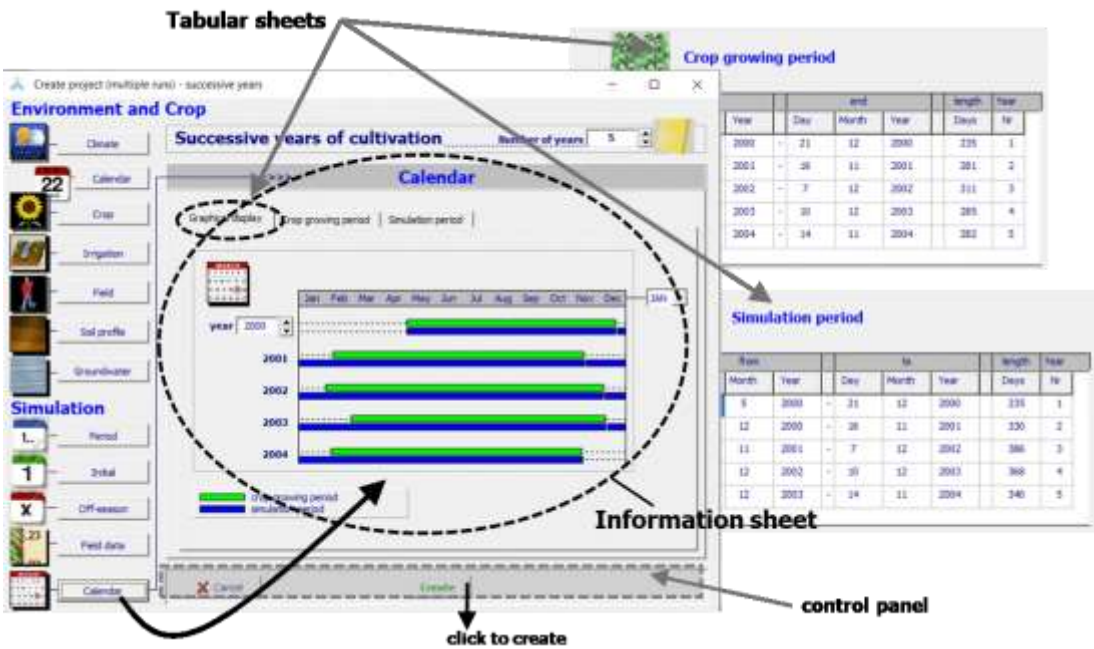


Figure 2.19e – The 'Calendar information sheet' in the Create project menu, with the graphical and numerical display of the start, end and length of the growing cycle (green bars) and simulation period (blue bars) in the various tabular sheets.

By selecting the <**Create**> command in the control panel at the bottom of the ***Create project file*** menu (Fig. 2.19e), the project is created. The structure and information of the project file is presented in section 2.19.7.

General remarks

1. If no file is selected default conditions are considered (see 2.3 Default settings at start).
2. Once a project is created, its content can be displayed in the ***Display of project characteristics*** menu (section 2.19.5) and the growing and simulation period, and the selection of files can be adjusted in the ***Project characteristics*** menu (section 2.19.6).

2.19.4 Running AquaCrop in project mode

Once a project is loaded (Fig. 2.19a) or created (Fig. 2.19e) the layout of the ***Main menu*** is adjusted (Fig. 2.19f). This is required to prevent the selection of files different from the one enclosed by the project, and the update of the content of the selected files. As such, the key commands for selecting other files are no longer available in the ***Main menu*** (Fig. 2.19f). 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 a multiple run 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), and
- all program parameters are rest to their default value

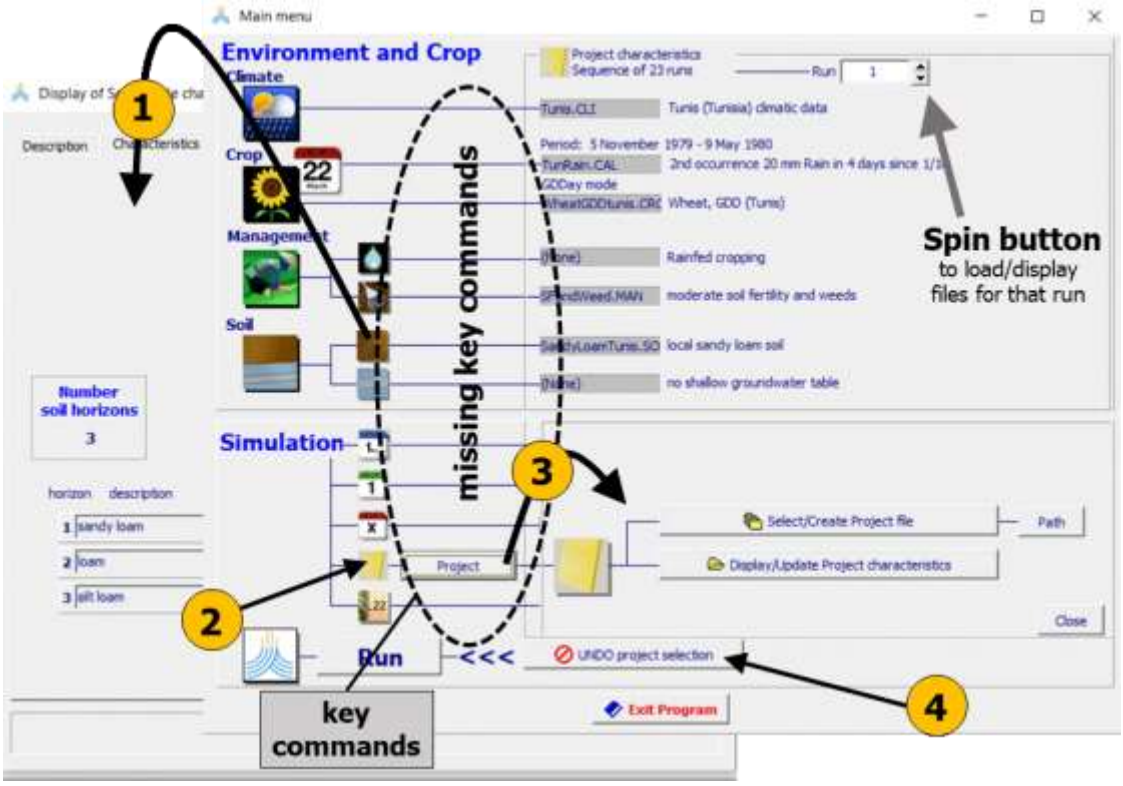


Figure 2.19f – The Main menu in project mode (with missing key commands), in which (1) characteristics of the input can be displayed, (2) characteristics of projects can be displayed (section 2.19.5), (3) characteristics of projects can be updated (section 2.19.6) and/or other projects can be created (section 2.19.3) or selected (section 2.19.2), and (4) the project selection can be undone (return to the default mode).

2.19.5 Display of project characteristics

By clicking on the project icon in the ***Main menu*** (Fig. 2.19f) the characteristics of the project are displayed (Fig. 2.19g). The files are listed in the 'Environment, Crop and Simulation files' tab-sheet. In case of a multiple run project the content for other runs (planting date, simulation period and set of files) can be displayed with the spin button at the top of the menu.

In the 'Calendar' tab-sheet, information on the start, end and length of the growing cycle and simulation period is available.

The selected program parameters are displayed in the 'Program settings' tabular sheet. In absence of a program parameter file, the default settings for the program parameters (Table 2.19a), by which the program will run, are displayed.

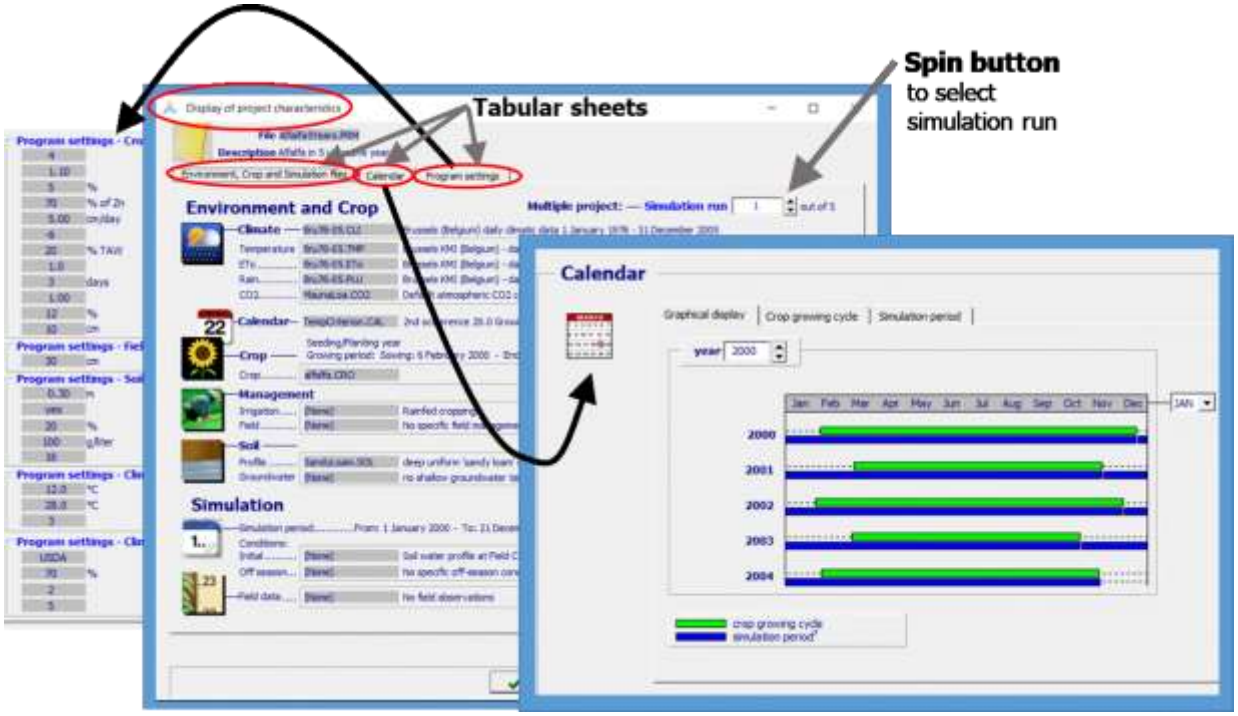


Figure 2.19g – The Display of project characteristics menu with its tabular sheets: 'Environment, Crop and Simulation files', 'Calendar', and 'Program settings'.

2.19.6 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. 2.19h).

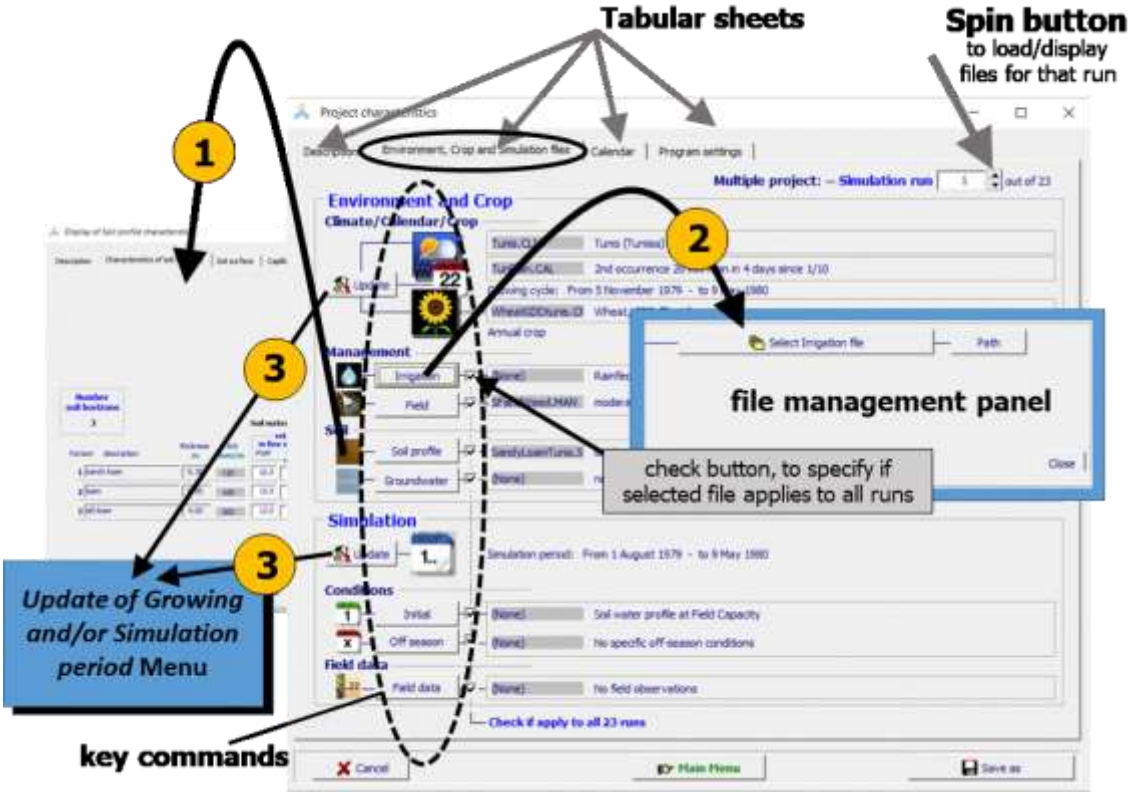


Figure 2.19h – The Project characteristics menu with its tabular sheets: 'Description', 'Environment, Crop and Simulation files' (displayed), 'Calendar', and 'Program settings'. In the 'Environment, Crop and Simulation files' tabular sheet (1) characteristics of the selected input files can be displayed, and (2) other input files can be selected in the appropriate file management panels, and (3) the growing and simulation period can be updated.

- **Tabular sheets**

<u>Description</u>

To adjust the description of the project file;

<u>Environment, Crop and simulation files</u>

In case of multiple run projects, each specific run can be selected with the spin button (Fig. 2.19h). The planting date, simulation period and set of files might differ between the runs.

In the ‘Environment, Crop and simulation files’ tabular sheet:

- The characteristics of the input files can be displayed by clicking on their icon (Fig. 2.19h – option 1);
- Another soil profile file, and other irrigation file(s), field management file(s), groundwater file(s), file(s) with initial conditions and with off-season conditions and field data file(s) can be selected in the corresponding file management panels (Fig. 2.19h – option 2):
  - Only the Soil profile file has to be common between the simulation runs of a multiple runs project;
  - The irrigation file(s), field management file(s), groundwater file(s), file(s) with initial conditions and with off-season conditions, and field data file(s), need not to be common between the simulation runs of a multiple runs project. Use the corresponding check buttons if the selected files are common or not in all runs of a multiple runs project;

Calendar

to display the start, end and length of the growing cycle and simulation period**;**

Program settings

to alter the settings of program parameters (Fig. 2.19i).

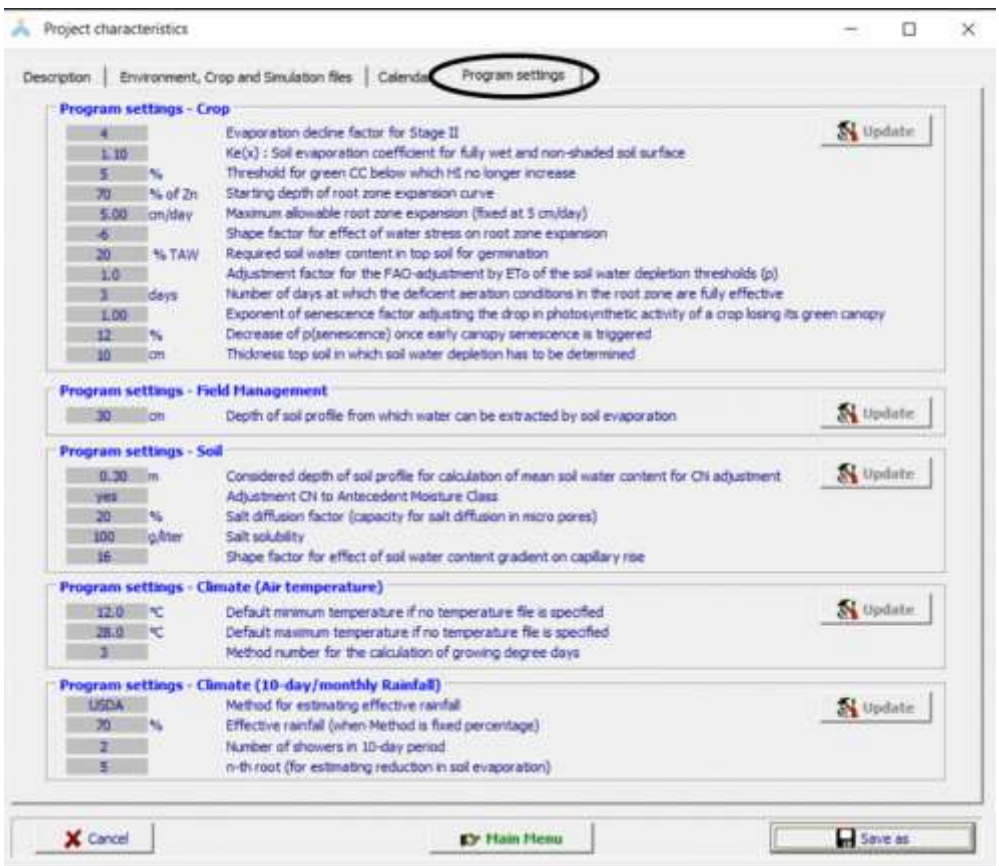


Figure 2.19i – The ‘Program settings’ tabular sheets of the *Project characteristics* menu in which the settings of the program parameters can be altered.

- **Update of the growing and simulation period**

The growing and simulation period, together with the corresponding climate, crop calendar and crop file, can be updated in the ***Update of growing and/or Simulation period*** menu, after clicking on the **<update>** command in the ***Project characteristics*** menu (Fig. 2.19h – option 3).

In the 'Growing period' tabular sheet of the ***Update of growing and/or Simulation period*** menu, the user can (1) select another Climate, Calendar and Crop file, (2) alter the number of simulation runs and (3) alter the onset of the growing period for the first run (Fig. 2.19j). The corresponding crop growing periods are displayed in the 'Calendar' tab-sheet.

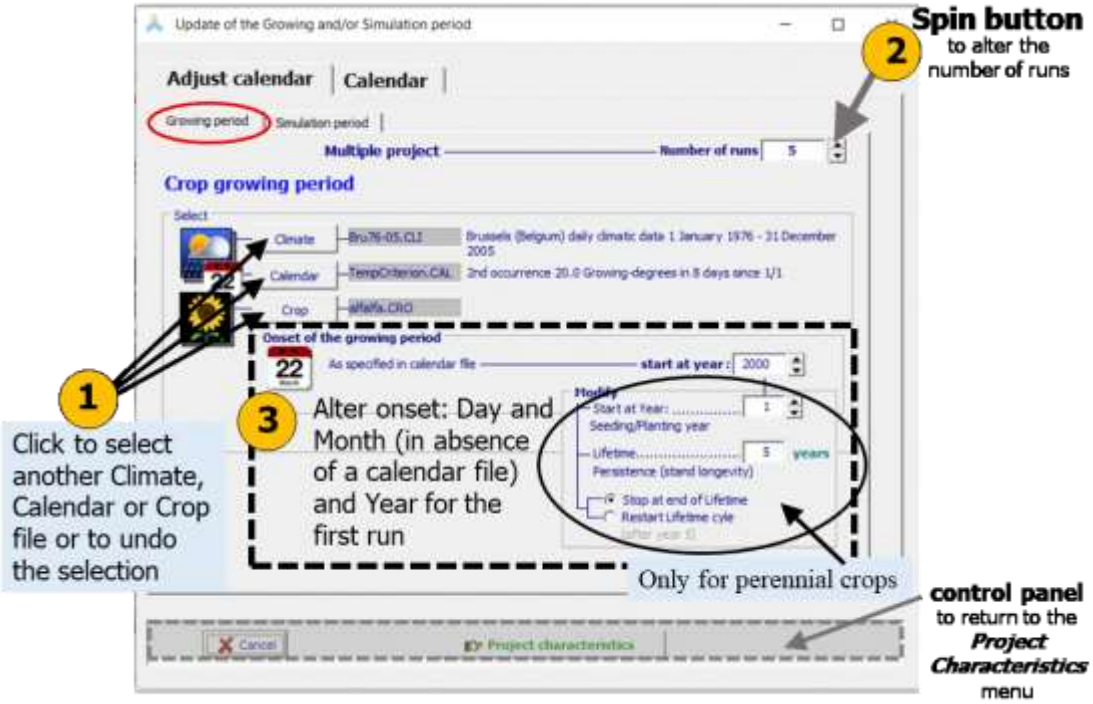


Figure 2.19j – The 'growing period' tabular sheet of the *Update of the Growing and Simulation period* menu in which (1) another climate, calendar and crop file can be selected. (2) the number of run to be displayed can be altered, and (3) the growing period can be updated.

There can be only one Climate, one crop Calendar, and one Crop file in a project. Therefore, the selected climate, crop calendar, and crop file are common between the simulation runs of a multiple-run project.

In the 'Simulation period' tabular sheet of the ***Update of growing and/or Simulation period*** menu, the user can alter the Simulation period for (1) the first and (2) successive runs, and (3) specify if the initial conditions need to be reset to the specified Initial conditions of the first run or if the final conditions of the previous run become the initial conditions for the next run (Fig. 2.19k). The corresponding simulation periods are displayed in the 'Calendar' tab-sheet.

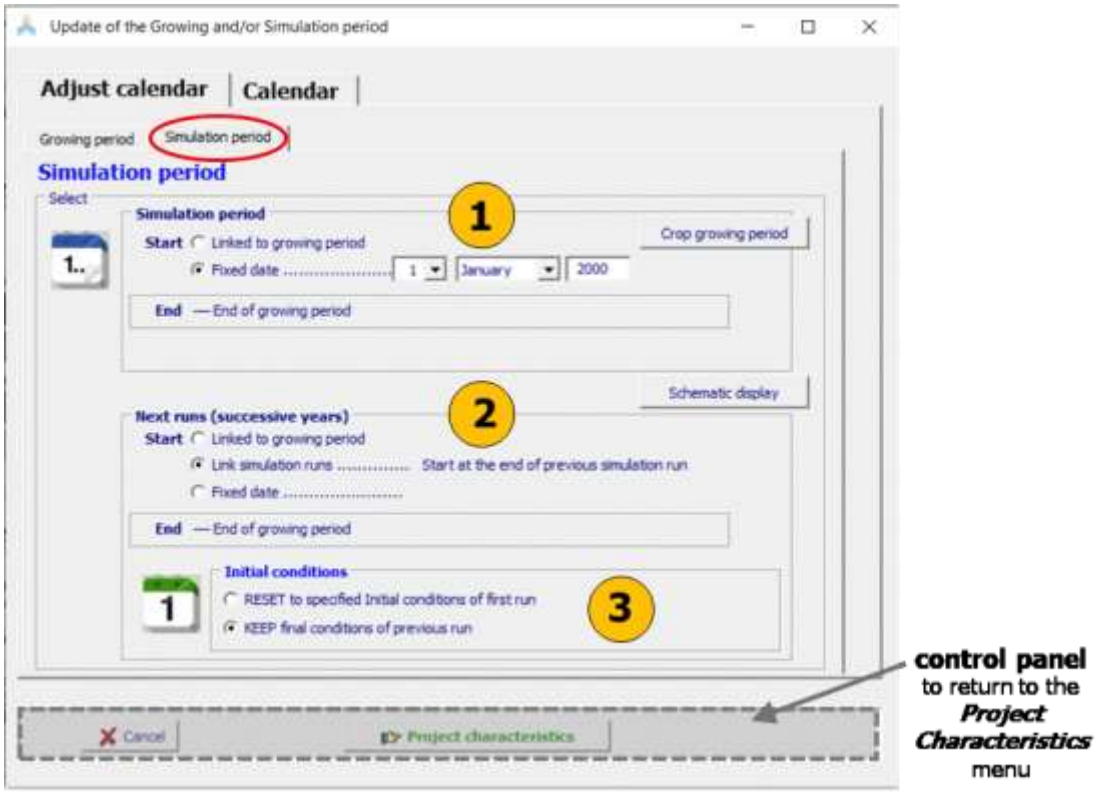


Figure 2.19k – The 'simulation period' tabular sheet of the *Update of the Growing and Simulation period* menu in which the simulation period of (1) the first and (2) successive runs can be updated and (3) the initial conditions can be specified.

The user returns to the ***Project characteristics*** menu, with one of the commands of the project panel (Fig. 11): with the **<Cancel>** command key (no saving) or with the **<Project characteristics>** command (saving of the updates).

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

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

By respecting the structure of the project file (Section 2.19.7), 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 run projects, or to build other types of multiple run projects than the one available through the interface. 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.

2.19.7 Structure of project and program parameter files

A project file is a text file which contains (a) information about the project, (b) the year number of cultivation and the start and end dates of the simulation and cropping period, and (c) the names of files (climate, calendar, crop, irrigation and field management, soil profile and ground water, initial and off-season conditions and field data). The structure of the project file is presented in Tab. 2.19ml.

The settings for the program parameters are saved in another text file which has the same file name as the project, but with the filename extension 'PP1' (for single projects) and 'PPn' (for multiple projects). Its structure is given in Tab. 2.19m4).

Table 2.19m1 – Structure of a project file (file with extension PRO or PRM)

Line Number	Description
a. – Information	
1	Description of the project
2	AquaCrop version number
b. – Simulation and the growing cycle for the first run	
3	Year number of cultivation (always 1 for annual crops; and 1, 2, 3 … for perennials), with 1 being the Seeding/planting year
4	Day number(1) for the first day of the simulation period
5	Day number(1) for the last day of the simulation period
6	Day number(1) for the first day of the growing cycle
7	Day number(1) for the last day of the growing cycle
c. – The names(2) and directories(3) for the 14 files containing the characteristics of the crop, crop calendar, environmental (climate, management and soil), initial and off-season conditions, and field data	
8 up to 49	1. Climate (CLI) file and the enveloped: 1.1 air temperature (Tnx or TMP) file, 1.2 reference ET (ETo) file, 1.3 rain (PLU) file, and 1.4 atmospheric CO_2 concentration (CO2) file; 2. Calendar (CAL) file; 3. Crop (CRO) file; 4. Irrigation management (IRR) file; 5. Field management (MAN) file; 6. Soil profile (SOL) file; 7. Groundwater table (GWT) file; 8. Initial conditions (SW0) file; 9. Off-season conditions (OFF) file; 10. Field Data (OBS) file.
In case of **multiple projects**, section 'b' (5 lines for the simulation and growing cycle) and section 'c' (42 lines for the 14 files) are specified for each of the successive runs, in successive blocks of (5 + 42 =) 47 lines.	
(1) Day number: The day number refers to the days elapsed since 0th January 1901 at 0 am (see Table 2.19m2 and 2.19m3 for the calculation procedure); (2) File name: in the absence of a file (None), the default conditions (see 2.3 Default settings at start) are considered; (3) Directory (path): in the absence of a file, (None) is specified as directory.	

Table 2.19m2 – 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 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 2.19m3 – 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 *)
```

Table 2.19m4 – Structure of program file parameters (file with extension PP1 or PPn)

Line No.	Description	Format	Example
Settings for crop program parameters (12 parameters)			
1	Evaporation decline factor for stage II	Integer	4
2	Ke(x) Soil evaporation coefficient for fully wet and non-shaded soil surface	XXX.XX	1.10
3	Threshold for green CC below which HI can no longer increase (% cover)	Integer	5
4	Starting depth of root zone expansion curve (% of Zmin)	Integer	70
5	Maximum allowable root zone expansion (fixed at 5 cm/day)	XXX.XX	5.00
6	Shape factor for effect water stress on root zone expansion	Integer	-6
7	Required soil water content in top soil for germination (% TAW)	Integer	20
8	Adjustment factor for FAO-adjustment soil water depletion (p) by ETo	XXX.X	1.0
9	Number of days after which deficient aeration is fully effective	Integer	3
10	Exponent of senescence factor adjusting drop in photosynthetic activity of dying crop	XXX.XX	1.00
11	Decrease of p(sen) once early canopy senescence is triggered (% of p(sen))	Integer	12
12	Thickness top soil (cm) in which soil water depletion has to be determined	Integer	10
Settings for field program parameters (1 parameter)			
13	Depth [cm] of soil profile affected by water extraction by soil evaporation	Integer	30
Settings for soil parameters (5 parameters)			
14	Considered depth (m) of soil profile for calculation of mean soil water content for CN adjustment	XXX.XX	0.30
15	Adjustment of CN to Antecedent Moisture Class (0 = Not adjusted; 1 = Adjusted)	0 or 1	1
16	Salt diffusion factor (capacity for salt diffusion in micro pores) [%]	Integer	20

17	Salt solubility [g/liter]	Integer	100
18	Shape factor for effect of soil water content gradient on capillary rise	Integer	16
Settings for temperature program parameters (3 parameters)			
19	Default minimum temperature (°C) if no temperature file is specified	XXX.X	12.0
20	Default maximum temperature (°C) if no temperature file is specified	XXX.X	28.0
21	Default method for the calculation of growing degree days	Integer	3
Settings for 10-day or monthly rain program parameters (4 parameters)			
22	Procedure to estimate daily rainfall (when input is 10-day/monthly rainfall) 0 : 100 % effective 1 : USDA-SCS procedure 2 : Fixed percentage	0, 1 or 2	1
23	Percentage of 10-day or monthly rainfall which is effective (when Procedure (option 2) is a fixed percentage)	Integer	70
24	Number of showers in a decade for run-off estimate (when input is 10-day/monthly rainfall)	Integer	2
25	Parameter for reduction of soil evaporation (when input is 10-day/monthly rainfall)	Integer	5

Table 2.19m5 – Example of a (multiple) project file

```
5 years of alfalfa
      7.0       : AquaCrop Version (April 2021)
      1         : Year number of cultivation (Seeding/planting year)
  36281         : First day of simulation period - 1 May 2000
  36515         : Last day of simulation period - 21 December 2000
  36281         : First day of cropping period - 1 May 2000
  36515         : Last day of cropping period - 21 December 2000
-- 1. Climate (CLI) file
   Bru76-05.CLI
   C:\FAO\AquaCrop7\DATA\
   1.1 Temperature (Tnx or TMP) file
   Bru76-05.TMP
   C:\FAO\AquaCrop7\DATA\
   1.2 Reference ET (ETo) file
   Bru76-05.ETo
   C:\FAO\AquaCrop7\DATA\
   1.3 Rain (PLU) file
```

```
   Bru76-05.PLU
   C:\FAO\AquaCrop7\DATA\
   1.4 Atmospheric CO2 concentration (CO2) file
   MaunaLoa.CO2
   C:\FAO\AquaCrop7\SIMUL\
-- 2. Calendar (CAL) file
   1May.CAL
   C:\FAO\AquaCrop7\DATA\
-- 3. Crop (CRO) file
   alfalfa.CRO
   C:\FAO\AquaCrop7\DATA\
-- 4. Irrigation management (IRR) file
   (None)
   (None)
-- 5. Field management (MAN) file
   (None)
   (None)
-- 6. Soil profile (SOL) file
   Loam.SOL
   C:\FAO\AquaCrop7\DATA\
-- 7. Groundwater table (GWT) file
   (None)
   (None)
-- 8. Initial conditions (SW0) file
   (None)
   (None)
-- 9. Off-season conditions (OFF) file
   (None)
   (None)
-- 10. Field data (OBS) file
   (None)
   (None)
```

```
      2         : Year number of cultivation (Non-seeding/planting
year)
  36516         : First day of simulation period - 22 December 2000
  36845         : Last day of simulation period - 16 November 2001
  36565         : First day of cropping period - 9 February 2001
  36845         : Last day of cropping period - 16 November 2001
```

```
-- 1. Climate (CLI) file
   Bru76-05.CLI
   C:\FAO\AquaCrop7\DATA\
   1.1 Temperature (Tnx or TMP) file
   Bru76-05.TMP
   C:\FAO\AquaCrop7\DATA\
   1.2 Reference ET (ETo) file
   Bru76-05.ETo
   C:\FAO\AquaCrop7\DATA\
   1.3 Rain (PLU) file
   Bru76-05.PLU
   C:\FAO\AquaCrop7\DATA\
   1.4 Atmospheric CO2 concentration (CO2) file
   MaunaLoa.CO2
   C:\FAO\AquaCrop7\SIMUL\
-- 2. Calendar (CAL) file
   1May.CAL
   C:\FAO\AquaCrop7\DATA\
-- 3. Crop (CRO) file
```

```
   alfalfa.CRO
   C:\FAO\AquaCrop7\DATA\
-- 4. Irrigation management (IRR) file
   (None)
   (None)
-- 5. Field management (MAN) file
   (None)
   (None)
-- 6. Soil profile (SOL) file
   Loam.SOL
   C:\FAO\AquaCrop7\DATA\
-- 7. Groundwater table (GWT) file
   (None)
   (None)
-- 8. Initial conditions (SW0) file
   KeepSWC
   Keep soil water profile of previous run
-- 9. Off-season conditions (OFF) file
   (None)
   (None)
-- 10. Field data (OBS) file
   (None)
   (None)
```

Etc.

Table 2.19m6 – Example of a Program Parameter file

```
  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) 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 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     : Daily rainfall is estimated by USDA-SCS procedure (when input is 10-day/monthly rainfall)
 70     : Percentage of effective rainfall (when input is 10-day/monthly rainfall)
  2     : Number of showers in a decade for run-off estimate (when input is 10-day/monthly rainfall)
  5     : Parameter for reduction of soil evaporation (when input is 10-day/monthly rainfall)
```

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).

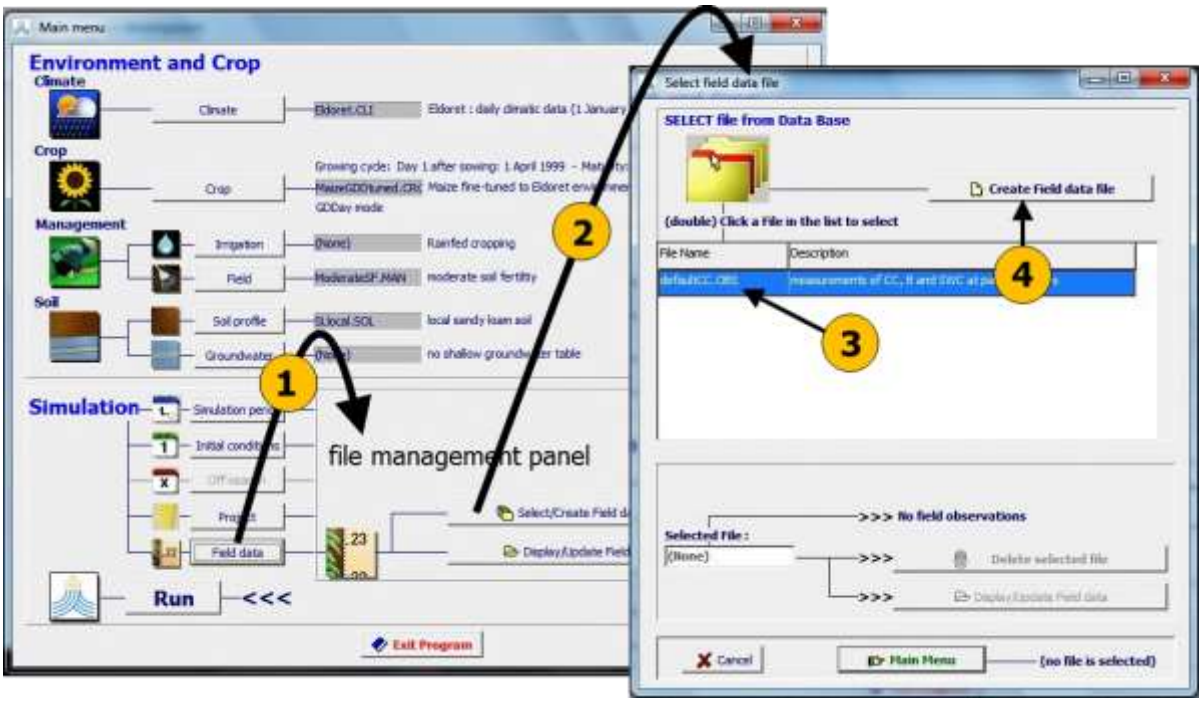


Figure 2.20a – By selecting (1) the <Field data> command and subsequently (2) the <Select/Create Field data file> command in the file management panel of the *Main menu*, the user gets access to the *Select field data file* menu, in which (3) one of the available field data files or (4) the command to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

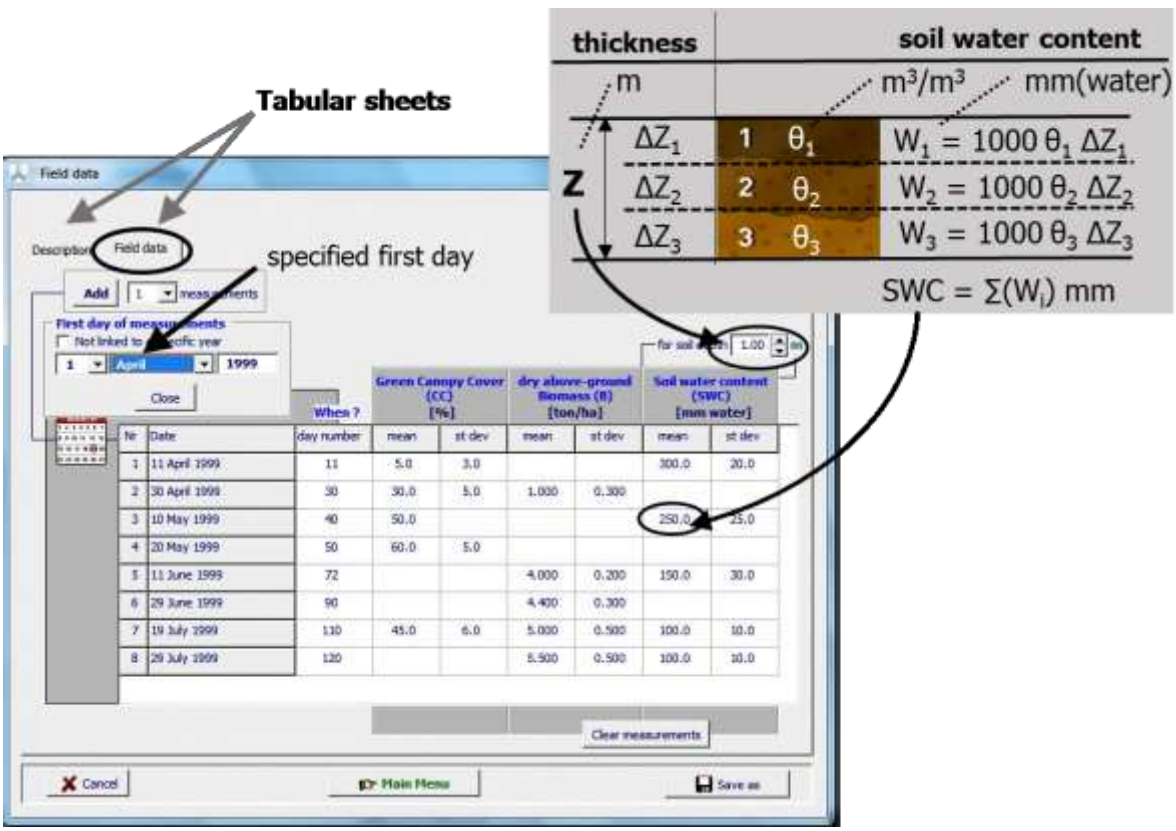


Figure 2.20b – The *Field data* menu with its tabular sheets 'Description' and 'Field data' (displayed) in which the first day of observations and field data (green canopy cover, dry above-ground biomass and/or soil water contents) at particular days are specified

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:

a) 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;
b) by the specified number of days; or
c) to a specified date.

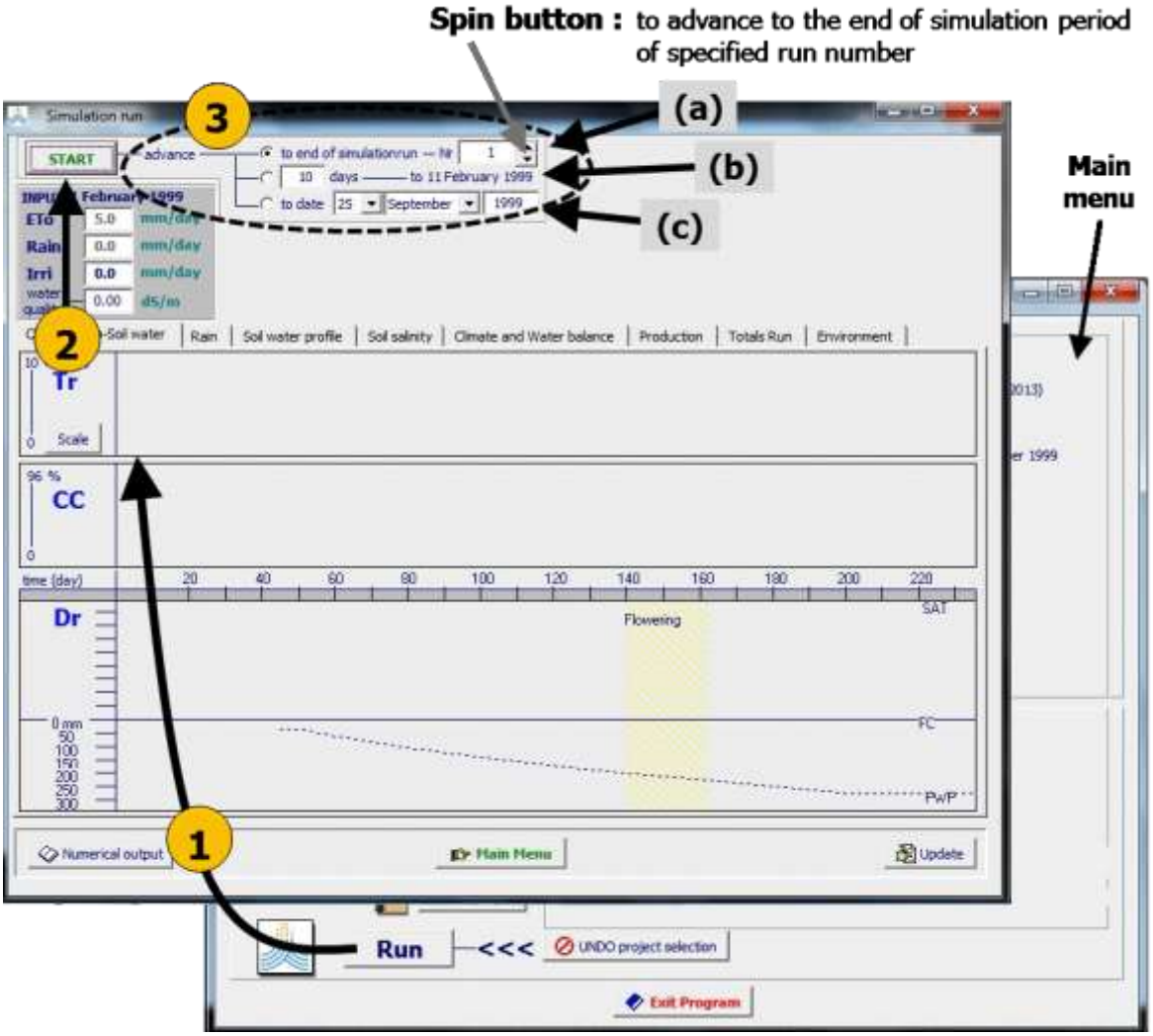


Figure 2.21a – By selecting (1) the <Run> command in the *Main menu*, the user gets access to the *Simulation run* menu, in which (2) the simulation can be started. Depending on (3) the selected advance option the simulation will (a) run to the end of the simulation period, (b) advance by a specified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

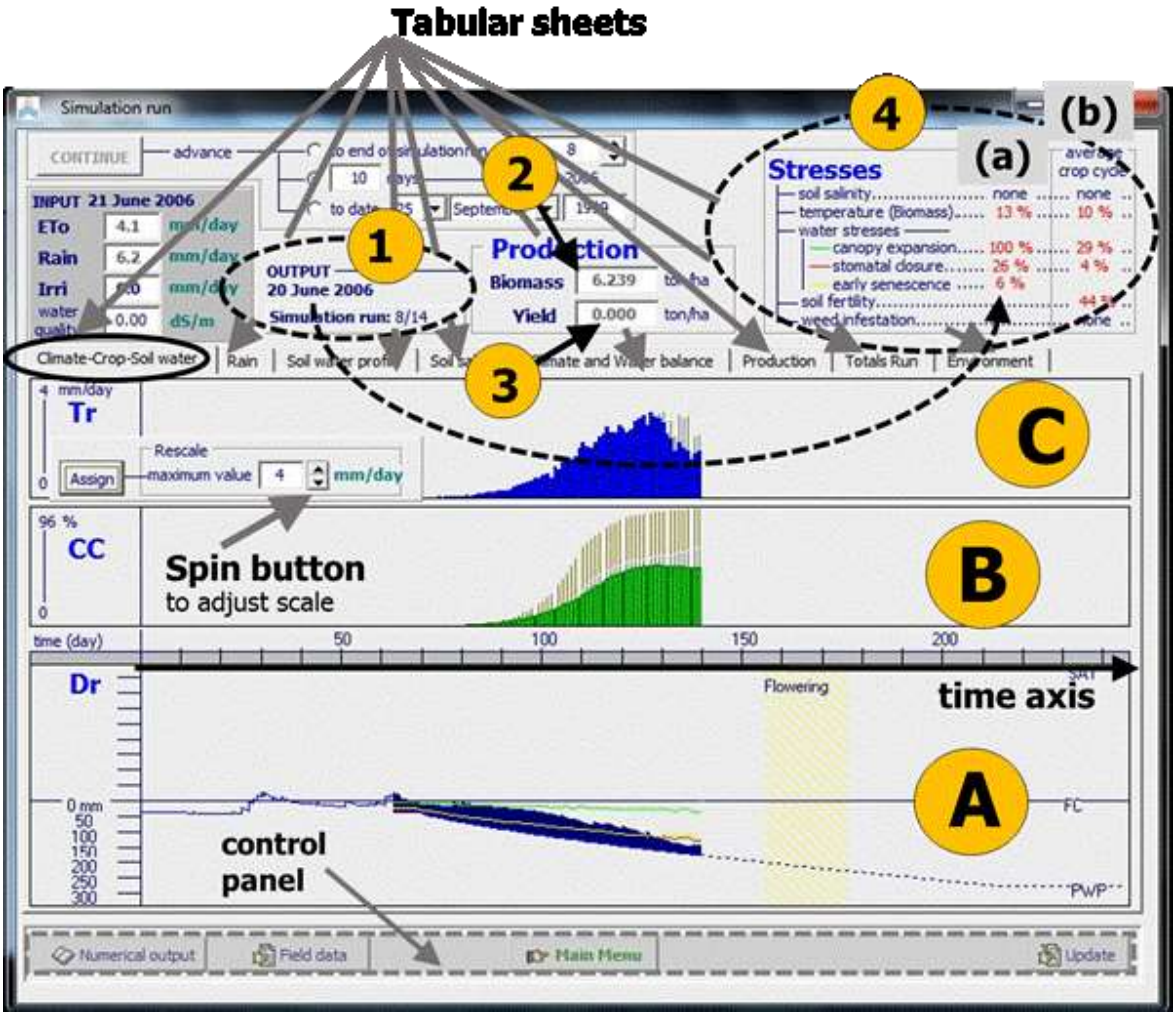


Figure 2.21b/1 – Display of simulation results in the *Simulation run* menu (1) for the day to which the simulation has advanced. Total (2) biomass and (3) crop yield produced so far at the end of that day, (4) stress levels occurring (a) on that day and (b) averages of stresses over the growing cycle 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

At the top of the ***Run menu*** of AquaCrop, the user can select the way in which the simulated yield is expressed: as dry or fresh mass (Fig. 2.21b/2). By moving the cursor over the Yield label, the dry matter content of the fresh yield, considered for the conversion, is displayed.

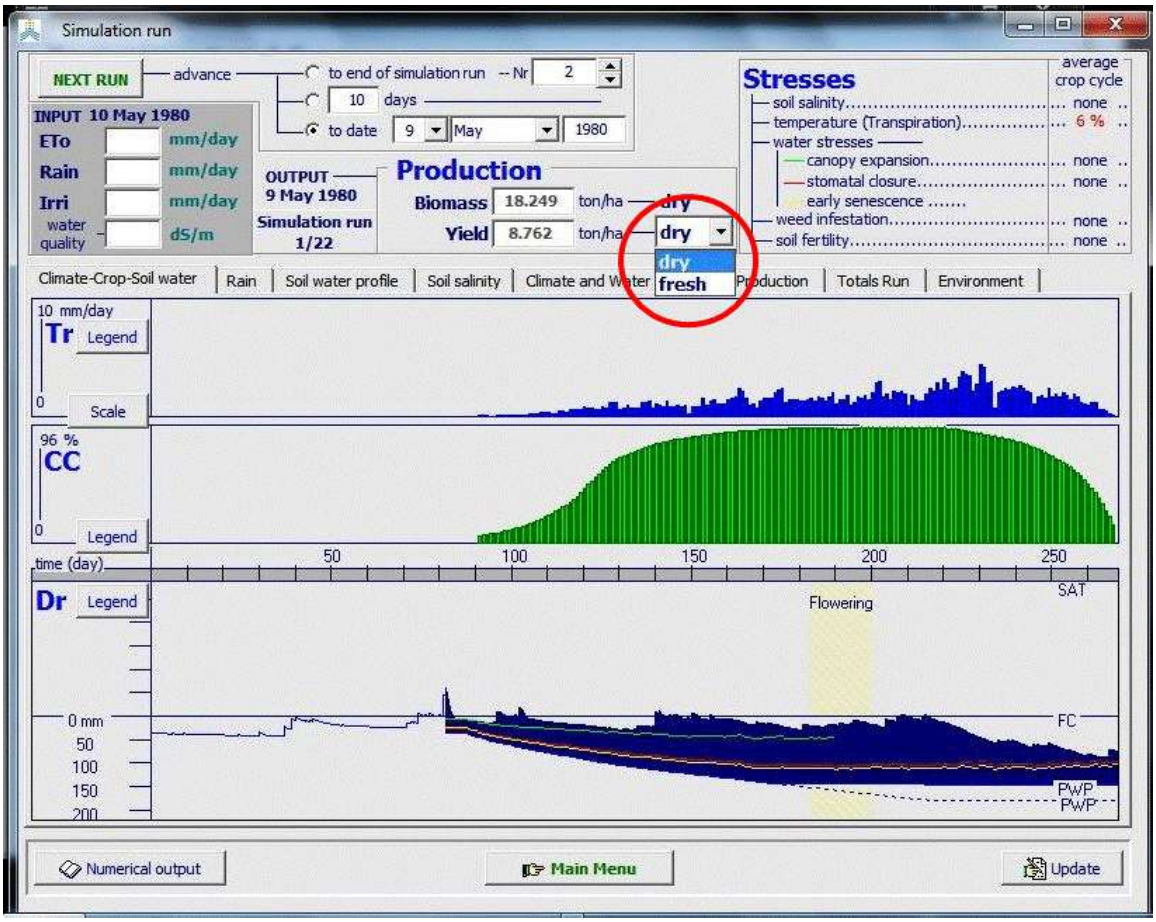


Figure 2.21b/2 – Altering the expression of simulated yield in the *Simulation run* menu

- **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).

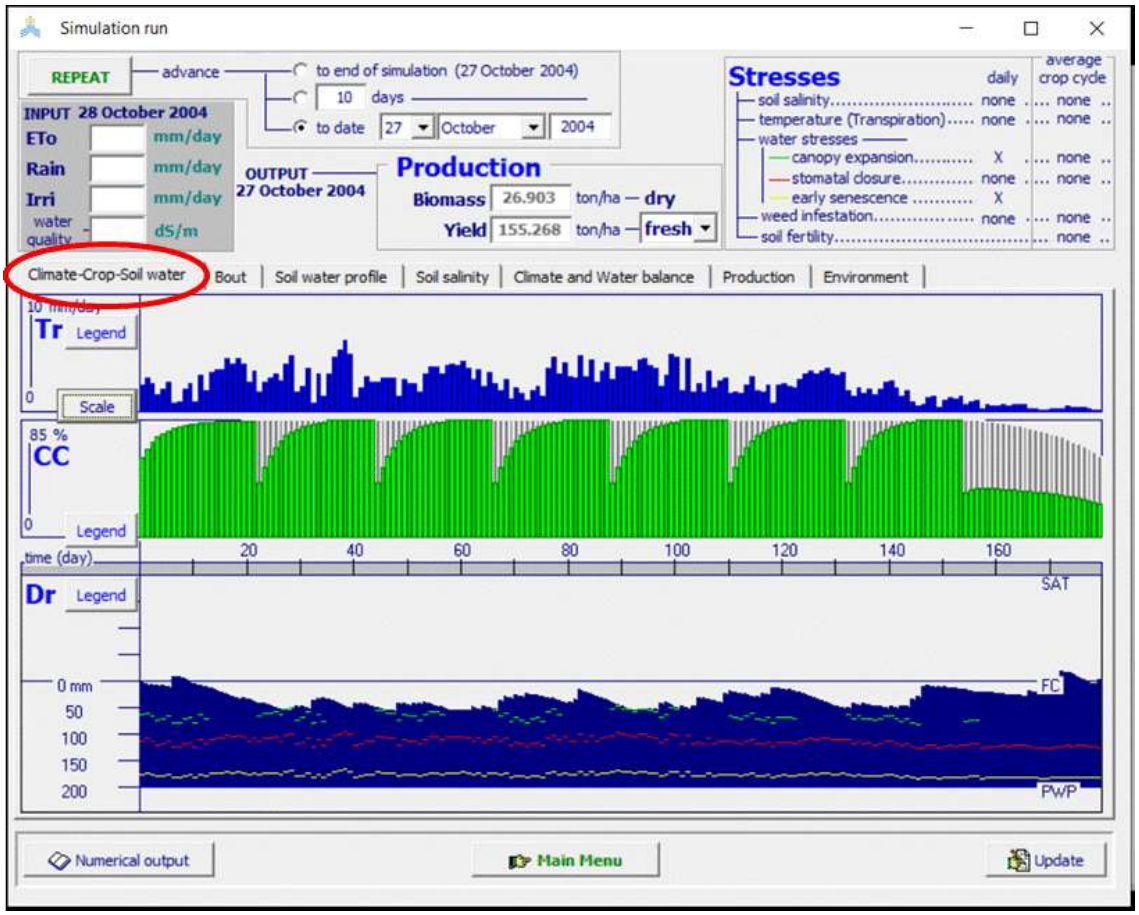


Figure 2.21b/3 – "Climate-Crop-Soil water" tab-sheet of the Run menu with multiple harvests

- **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
Y(dry)	Dry yield	ton/ha
Y(fresh)	Fresh yield	ton/ha
Bin	Mobilized biomass from root system	kg/ha
Bout	Stored biomass in root system	kg/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)	%

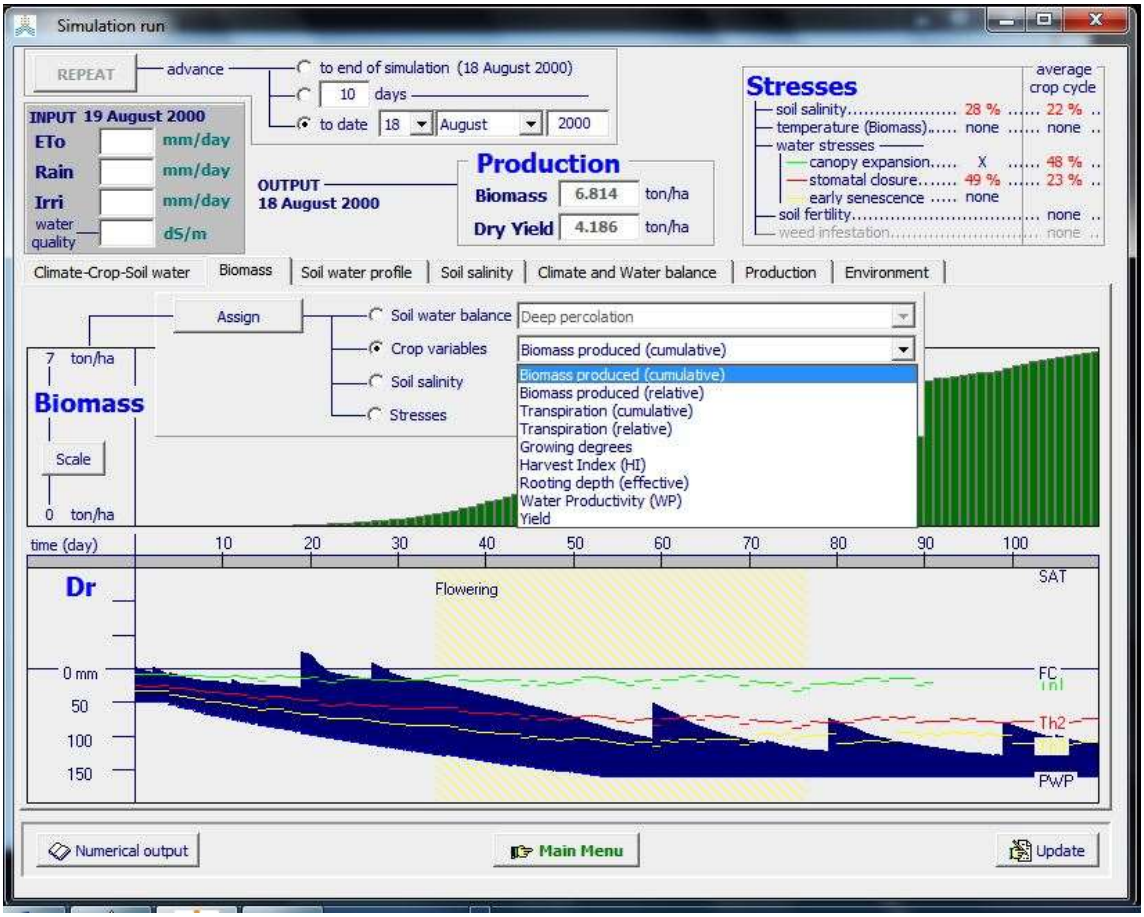


Figure 2.21c/1 - Selection of a parameter for display in the *Simulation run* menu

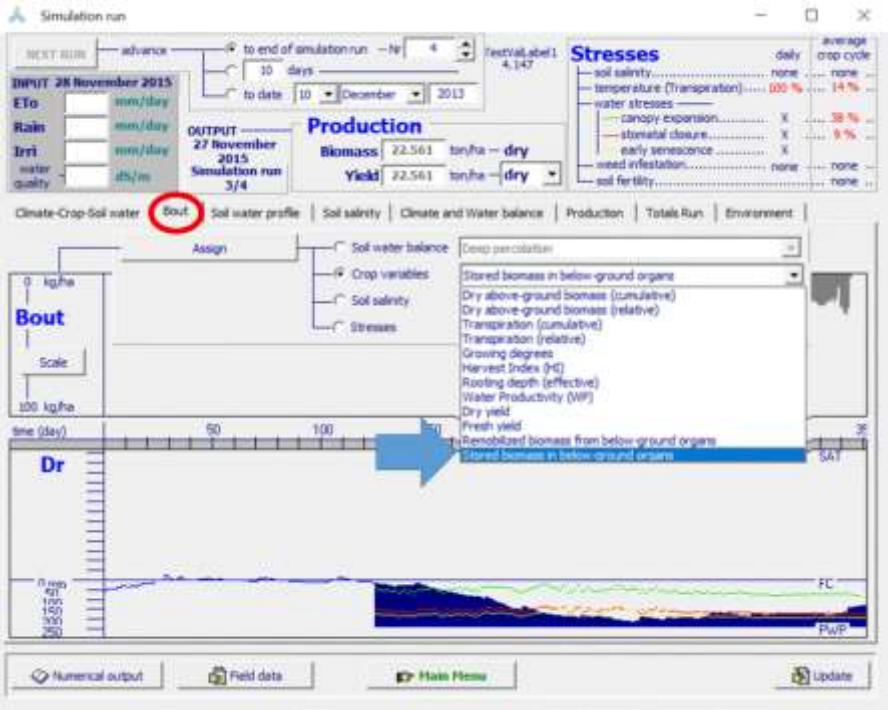


Figure 2.21c/2 – 2nd tab sheet of the Run menu, in which several displays can be selected

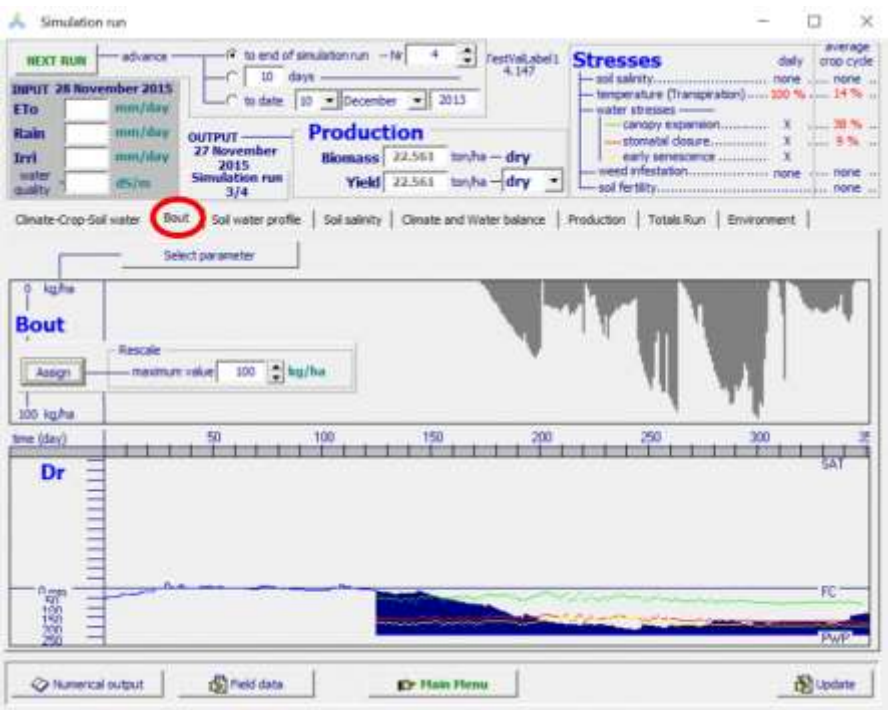


Figure 2.21c/3 – Graphical display in the 2nd tab sheet of the daily stored biomass in the root system at the end of the crop cycle.

- **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).

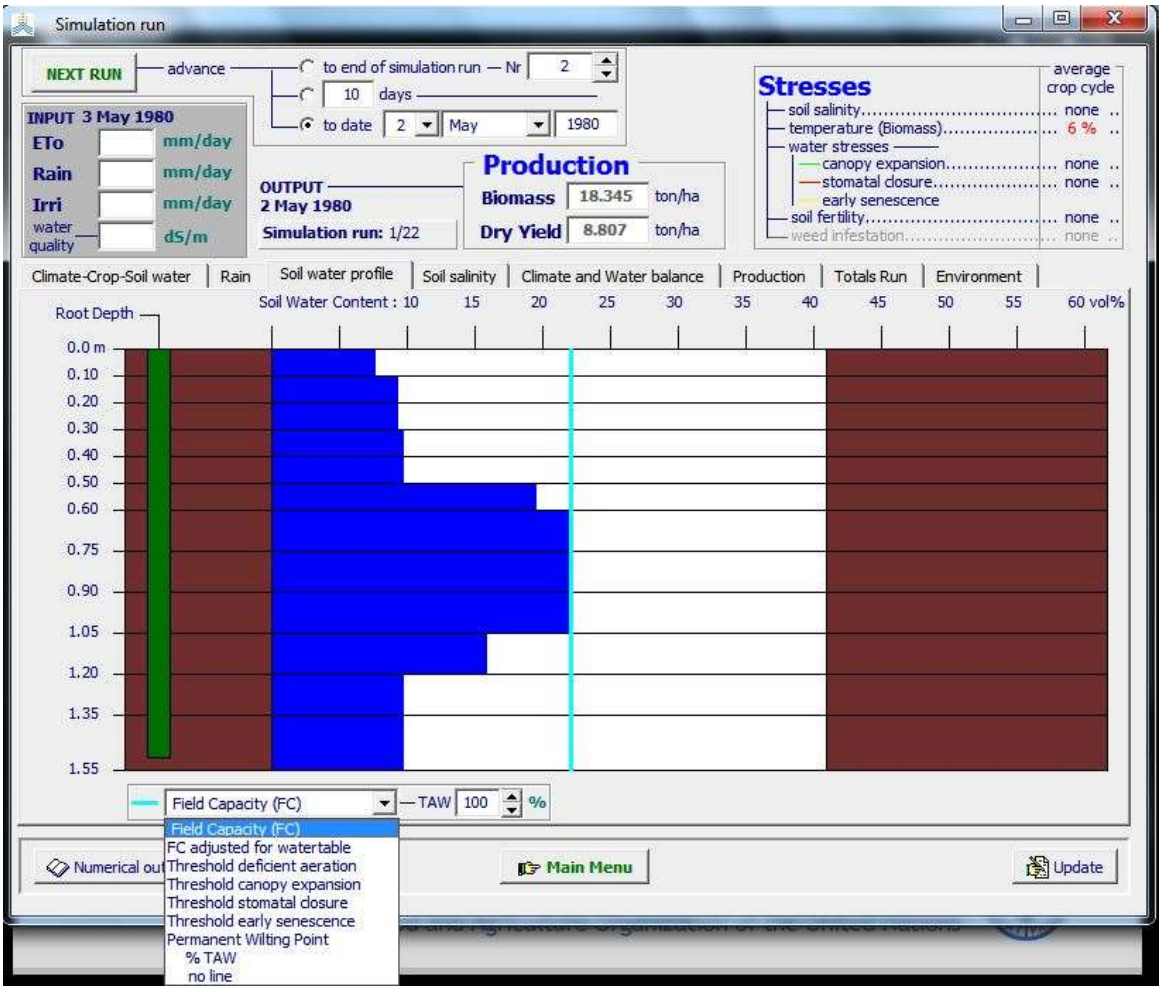


Figure 2.21d - Selection of a specific soil water content for display in the tabular sheet 'Soil water profile' of the *Simulation run* menu

- **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).

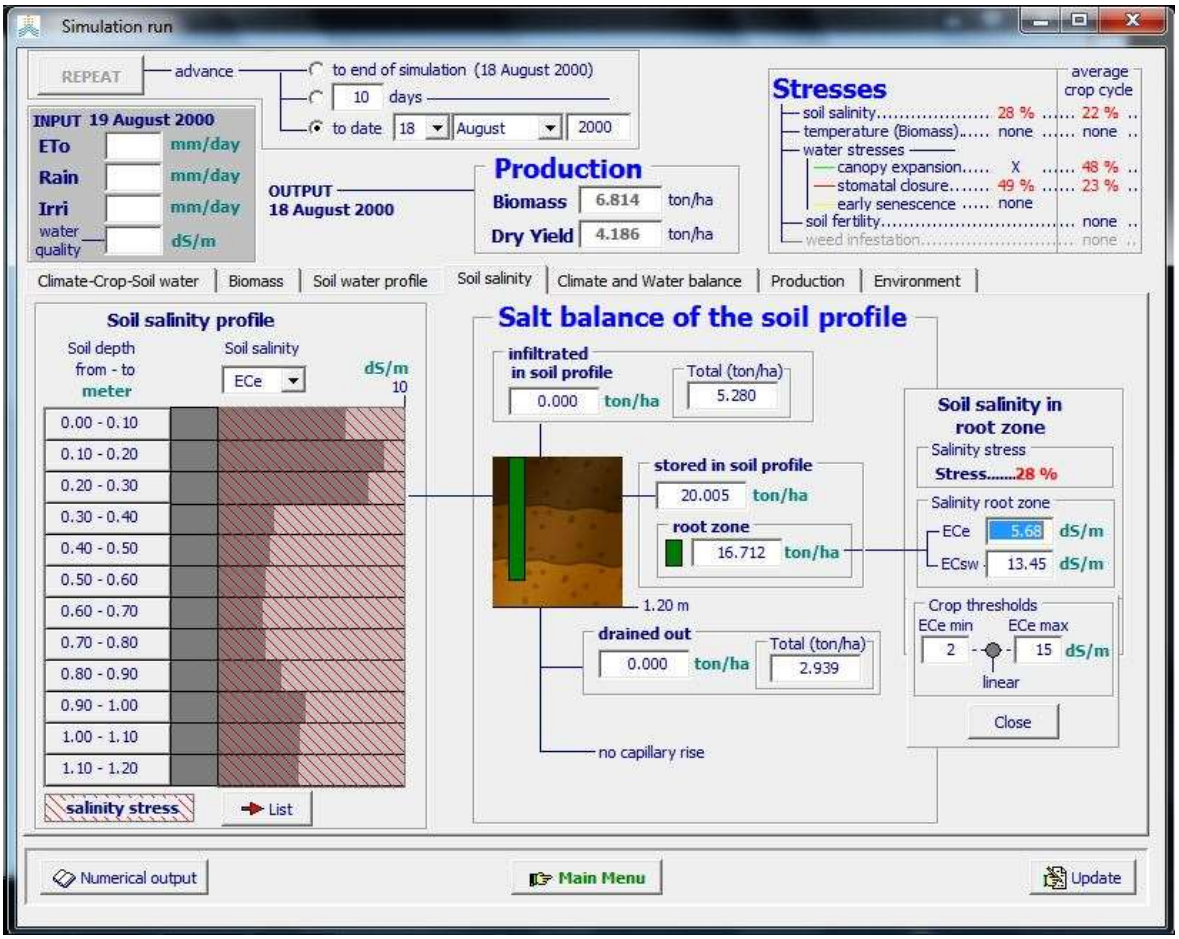


Figure 2.21e – Display of the soil salinity profile and the salt balance in the tabular sheet 'Soil salinity' of the *Simulation run* menu

- **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).

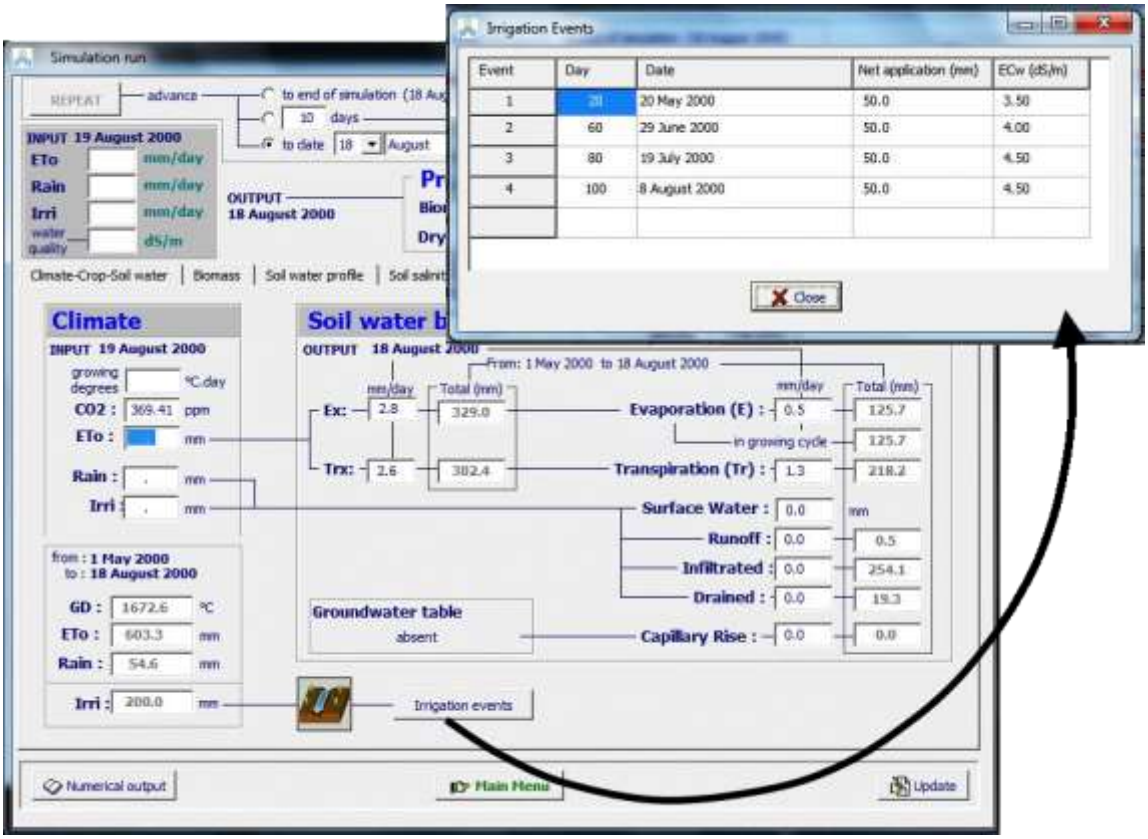
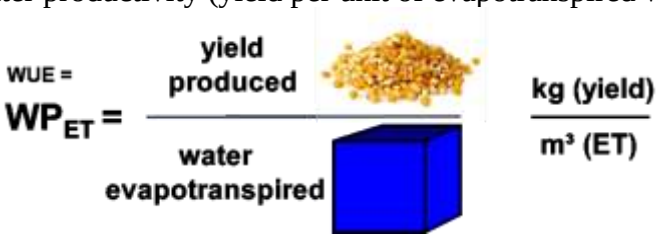


Figure 2.21f – Display of the parameters of the climate and soil water balance in the tabular sheet: 'Climate and Water balance' of the *Simulation run* menu and the irrigation events in the *Irrigation Events* menu

- **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):



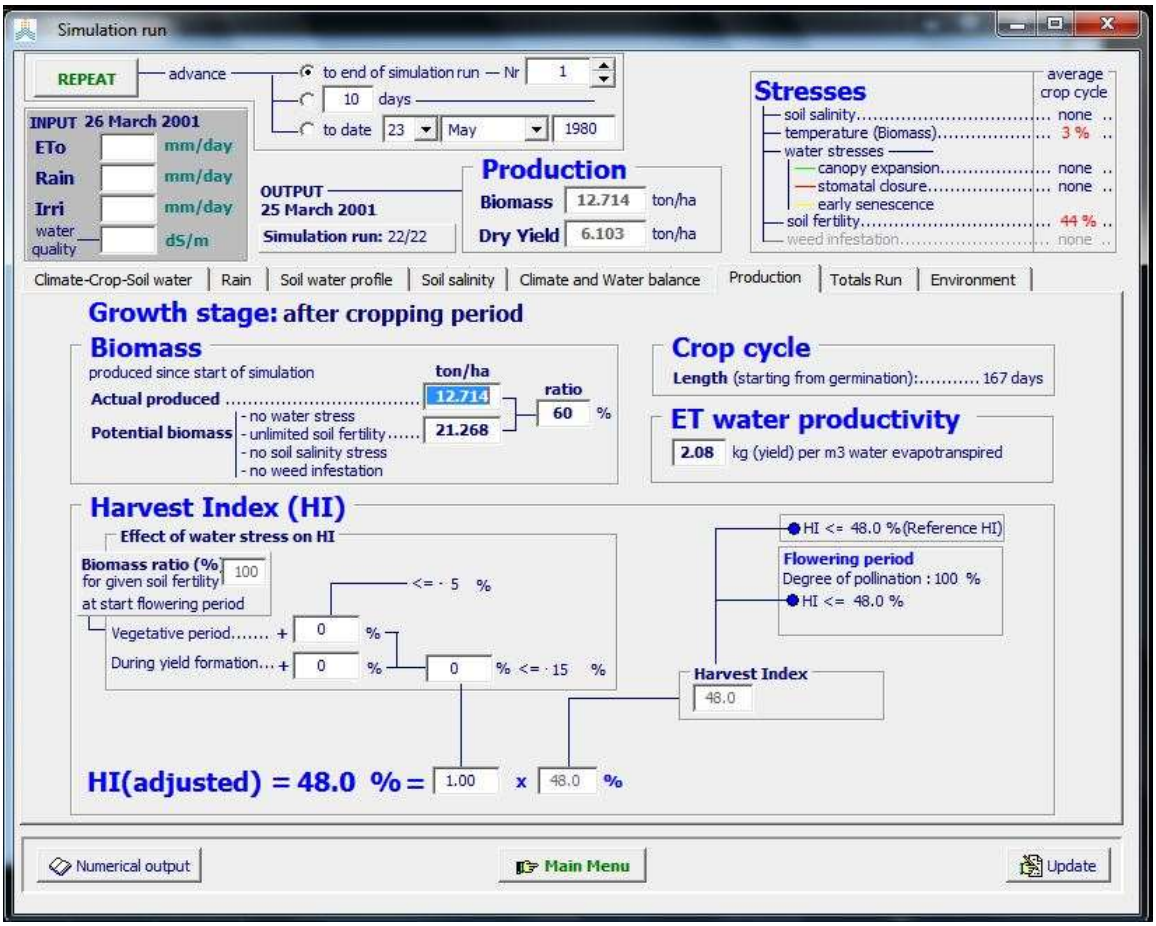


Figure 2.21g/1 – Information on biomass production, ET water productivity, and the ante and post-anthesis impact of water stress on the adjustment of HI in the tabular sheet 'Production' of the *Simulation run* menu

When running a simulation for perennial herbaceous forage crops, the mass of biomass that was mobilized at the start of the season and stored at the end of the season is displayed in the 'Production' tab-sheet of ***the Simulation Run*** menu (Fig. 2.21g/2). The crop production (Dry biomass, Dry Yield and Fresh yield) at the several harvest events are displayed in the ***Harvest events*** menu (Fig. 2.21g/3).

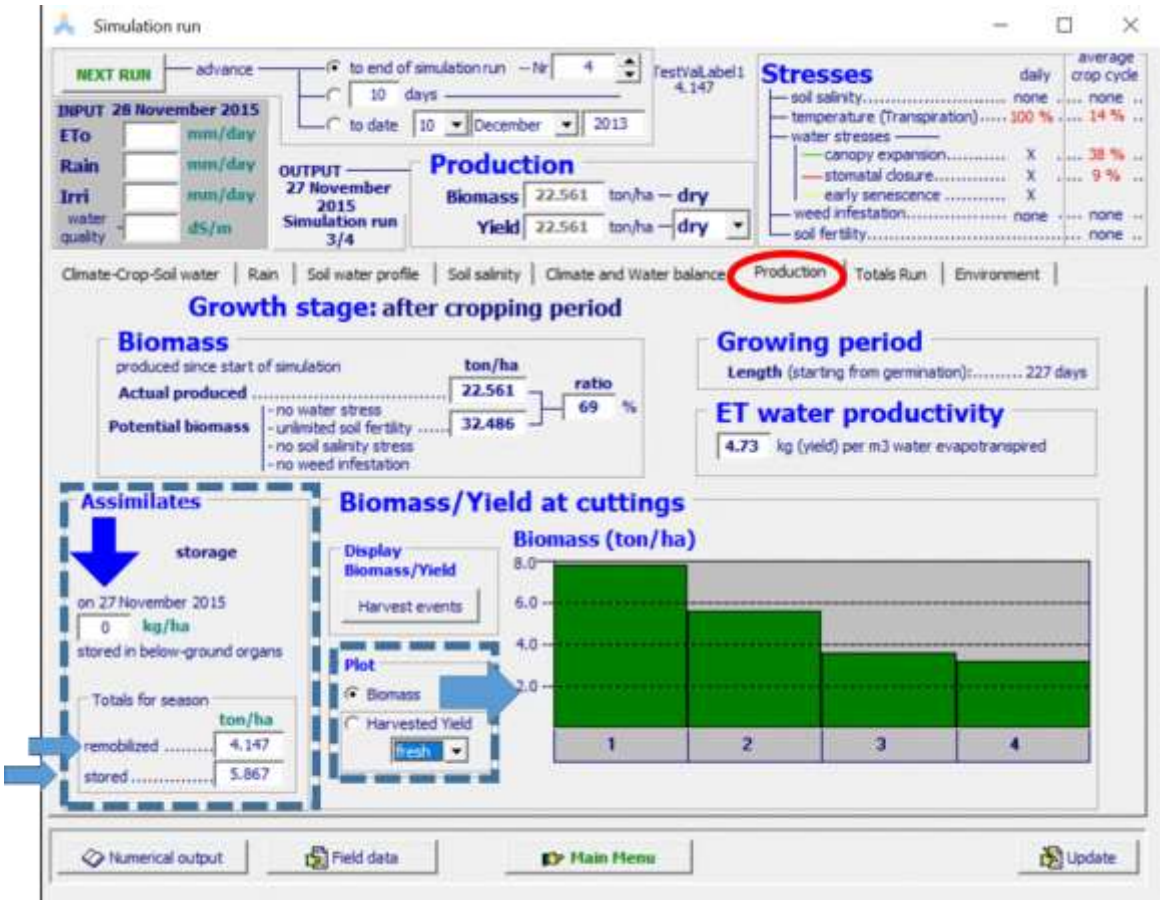


Figure 2.21g/2 – "Production" tab-sheet of the Run menu with information on the amount of assimilates stored and mobilized, and the harvested biomass or yield at the various cuttings.

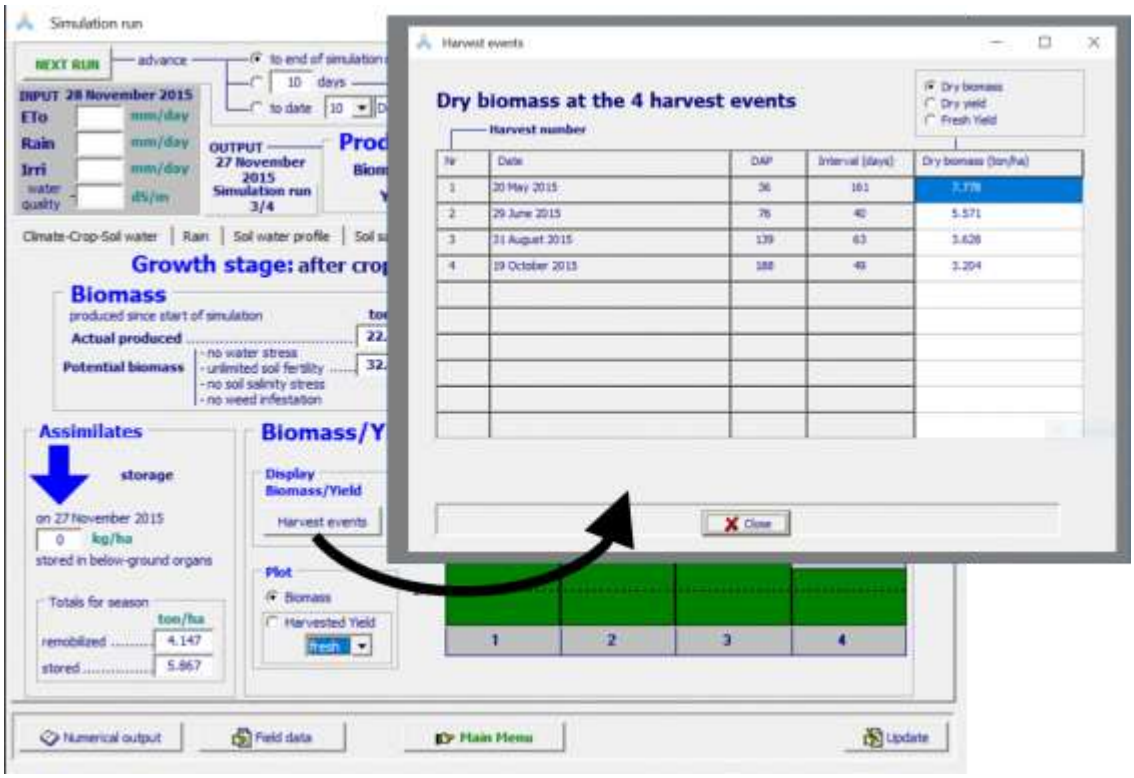


Figure 2.21g/3 – Display of the amount of assimilates stored and mobilized, and the harvested biomass or yield at the various cuttings in the "Production" tab-sheet of the Run menu and the crop production (Dry biomass, Dry Yield and Fresh yield) at the several harvest events displayed in the *Harvest events* 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).

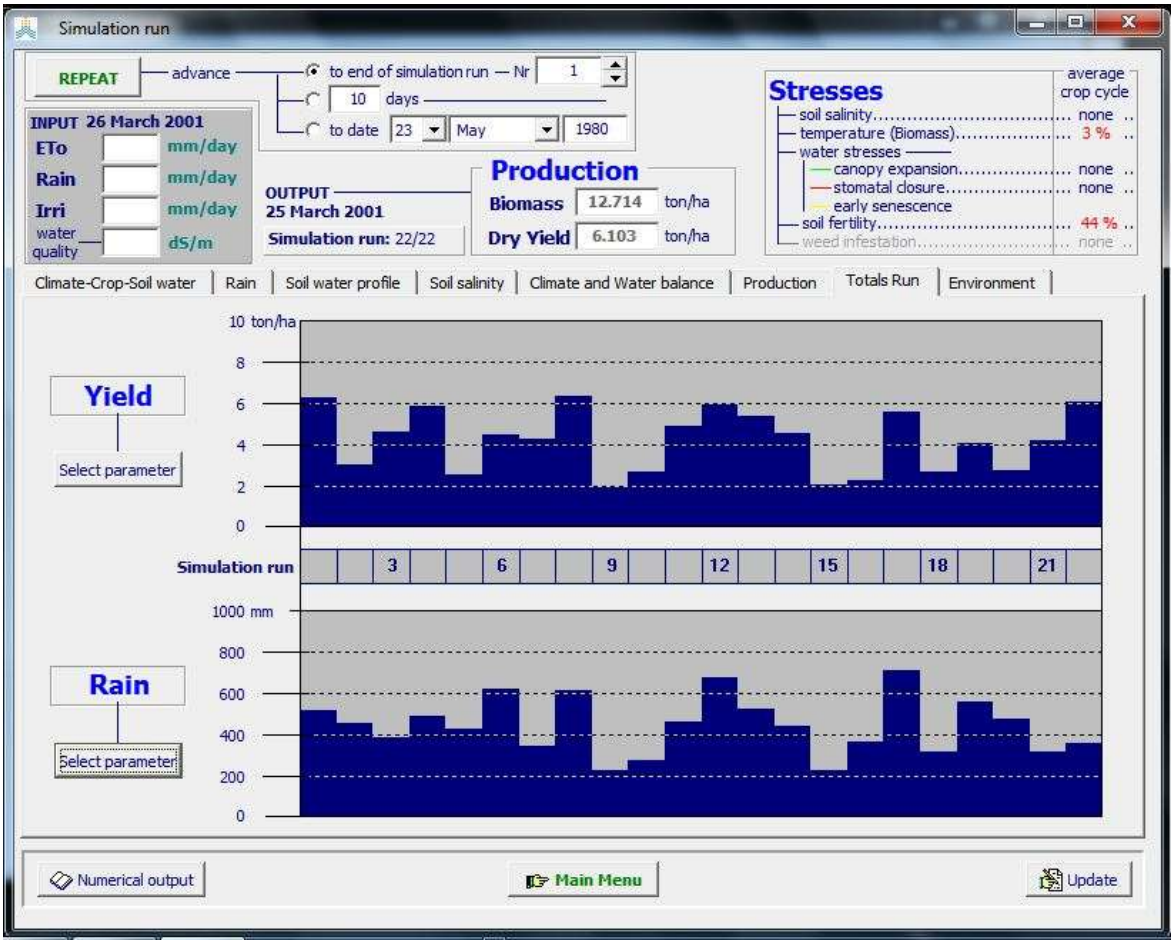


Figure 2.21h – Information on the simulated yield and total rainfall (during the simulation period) for the successive years of a multiple run project in the tabular sheet 'Totals Run' of the *Simulation run* menu

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	-
Y(dry)	Dry yield	ton/ha
Y(fresh)	Fresh yield	ton/ha
WP(ET)	ET water productivity (kg yield per m3 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.

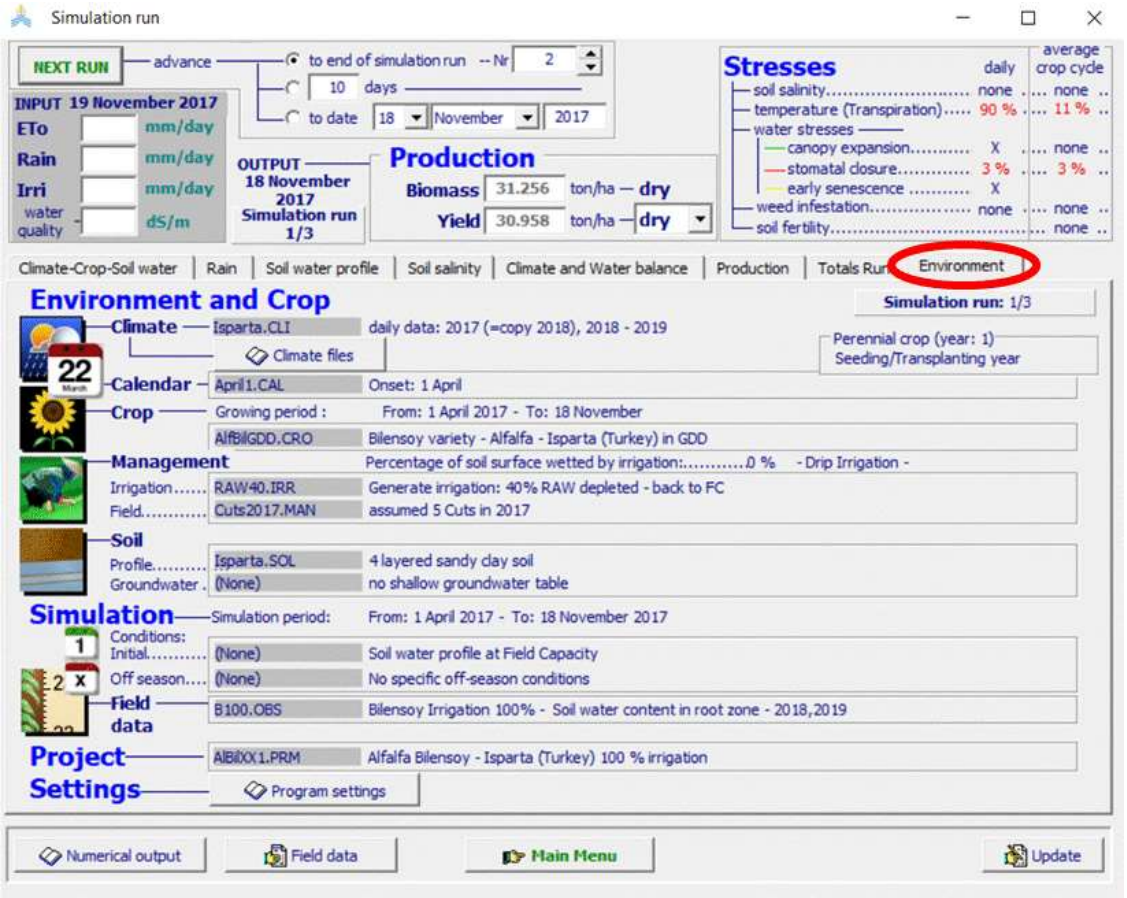


Figure 2.21i – Display of the selected input files in the tabular sheet 'Environment' of the *Simulation run* menu

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):

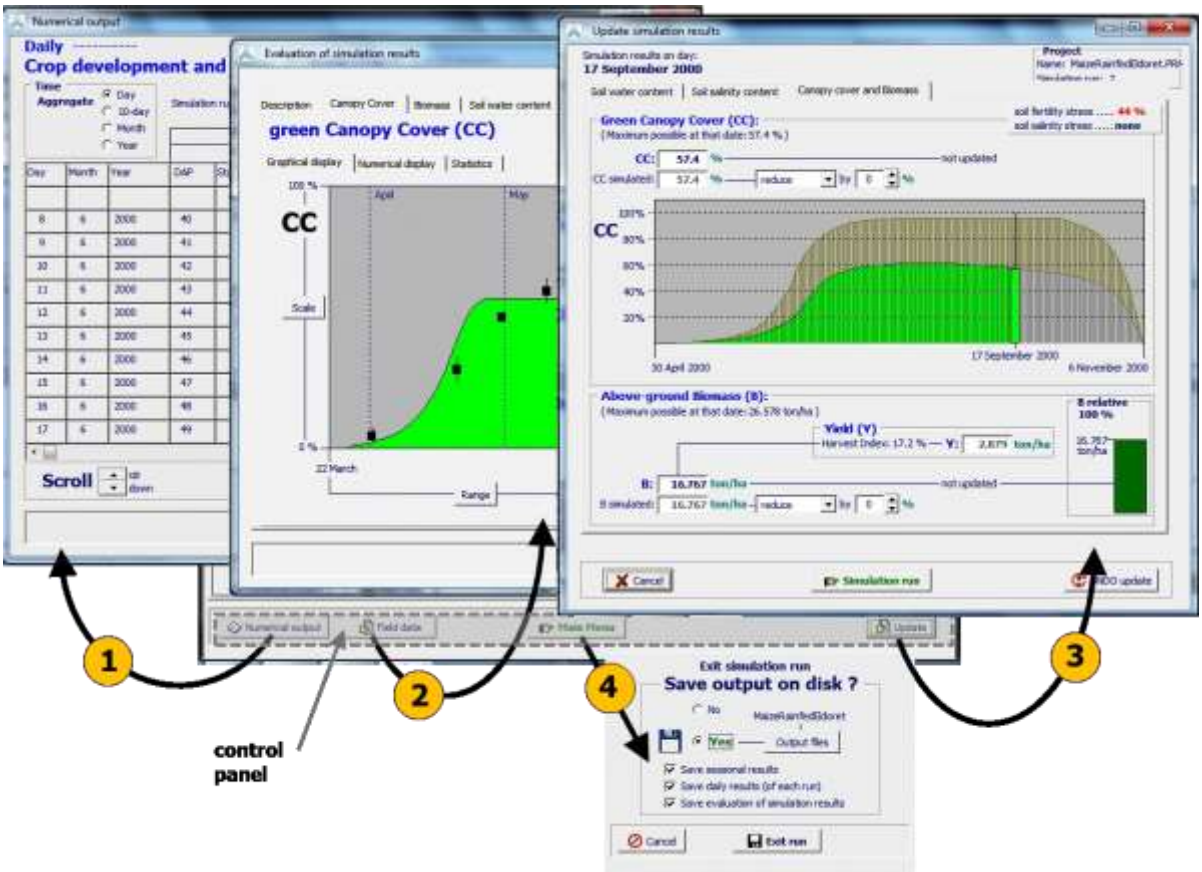


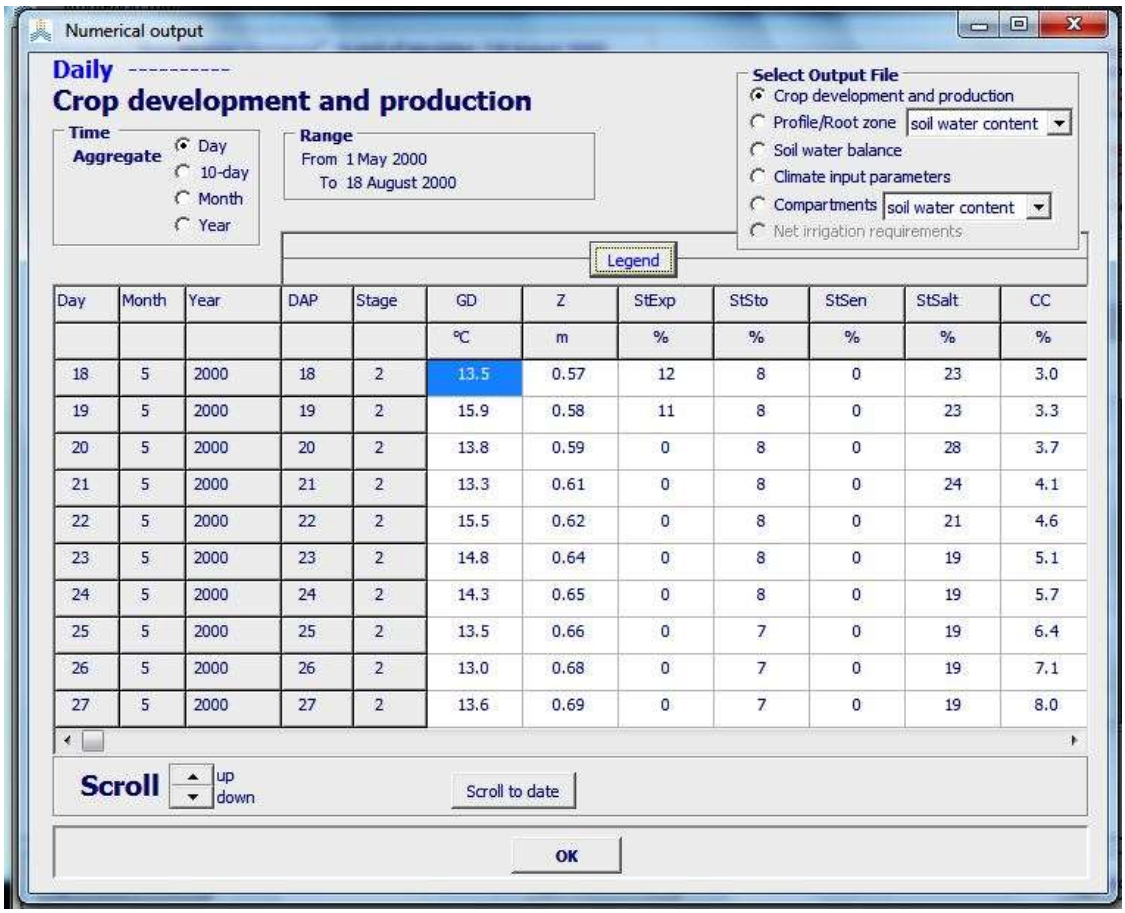
Figure 2.21j – By selecting the (1) <Numerical output>, (2) <Field data>, (3) <Update> or (4) <Main menu> command in the control panel at the bottom of the *Simulation run* menu, the user gets access to respectively the *Numerical output* menu, *Evaluation of simulation results* menu, *Update simulation 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.



Day	Month	Year	DAP	Stage	GD	Z	StExp	StSto	StSen	StSalt	CC
					°C	m	%	%	%	%	%
18	5	2000	18	2	13.5	0.57	12	8	0	23	3.0
19	5	2000	19	2	15.9	0.58	11	8	0	23	3.3
20	5	2000	20	2	13.8	0.59	0	8	0	28	3.7
21	5	2000	21	2	13.3	0.61	0	8	0	24	4.1
22	5	2000	22	2	15.5	0.62	0	8	0	21	4.6
23	5	2000	23	2	14.8	0.64	0	8	0	19	5.1
24	5	2000	24	2	14.3	0.65	0	8	0	19	5.7
25	5	2000	25	2	13.5	0.66	0	7	0	19	6.4
26	5	2000	26	2	13.0	0.68	0	7	0	19	7.1
27	5	2000	27	2	13.6	0.69	0	7	0	19	8.0

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).

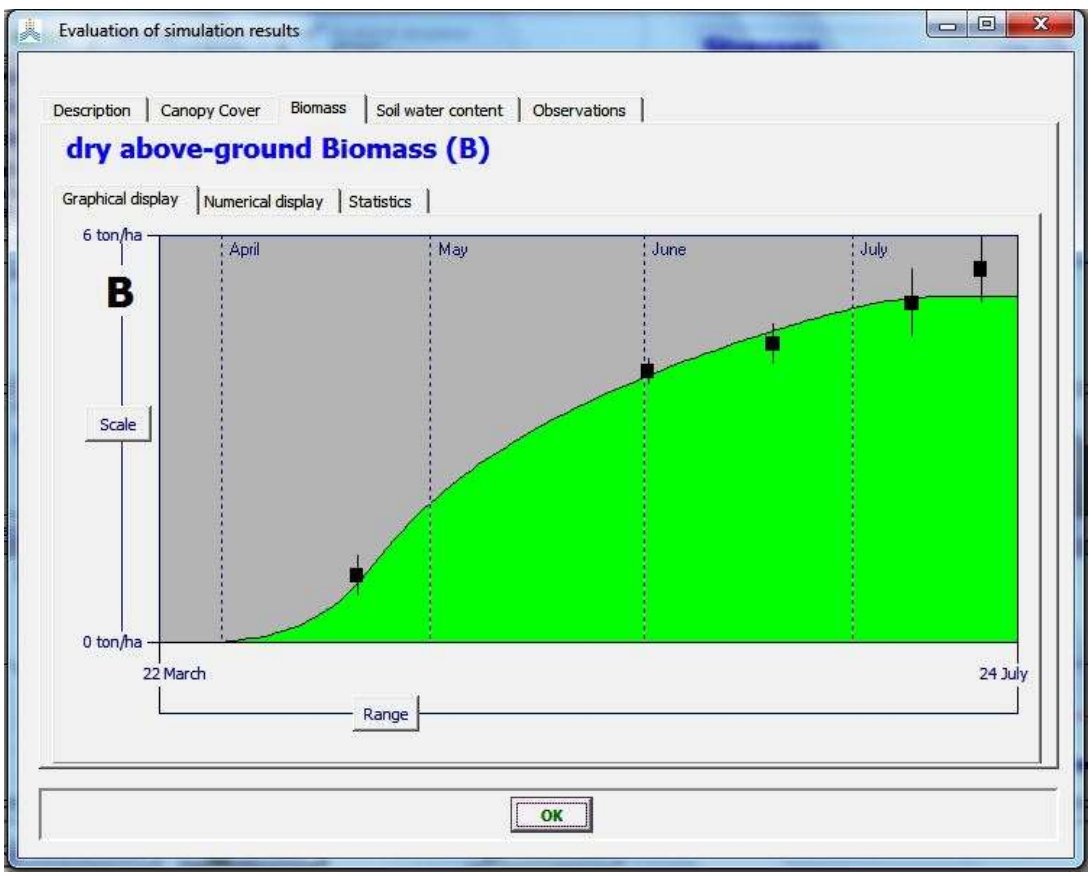


Figure 2.21m – Simulated (line) and observed (dots) dry above-ground Biomass with their standard deviations (vertical lines) in the tabular sheet 'Biomass' of the *Evaluation of simulation results* menu

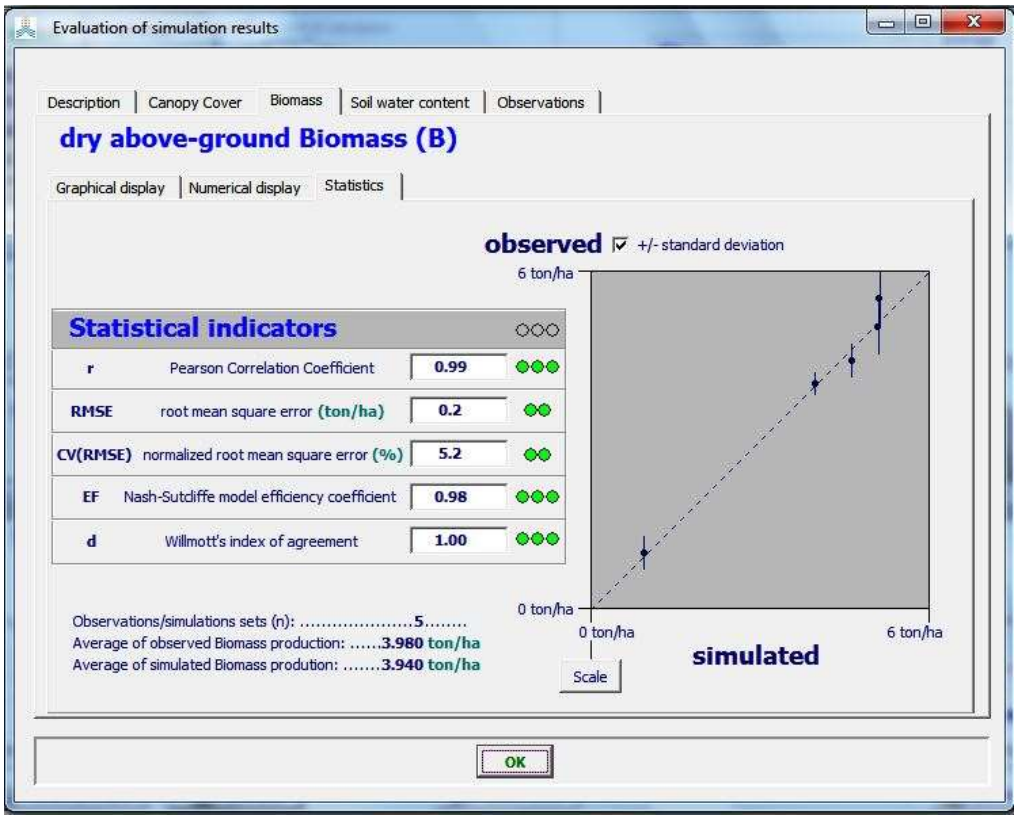


Figure 2.21n – Statistical indicators for the assessment of the simulated dry above-ground Biomass in the tabular sheet 'Biomass' of the *Evaluation of simulation results* menu

- **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:

$$= \left[\frac{\sum(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum(O_i - \bar{O})^2 \sum(P_i - \bar{P})^2}}\right] \qquad (2.21a)$$

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.

$$RMSE = \sqrt{\frac{\sum(P_i - O_i)^2}{n}} \qquad (2.21b)$$

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 (Jacovides 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.

$$CV(RMSE) = \frac{1}{\bar{O}} \sqrt{\frac{\sum (P_i - O_i)^2}{n}}\, 100 \qquad (2.21c)$$

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
≤ 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 then the model.

$$EF = 1 - \frac{\sum (P_i - O_i)^2}{\sum (O_i - \bar{O})^2} \qquad (2.21d)$$

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 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.

$$d = 1 - \frac{\sum (P_i - O_i)^2}{\sum \left(\left| P_i - \overline{O} \right| + \left| O_i - \overline{O} \right| \right)^2} \qquad (2.21e)$$

A disadvantages 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 systemic over- or underestimations (Krause et al., 2005).

The Wilmott'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.

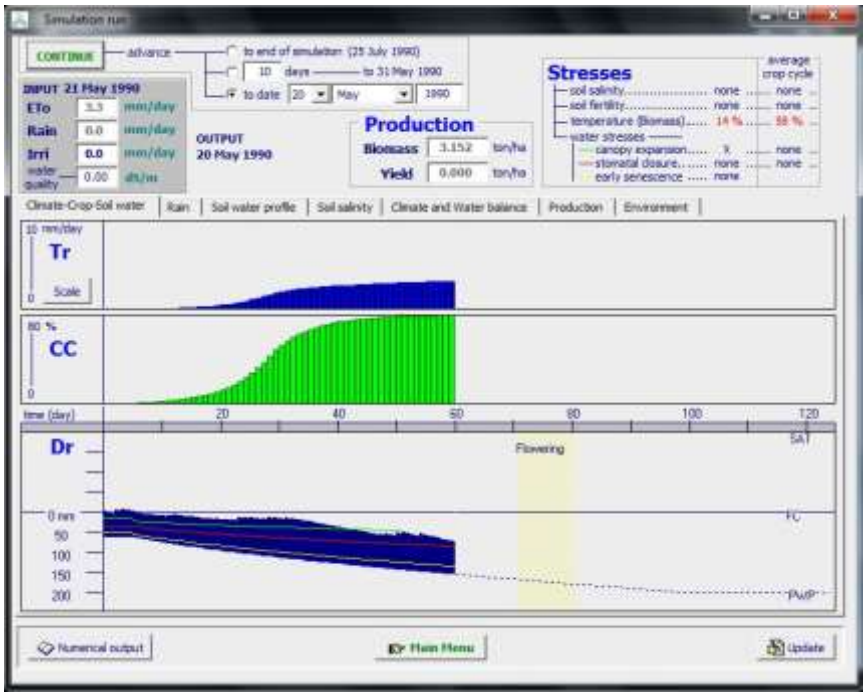
Before such changes are made, the user should check if the mismatch between observations and simulation results is not the result of a wrong setting of non-conservative crop parameters and/or a poor description of the environment in which the crop develops. Only events not simulated in AquaCrop may justify 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).

(a)



(b)

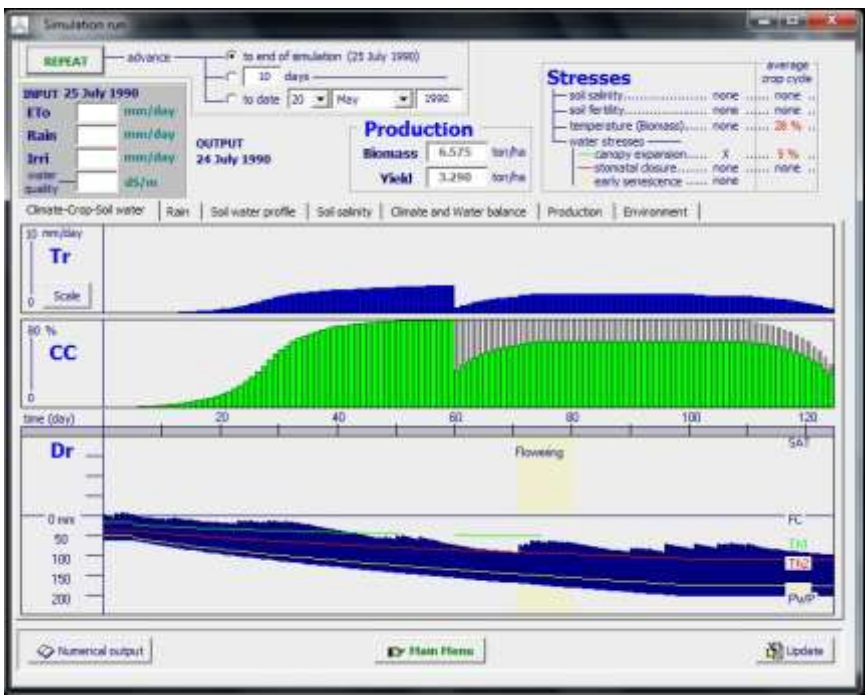
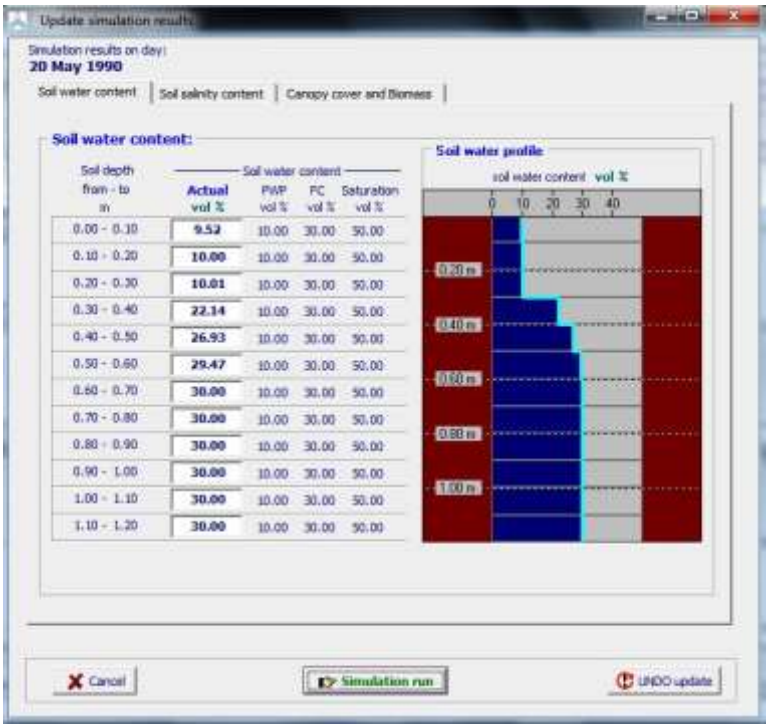


Figure 2.21p – Simulated Crop transpiration (Tr), green Canopy cover (CC) and root zone depletion (Dr) displayed in the ***Simulation run*** menu (a) before the update on 20 May 1990 (in the ***Update simulation results*** menu), and (b) and at the end of the simulation run.

(a)



(b)

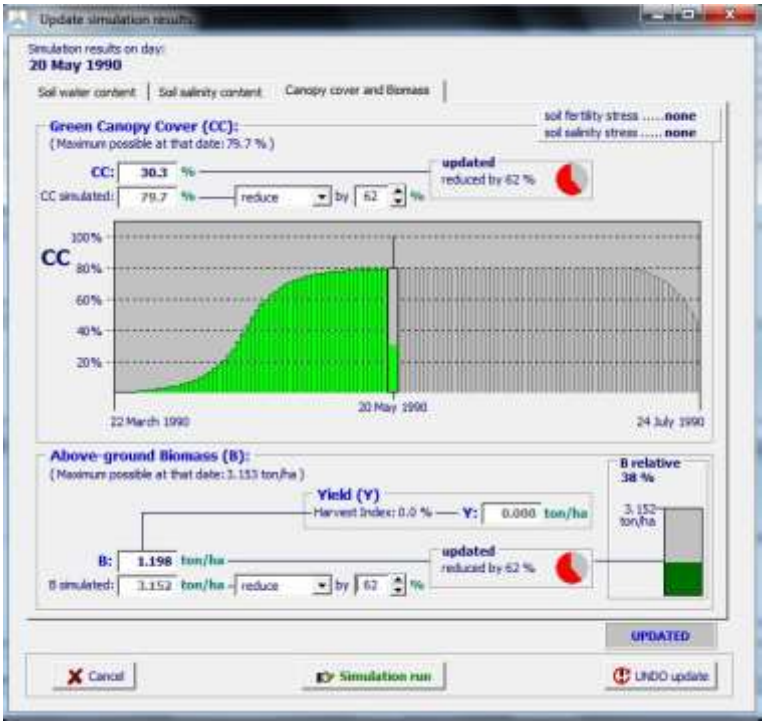


Figure 2.21q – The (a) actual soil water content and (b) green Canopy Cover and above-ground Biomass on 20 May 1990, as simulated and/or updated in the ***Update simulation results*** menu.

- **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 θ_{PWP} – θ_{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.

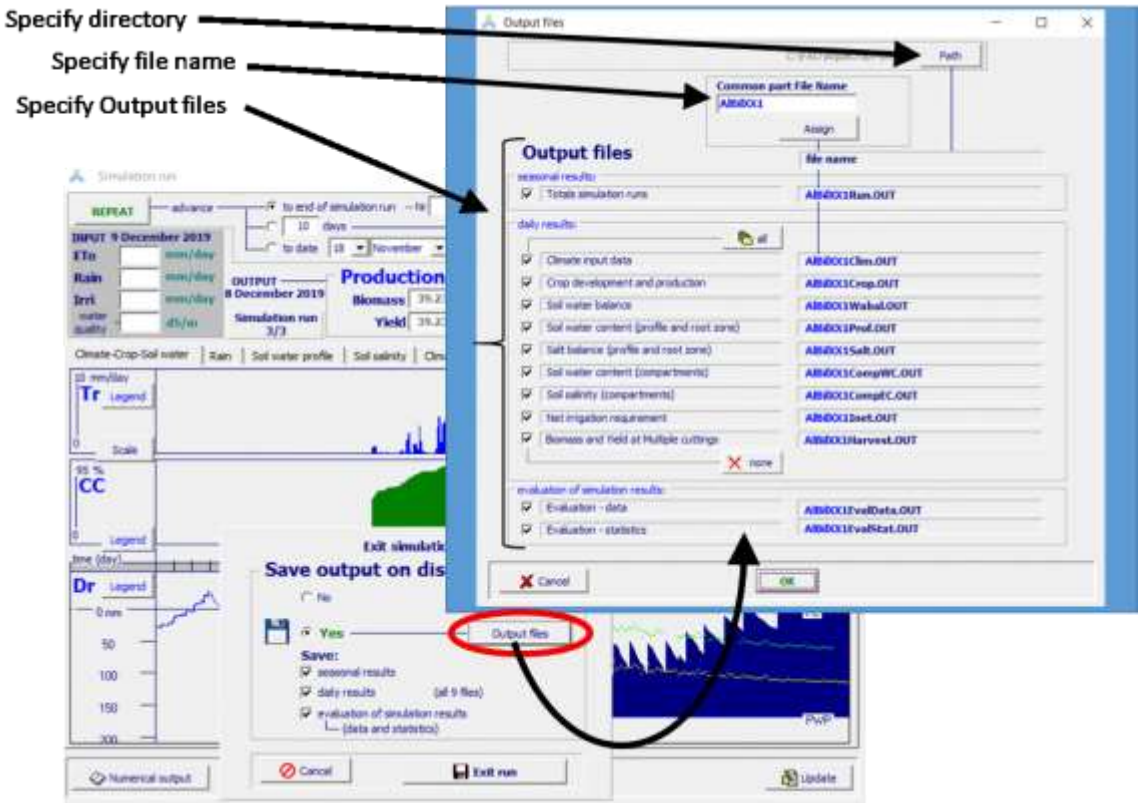


Figure 2.21r – Specification of the files to be recorded, and the path and file name for the Output files in the *Output files* menu

- **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
ProjectHarvest.OUT	Biomass and Yield at Multiple cuttings

- **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);
PorjectEvalStat.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 (HIo) with an adjustment factor for stress effects.

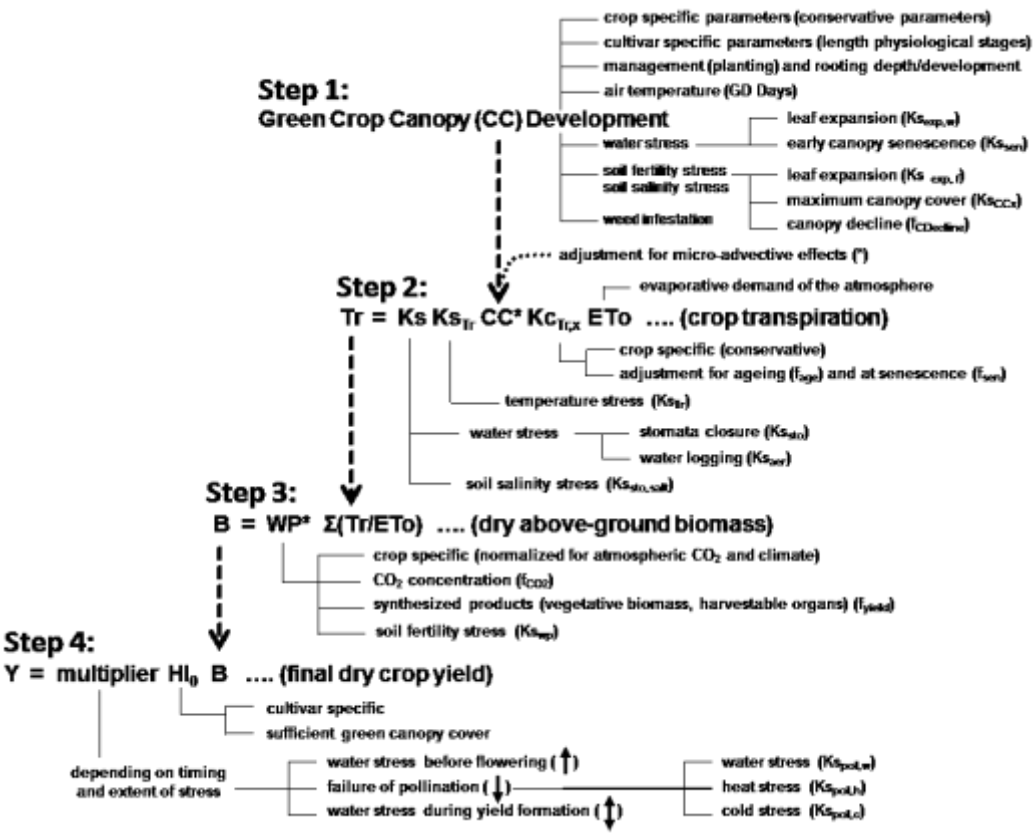


Figure 2.22a – Schematic outline of the model operation of AquaCrop

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 consists 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

Available software packages, to estimate CC from pictures: ***FREEWARE:*** - 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 ***OTHER OPTION (not freeware):*** - 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
Guidelines: - 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 ECe, and/or the ECw 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 Ks functions are conservative crop parameters and should not be adjusted.

☐ **Check reference evapotranspiration (ETo):**

AquaCrop runs with ETo estimated with the FAO Penman-Monteith method (see 2.9 'Climatic data'). To check if ETo is well calculated, the (daily) ETo 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.

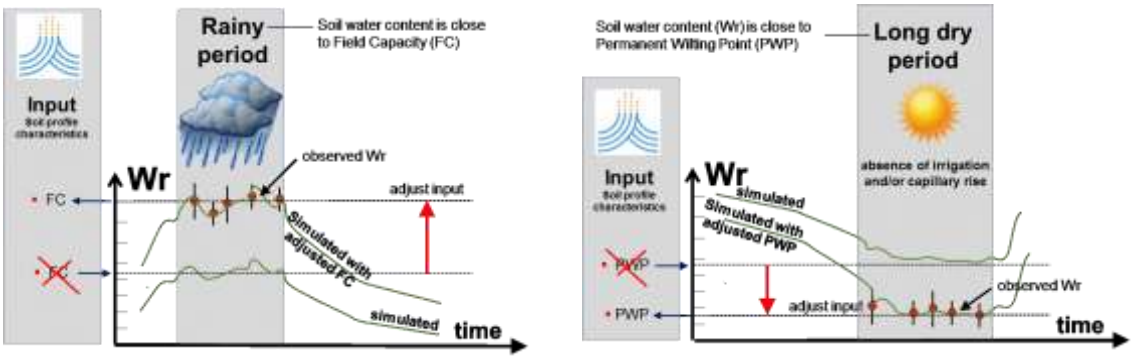
☐ **Check the soil water balance:**

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 chartacteristics'). 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.



(a) **(b)**

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 m^2) 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 (HIo):**
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 (HIo). 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, HIo is likely to increase in the future. On the other hand, local land races are likely to have a smaller HIo 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 -------|- DATA
                             AquaCrop.EXE     |
                                              |- IMPORT
                                              |
                                              |- OBS
                                              |
                                              |- OUTPUT
                                              |
                                              |- SIMUL
                                                     |-  Default.PAR
                                                     |-  General.PAR
                                                     |-  Planting.PAR
                                                     |-  Onset.PAR
                                                     |-  Soil.PAR
                                                     |-  Rainfall.PAR
                                                     |-  Crop.PAR
                                                     |-  Field.PAR
                                                     |-  Temperature.PAR
                                                     |-  EndSeason.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).

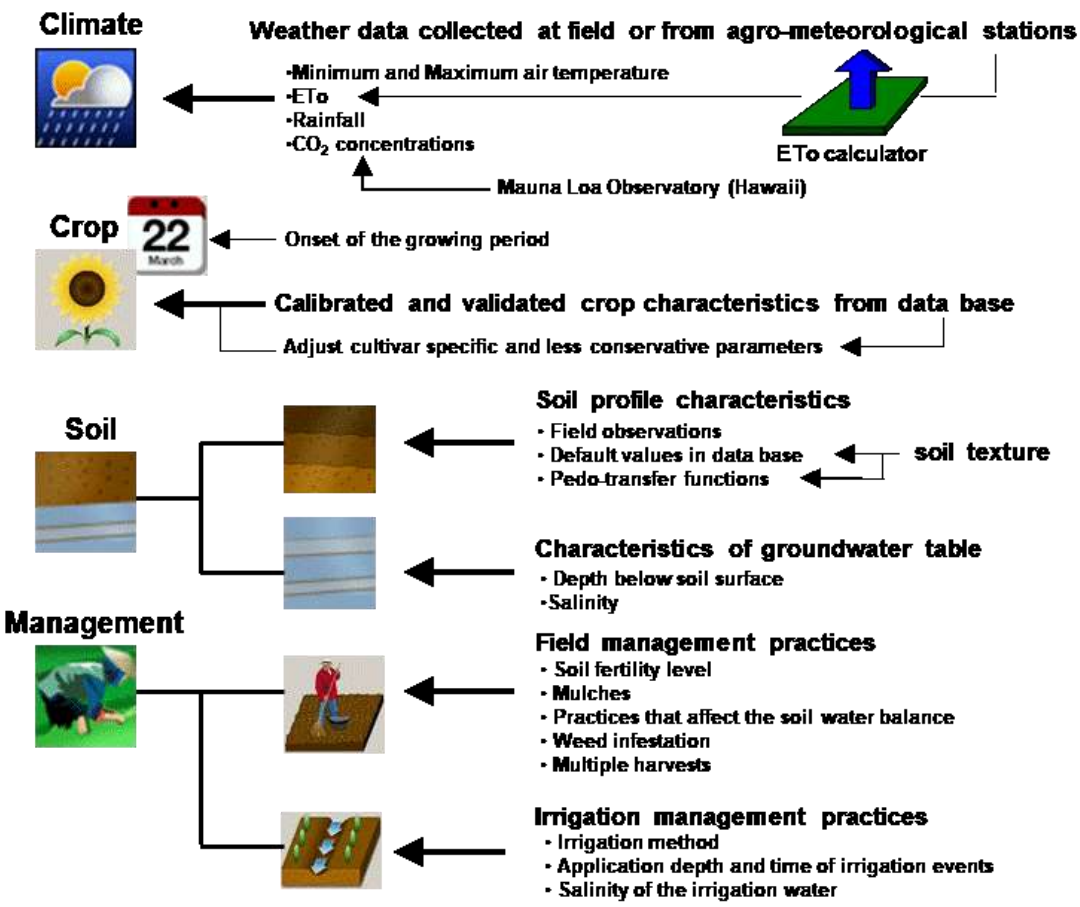


Figure 2.23a – Required input data for AquaCrop

The input is stored in text files which are retrieved through the user-interface. Input files contain the characteristics of the crop and calendar, 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.

For the **input files**, distinction is made between:

- Climate files (*.CLI) which contains the names of a set of files containing
  - air temperature data (*.Tnx),
  - reference evapotranspiration data (*.ETo),
  - rainfall data (*.PLU), and
  - atmospheric CO_2 data (*.CO2);
- Calendar files (*.CAL) with the determination of the onset of the growing period
- 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, 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 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.

The settings for the program parameters are saved in another text file which has the same file name as the project, but with the filename extension 'PP1' (for single projects) and 'PPn' (for multiple projects).

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 CO_2 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)

```
Tunis (Tunisia) climatic data
 7.1   : AquaCrop Version (August 2023)
Tunis.TMP
Tunis.ETo
Tunis.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 CO_2 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 CO_2 concentration by linear interpolation between the specified CO_2 values for an earlier and later year;
- for years out of the listed range, the atmospheric CO_2 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).

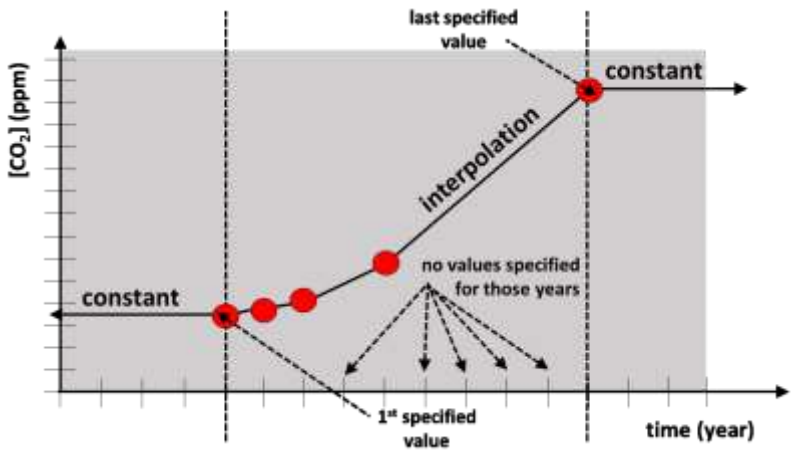


Figure 2.23c – Rules applicable in CO2 file

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 CO_2 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 Antarctica[1] 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 CO_2 concentrations in ppm in the MaunaLoa.CO2 file

Year	Annual Mean [CO_2] ppm	Year	Annual Mean [CO_2] ppm	Year	Annual Mean [CO_2] ppm
1902	297.4	1968	323.05	1995	360.62
1905	298.2	1969	324.62	1996	362.37
1912	300.7	1970	325.68	1997	363.47
1915	301.3	1971	326.32	1998	366.50
1924	304.5	1972	327.46	1999	368.14
1926	305.0	1973	329.68	2000	369.41
1929	305.2	1974	330.17	2001	371.13
1932	307.8	1975	331.08	2002	373.22
1934	309.2	1976	332.06	2003	375.77
1936	307.9	1977	333.78	2004	377.49
1938	310.5	1978	335.40	2005	379.80
1939	310.1	1979	336.78	2006	381.90
1940	310.5	1980	338.70	2007	383.77
1944	309.7	1981	340.11	2008	385.59
1948	310.7	1982	341.22	2009	387.37
1953	311.9	1983	342.84	2010	389.85
1954	314.1	1984	344.40	2011	391.63
1958	315.29	1985	345.87	2012	393.82
1959	315.98	1986	347.19	2013	396.48
1960	316.91	1987	348.98	2014	398.65
1961	317.65	1988	351.45	2015	400.83
1962	318.45	1989	352.89	2016	404.28
1963	318.99	1990	354.16	2017	406.59
1964	319.61	1991	355.48	2018	408.59
1965	320.03	1992	356.27	2019	411.49
1966	321.37	1993	356.95	2025	423.49
1967	322.18	1994	358.63	2099	871.49

When the effect of a specific [CO_2] 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 CO_2 concentration corresponds to 550 ppm. For all years, AquaCrop will assume that the CO_2 concentration remains constant (550 ppm).

Table 2.23n – Example of a CO2 file containing only one specific annual atmospheric [CO_2] for testing its effect on crop production in any year of the simulation period.

```
Constant CO2 concentration of 550 ppm
Year        CO2 (ppm by volume)
============================
2050        550
```

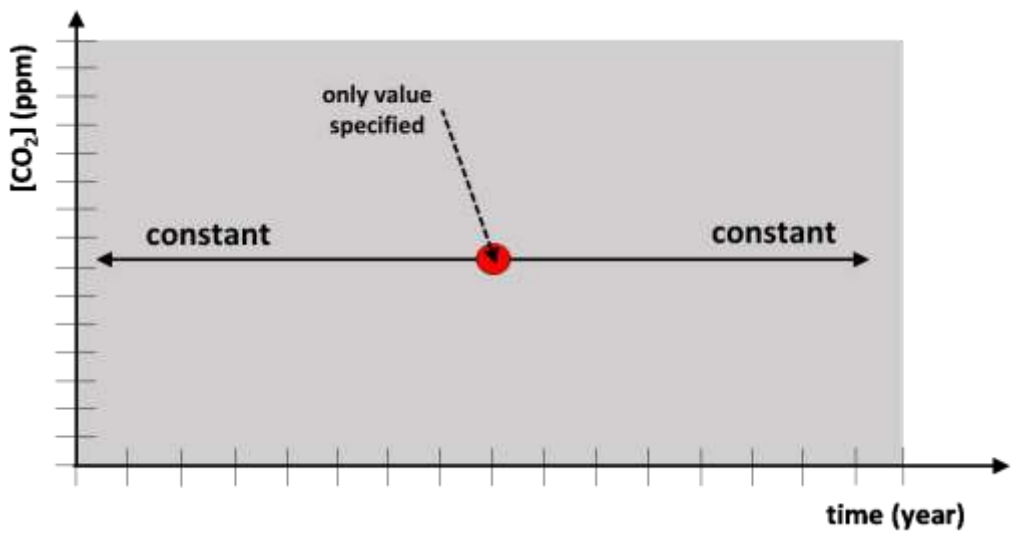


Figure 2.23d – Rules applicable in CO2 file when only one value is specified (example of Tab. 2.23n)

2.23.4 Crop calendar file (*.CAL)

The structure of the calendar file is given in Table 2.23o1. The criteria numbers (line 6 of the calendar file) for the generation of the Onset day by a Rainfall criterion or an Air temperature criterion are given in Table 2.23o2 and 2.23o3. An example of a crop calendar file is presented in Table 2.23o4. Day numbers are given in Table 2.23o5.

Table 2.23o1 – Structure of the calendar file (*.CAL)

Line	Type	Value	Description
1	text string		File description
2	double	7.0	AquaCrop Version (2021)
Specification of the onset of the growing period			
3	Switch	0	The onset of the growing period is ***fixed on a specific*** date
		1	The onset of the growing period is ***generated*** by a rainfall, air temperature or ETo criterion
Start and End of the time window for onset criterion (-9 in case onset is fixed on a specific day)			
4	Integer	(1 … …365)	Day-number (Table 6) of the Start of the time window for the onset criterion
5	Integer	XXXX	Length (days) of the time window for the onset criterion
Day-number or number of rainfall or temperature criterion for the onset of the growing period			
6	Integer	(1 … …365)	***Day-number*** (Table 6) for the onset of the growing period if fixed on a specific date (switch = 0 in line 3)
		(1..4) or (11..14)	***Criterion number*** (Table 3 or 4) when onset is generated based on rainfall or temperature (switch = 1 in line 3) –
Lines 7 to 9: description of the onset criterion (-9 in case onset is fixed on a specific day)			
7	Double	XXXX.XX	Value of the onset criterion (in mm , mm/day, °C, degree-days, or percentage of Rain/ETo ratio)
8	Integer	XXXX	Number of successive days for the onset criterion (days)
9	ShortInt	X	Number of occurrences before the onset criterion applies (max = 3)

Table 2.23o2 – The number (from 1 to 4) for the Onset rainfall criteria

Number	Description	Value	Period
1	***cumulative rainfall*** since the start of the time period is equal to or exceeds the pre-set value	mm	-
2	observed ***rainfall during a number of successive days*** is equal to or exceeds the pre-set value	mm	Days
3	***10-day rainfall*** is equal to or exceeds the pre-set value	mm	-
4	***10-day rainfall exceeds*** the pre-set ***percentage of the 10-day ETo***	%	-

Table 2.23o3 – The number for the Onset air temperature criteria (from 11 to 14)

Number	Description	Value	Period
11	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	°C	Days
12	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	°C	Days
13	The sum of Growing Degrees in a given number of successive days is equal to or exceeds the specified growing degree days	Degree-days	Days
14	The cumulative Growing Degrees since the start of the time period is equal to or exceeds the specified growing degree days	Degree-days	-

Table 2.23o4 – Example of a crop calendar (Figure 5)

1st occurrence 20 mm Rain in 4 days since 1/10

7.1 : AquaCrop Version (August 2023)
1 : The onset of the growing period is generated by a rainfall or air temperature criterion
274 : Day-number (1 ... 366) of the Start of the time window for the onset criterion
92 : Length (days) of the time window for the onset criterion
2 : Criterion Nr (Observed rainfall during a number of successive days is equal to or exceeds a preset value)
20 : Preset value of Observed rainfall (mm)
4 : Number of successive days for the onset criterion
1 : Number of occurrences before the onset criterion applies (max = 3)

Table 2.23o5 – Day numbers

Day	January	February	March	April	May	June
1	1	32	60	91	121	152
2	2	33	61	92	122	153
3	3	34	62	93	123	154
4	4	35	63	94	124	155
5	5	36	64	95	125	156
6	6	37	65	96	126	157
7	7	38	66	97	127	158
8	8	39	67	98	128	159
9	9	40	68	99	129	160
10	10	41	69	100	130	161
11	11	42	70	101	131	162
12	12	43	71	102	132	163
13	13	44	72	103	133	164
14	14	45	73	104	134	165
15	15	46	74	105	135	166
16	16	47	75	106	136	167
17	17	48	76	107	137	168
18	18	49	77	108	138	169
19	19	50	78	109	139	170
20	20	51	79	110	140	171
21	21	52	80	111	141	172
22	22	53	81	112	142	173
23	23	54	82	113	143	174
24	24	55	83	114	144	175
25	25	56	84	115	145	176
26	26	57	85	116	146	177
27	27	58	86	117	147	178
28	28	59	87	118	148	179
29	29	(60)	88	119	149	180
30	30	-	89	120	150	181
31	31	-	90	-	151	-

Table 2.23o5 – Day numbers (continue)

Day	July	August	September	October	November	December
1	182	213	244	274	305	335
2	183	214	245	275	306	336
3	184	215	246	276	307	337
4	185	216	247	277	308	338
5	186	217	248	278	309	339
6	187	218	249	279	310	340
7	188	219	250	280	311	341
8	189	220	251	281	312	342
9	190	221	252	282	313	343
10	191	222	253	283	314	344
11	192	223	254	284	315	345
12	193	224	255	285	316	346
13	194	225	256	286	317	347
14	195	226	257	287	318	348
15	196	227	258	288	319	349
16	197	228	259	289	320	350
17	198	229	260	290	321	351
18	199	230	261	291	322	352
19	200	231	262	292	323	353
20	201	232	263	293	324	354
21	202	233	264	294	325	355
22	203	234	265	295	326	356
23	204	235	266	296	327	357
24	205	236	267	297	328	358
25	206	237	268	298	329	359
26	207	238	269	299	330	360
27	208	239	270	300	331	361
28	209	240	271	301	332	362
29	210	241	272	302	333	363
30	211	242	273	303	334	364
31	212	243	-	304	-	365

2.23.5 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 2.23p1. The internal crop calendar, for perennial herbaceous forage crops, is appended to the crop file (Table 2.23p2).

Table 2.23p1 – Example of crop file (Default.CRO)

```
a generic crop
     7.1       : AquaCrop Version (August 2023)
     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)
    50         : Sum(ETo) during dormant period to be exceeded before crop is permanently wilted
     0.90      : Soil water depletion factor for pollination (p - pol) - Upper threshold
     5         : Vol% for Anaerobiotic 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 (m3water/m3soil.day) in top quarter of root zone
    0.012     : Maximum root water extraction (m3water/m3soil.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 (cm2)
    6.50      : Canopy size of individual plant (re-growth) at 1st day (cm2)
  185000      : Number of plants per hectare
    0.15000   : Canopy growth coefficient (CGC): Increase in canopy cover (fraction soil cover per day)
   -9         : Number of years at which CCx declines to 90 % of its value due to self-thinning - Not Applicable
   -9.00      : Shape factor of the decline of CCx over the years due to self-thinning - Not Applicable
   -9         : dummy - Parameter no Longer required
    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 ETo and CO2 (WP*) (gram/m2)
  100         : Water Productivity normalized for ETo and CO2 during yield formation (as % WP*)
  100         : Sink strength (%) quatifying biomass response to elevated atmospheric CO2 concentration
   50         : Reference Harvest Index (HIo) (%)
    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 GGDays: Increase in canopy cover (in fraction soil cover per growing-degree day)
   -9.000000  : CDC for GGDays: Decrease in canopy cover (in fraction per growing-degree day)
   -9         : GDDays: building-up of Harvest Index during yield formation
   25         : dry matter content (%) of fresh yield
    0.30      : Minimum effective rooting depth (m) in first year - required only in case of regrowth
    1         : Crop is sown in 1st year - required only in case of regrowth
    0         : Transfer of assimilates from above ground parts to root system is NOT considered
```

0	**: Number of days at end of season during which assimilates are stored in root system**
0	**: Percentage of assimilates transferred to root system at last day of season**
0	**: Percentage of stored assimilates transferred to above ground parts in next season**

The internal crop calendar is appended to the crop file of a perennial crop (Table 2.23p2). The selected options, dates and threshold values in these lines are loaded together with the crop characteristics. The criteria numbers (line 4 and 11) for the generation of the Restart and End of growth are given in Table 2.23p3 and 2.23p4. An example is provided in Table 2.23p5.

Table 2.23p2 – Added lines to the crop file of a perennial crop

Line	Type	Value	Description
Title			
1			Empty line
2	String		Internal crop calendar
3	String		==========
Specification of the ***Restart*** of growth			
4	ShortInt	0	zero when the Restart of growth is ***fixed on a specific date***
		(12, 13)	The ***criterion number*** in case the Restart is generated (Table 9)
5	Integer	(1..31)	The day, if the Restart is fixed, or The first day of the time window in case the restart is generated
6	Integer	(1..12)	The month, if the Restart is fixed, or The first month of the time window in case the restart is generated
7	Integer	XXXX	Length (days) of the time window in case the restart is generated Default is 90 days
Lines 8 to 10: description of the restart criterion (-9 in case restart is fixed on a specific date)			
8	Double	XXXX.X	Value of the restart criterion (in °C or degree-days)
9	Integer	XXXX	Number of successive days for the restart criterion (days)
10	ShortInt	(1..3)	Number of occurrences before the restart criterion applies (max = 3)
Specification of the ***End*** of growth			
11	ShortInt	0	zero when the End of growth is ***fixed on a specific date***
		(62, 63)	The ***criterion number*** in case the End is generated (Table 10)
12	Integer	(1..31)	The day, if the End is fixed, or The first day of the time window in case the end is generated
13	Integer	(1..12)	The month, if the end is fixed, or The first month of the time window in case the end is generated
14	ShortInt	(0..X)	Number of years to add to the Restart year
15	Integer	XXXX	Length (days) of the time period for the end criterion Default is 90 days

Lines 16 to 18: description of the end criterion (-9 in case end is not generated)			
16	Double	XXXX.X	Value of the end criterion (°C or degree-days)
17	Integer	XXXX	Number of successive days for the end criterion (days)
18	ShortInt	(1..3)	Number of occurrences before the end criterion applies (max = 3)

Table 2.23p3 – The numbers for the Restart air temperature criteria (line 4)

Number	Description	Value	Period
12	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	°C	Days
13	The sum of Growing Degrees in a given number of successive days is equal to or exceeds the specified growing degree days	Degree-days	Days

Table 2.23p4– The number for the End air temperature criteria (line 11)

Number	Description	Value	Period
62	The daily average air temperature, in each day of a given number of successive days, is less than a specified average air temperature	°C	Days
63	The sum of Growing Degrees in a given number of successive days is less than the specified growing degree days	Degree-days	Days

Table 2.23p5 – Example of internal crop calendar

```
Internal crop calendar
 ==========================================================
   13        : The Restart of growth is generated by Growing-degree days
    1       : First Day for the time window (Restart of growth)
    1       : First Month for the time window (Restart of growth)
   60        : Length (days) of the time window (Restart of growth)
   20.0       : Threshold for the Restart criterion: Growing-degree days
    8       : Number of successive days for the Restart criterion
    2       : Number of occurrences before the Restart criterion applies
   63        : The End of growth is generated by Growing-degree days
   31        : Last Day for the time window (End of growth)
   12        : Last Month for the time window (End of growth)
    0       : Number of years to add to the Onset year
   60        : Length (days) of the time window (End of growth)
   10.0       : Threshold for the End criterion: Growing-degree days
    8       : Number of successive days for the End criterion
    1       : Number of occurrences before the End criterion applies
```

2.23.6 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)

Description	Format
First line is a description of the file content	String of characters
Version number of AquaCrop	Real (1 digit)
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
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
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)	
Day number of reference day (use -9 if the reference day is the onset of the growing period)	Integer
Title (‘Day Depth (mm) ECw (dS/m)’)	String of characters

Dotted line ('==========')	String of characters
For the 1st irrigation event: – The number of days after sowing/planting – The net irrigation application depth (mm) – The Electrical Conductivity (dS/m) of the irrigation water 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.	 Integer Integer Real (1 digit)
Repeat for each successive irrigation event	
Code = 2 (in line 5): Generation of an irrigation schedule (Example Table 2.23q - 4)	
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
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
Empty line	-
Title ('From day … ECw (dS/m)')	String of characters
Dotted line ('==========')	String of characters
For the 1st rule: – 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: ○ 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: ○ Extra water on top of the amount of irrigation water required to bring the root zone back to Field Capacity.	Integer Integer Integer Real (1 digit)

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. – The Electrical Conductivity (dS/m) of the irrigation water. 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. 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	
If applicable specifies values for 2nd , 3rd , 4th , .. rule	
Code = 3 (in line 5): Determination of net irrigation requirement. (Example Table 2.23q - 5)	
The depletion (% RAW) below which the soil water content in the root zone may not drop (0 % RAW corresponds to Field Capacity). 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.	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
   7.1   : AquaCrop Version (August 2023)
   1     : Sprinkler irrigation
 100     : Percentage of soil surface wetted by irrigation
   1     : Irrigation schedule
   28490 : Reference DayNr for Day 1 (= 1 January 1979   )
   Day    Depth (mm)   ECw (dS/m)
===================================
    91        50          1.5
   101        50          1.5
   111        50          1.5
   121        50          1.5
   131        50          1.5
   141        50          1.5
  1161        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
   7.1   : AquaCrop Version (August 2023)
   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:

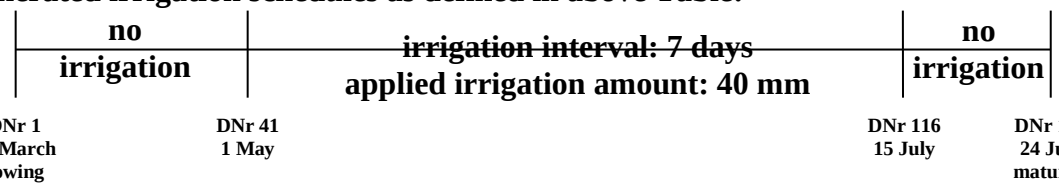


Table 2.23q – 5. – Example of an irrigation file (file with extension IRR) in which the request for the determination of the Net irrigation water requirement is specified

```
Determination of Net irrigation requirement (allowable depletion 73 % RAW)
   7.1    : AquaCrop Version (August 2023)
   1      : irrigation method - not considered
 100      : soil surface wetted by irrigation - not considered
   3      : Determination of Net Irrigation requirement
  73      : Allowable depletion of RAW (%)
```

2.23.7 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), weed infestation and multiple harvests 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, that weed management is perfect, and that there are no multiple harvests during the growing cycle.

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.)	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	Surface run-off may or may not be affected by field surface practices. A number (0 or 1) is used as code to specify if surface runoff is affected/prevented by field surface practices: 0: surface runoff is not affected by field surface practices 1 : surface runoff is affected or completely prevented by field surface practices	Integer

	(Default = 0)	
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 (%) at canopy closure	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)
12	Replacement (%) by weeds of the self-thinned part of the CC - only applicable to perennial crops	Integer
13	Multiple cuttings may or may not be considered. A number (0 or 1) is used as code to specify if multiple cuttings are considered: 0: multiple cuttings are considered 1: multiple cuttings are not considered (Default = 0)	Integer
14	Canopy cover (%) after cutting	Integer
15	Parameter no longer considered	Integer
16	Start day for generating harvests (1 = start of growth cycle)	Integer
17	Number of days in which harvests can be generated (use -9 for total growth cycle)	Integer
18	Timing of multiple cuttings. A number (-9, 0 or 1) is used as code to indicate how the time of harvest is determined: -9: Timing of multiple cuttings: Not Applicable 0: Harvest events are specified by the user 1: Multiple cuttings are generated by a time criterion	Integer
19	Time criterion for multiple cutting. A number (0 to 5) is used as code to specify the time criterion for multiple cutting: 0: Time criterion: Not Applicable 1: Time criterion: Interval in days 2: Time criterion: Interval in Growing Degree Days 3: Time criterion: Mass (ton/ha) dry above ground biomass 4: Time criterion: Mass (ton/ha) dry crop yield 5: Time criterion: Mass (ton/ha) fresh crop yield	Integer
20	Final harvest at crop maturity may be or may not be considered, when generating harvests. A number (0 or 1) is used as code to specify if final harvest at crop maturity is considered 0: final harvest at crop maturity is not considered 1: final harvest at crop maturity is considered	Integer
21	Day number of the reference day for the harvest calendar (use -9 if the reference is the start of the growing period)	

Extra lines provide the details of the Multiple harvests (only required if multiple cuttings are considered)			
22	Empty line		
	A. When harvest days are specified (Code is 0 in line 18 for timing of multiple cuttings)		
23	Title (‘Harvest Day’)		String of characters
24	==========		String of characters
25	Number of days after the reference day of the 1st harvest		Integer
26..	Number of days after the reference day of next harvest (if any)		Integer
	B. When Multiple cuttings are generated by a time criterion (Code is 1 in line 18 for timing of multiple cuttings)		
	Title	Time criterion (line 19)	
23	‘From day Interval (days)’ ‘From day Interval (GDDays)’ ‘From day Dry biomass (ton/ha)’ ‘From day Dry yield (ton/ha)’ ‘From day Fresh yield (ton/ha)’	1 2 3 4 5	String of characters
24	==========		String of characters
25	Day Number Interval or Day Number Biomass or Yield		Integer/ Integer or Integer/Real(3 digits)
26..	Etc. ..		

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 affecting surface run-off, weed infestation and multiple harvests

```
 Description…
     7.1       : AquaCrop Version (August 2023)
     0         : percentage (%) of ground surface covered by mulches IN growing period
    50         : effect (%) of mulches on reduction of soil evaporation
     0         : Non-limiting soil fertility
     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)
     0         : relative cover of weeds at canopy closure (%)
     0         : increase of relative cover of weeds in mid-season (+%)
    -0.01      : shape factor of the CC expansion function in a weed infested field
   100         : replacement (%) by weeds of the self-thinned part of the CC - only for perennials
     1         : Multiple cuttings are considered
    25         : Canopy cover (%) after cutting
    -9         : parameter no longer considered
     1         : First day of window for multiple cuttings (1 = start of growth cycle)
    -9         : Number of days in window for multiple cuttings (-9 = total growth cycle)
     0         : Multiple cuttings schedule is specified
     0         : Time criterion: Not Applicable
     0         : final harvest at crop maturity is not considered
 40909         : dayNr for Day 1 of list of cuttings

 Harvest Day
==============
   174
   203
   244
   293
```

No soil fertility stress, no organic mulches, no practices affecting or preventing surface run-off, perfect weed management and no multiple harvests

```
   Description….
        7.1       : AquaCrop Version (August 2023)
        0         : percentage (%) of ground surface covered by mulches IN growing period
       50         : effect (%) of mulches on reduction of soil evaporation
        0         : Non-limiting soil fertility
        0.00      : height (m) of soil bunds
        0         : surface runoff NOT affected by field surface practices
        0         : N/A (surface runoff is not affected or completely prevented)
        0         : relative cover of weeds at canopy closure (%)
        0         : increase of relative cover of weeds in mid-season (+%)
       -0.01      : shape factor of the CC expansion function in a weed infested field
      100         : replacement (%) by weeds of the self-thinned part of the CC - only for perennials
        0         : Multiple cuttings are not considered
       30         : Canopy cover (%) after cutting - not considered
       -9         : parameter no longer considered
        1         : First day of window for multiple cuttings (1 = start of growth cycle)
       -9         : Number of days in window for multiple cuttings (-9 = total growth cycle)
       -9         : Timing of multiple cuttings: Not Applicable
        0         : Time criterion: Not Applicable
        0         : final harvest at crop maturity is not considered
       -9         : Start of the growing cycle is Day 1 in list of cuttings
```

2.23.8 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)	Real (2 digits)
	- soil water content at saturation (vol%)	Real (1 digit)
	- soil water content at Field Capacity (vol%)	Real (1 digit)
	- soil water content at Permanent Wilting Point (vol%)	Real (1 digit)
	- saturated hydraulic conductivity (mm/day)	Real (1 digit)
	- penetrability (%) for root zone expansion rate	Integer
	- mass percentage (%) of the gravel fraction	Integer
	- parameter 'a' for estimation of capillary rise	Real (6 digits)
	- parameter 'b' for estimation of capillary rise	Real (6 digits)
	- description	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

```
4 layered sandy clay soil
        7.1                 : AquaCrop Version (August 2023)
       72                   : CN (Curve Number)
        5                   : Readily evaporable water from top layer (mm)
        4                   : 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    43.8  41.6  27.1   150.0        100         0     -0.573700 -0.751602   sandy clay
    0.30    48.7  42.5  27.7   150.0        100         0     -0.573700 -0.751602   sandy clay
    0.30    48.3  40.9  28.0   150.0        100         0     -0.573700 -0.751602   sandy clay
    0.65    45.7  42.2  28.1   150.0        100         0     -0.573700 -0.751602   sandy clay
```

- **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:

$$SAT = 100 \frac{(\rho_p - \rho_b)}{\rho_p} \qquad \text{(Eq. 2.23s - 1)}$$

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]

- **<u>'a' and 'b' parameters for estimating capillary rise</u>**

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
   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} mm.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	$-0.4986 + 9 (10^{-5}) K_{sat}$	$-2.1320 + 0.4778 \ln(K_{sat})$
III. Sandy clayey soils sandy clay, sandy clay loam, clay loam	5 to 150	$-0.5677 - 4 (10^{-5}) K_{sat}$	$-3.7189 + 0.5922 \ln(K_{sat})$
IV. Silty clayey soils silty clay loam, silty clay, clay	1 to 150	$-0.6366 + 8 (10^{-4}) K_{sat}$	$-1.9165 + 0.7063 \ln(K_{sat})$

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 (Ksat) 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 %):

$$0 \leq REW = 10\left(FC - PWP/2\right) Z_{e,\,surf} \leq 15 \qquad \text{(Eq. 2.23s - 4)}$$

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
```

2.23.9 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 7.1 : AquaCrop Version (August 2023) 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

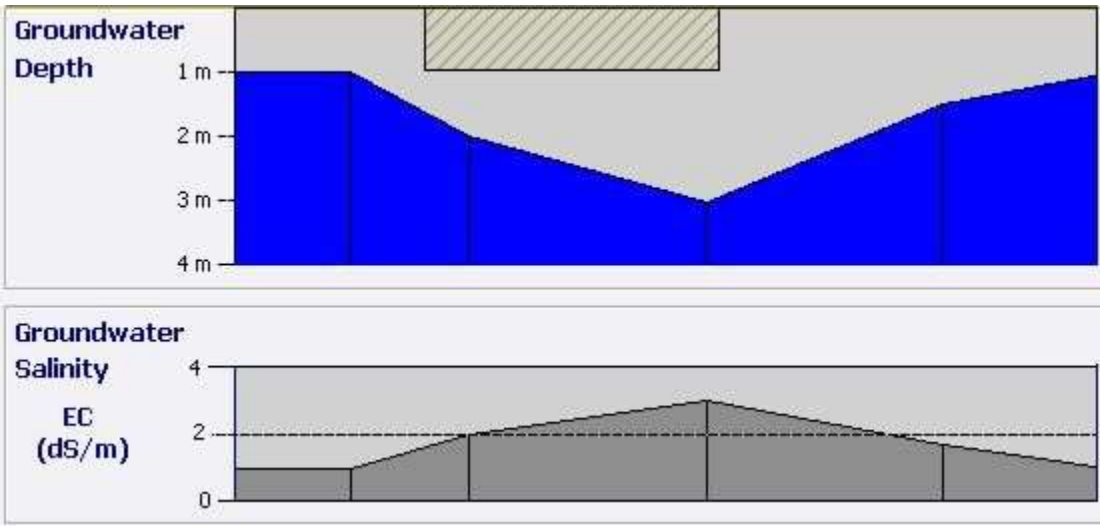
```
constant groundwater table at 1.50 m and with salinity level of 1.5 dS/m
     7.1   : AquaCrop Version (August 2023)
     1     : groundwater table at fixed depth and with constant salinity

   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
     7.1   : AquaCrop Version (August 2023)
     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 1st value in the list (for earlier dates) or the last value in the list (for later dates).

2.23.10 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 1st 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 1st 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
   7.1   : AquaCrop Version (August 2023)
  -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
```

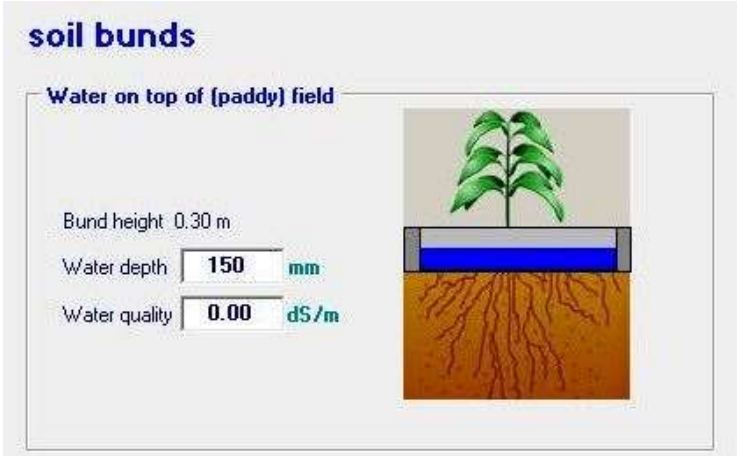


Table 2.23u – 3. – Example of initial conditions specified for specific soil layers

```
Soil water and salinity content in Field AZ123 on 21 March 2010
    7.1    : AquaCrop Version (August 2023)
  -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
```

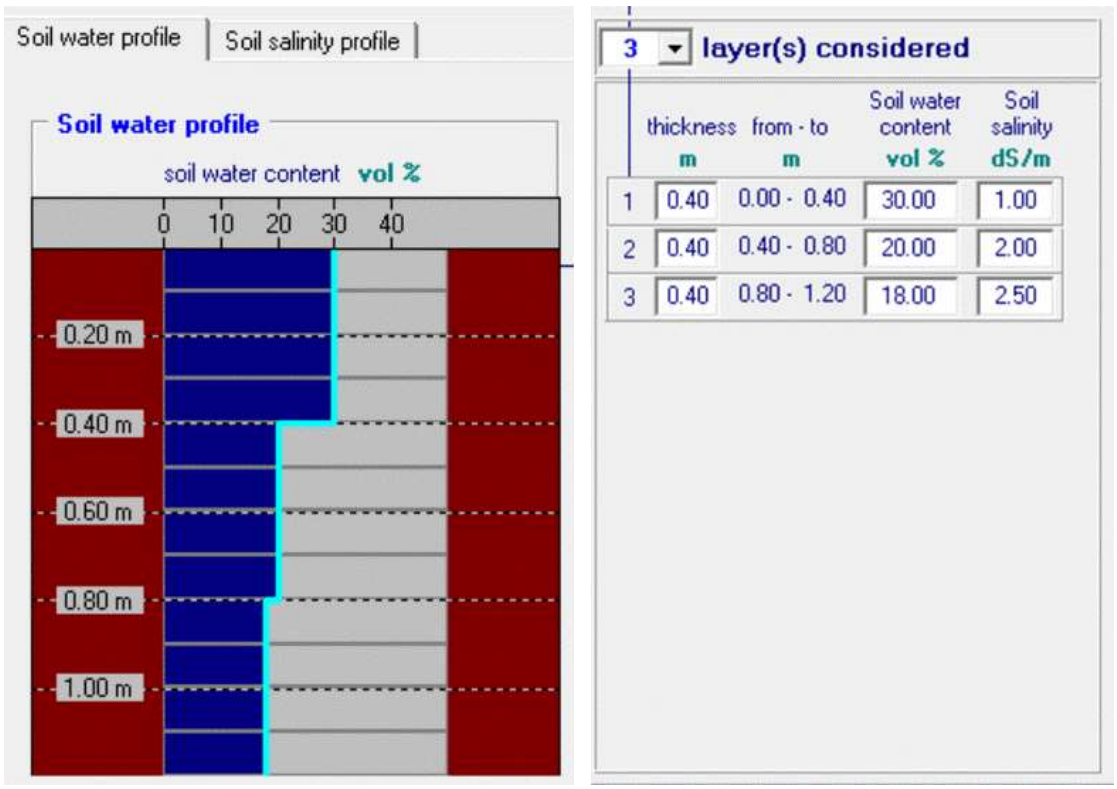


Table 2.23u – 4. – Example of initial conditions specified at particular soil depths

```
example with soil water content at particulars depths
    7.1    : AquaCrop Version (August 2023)
  -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)
    1      : soil water content specified at particular depths
    5      : number of soil depths considered

     Soil depth (m)      Water content (vol%)      ECe (dS/m)
================================================================
          0.10                 23.00                   0.00
          0.29                 15.00                   0.00
          0.45                 34.00                   0.00
          0.66                 15.00                   0.00
          1.00                 10.00                   0.00
```

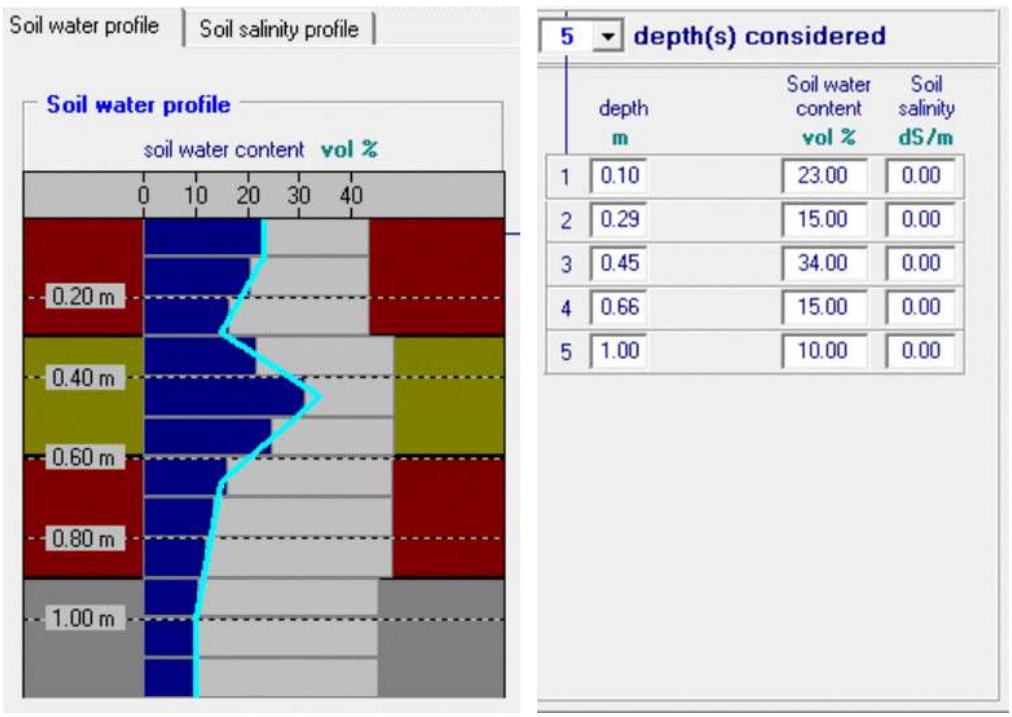
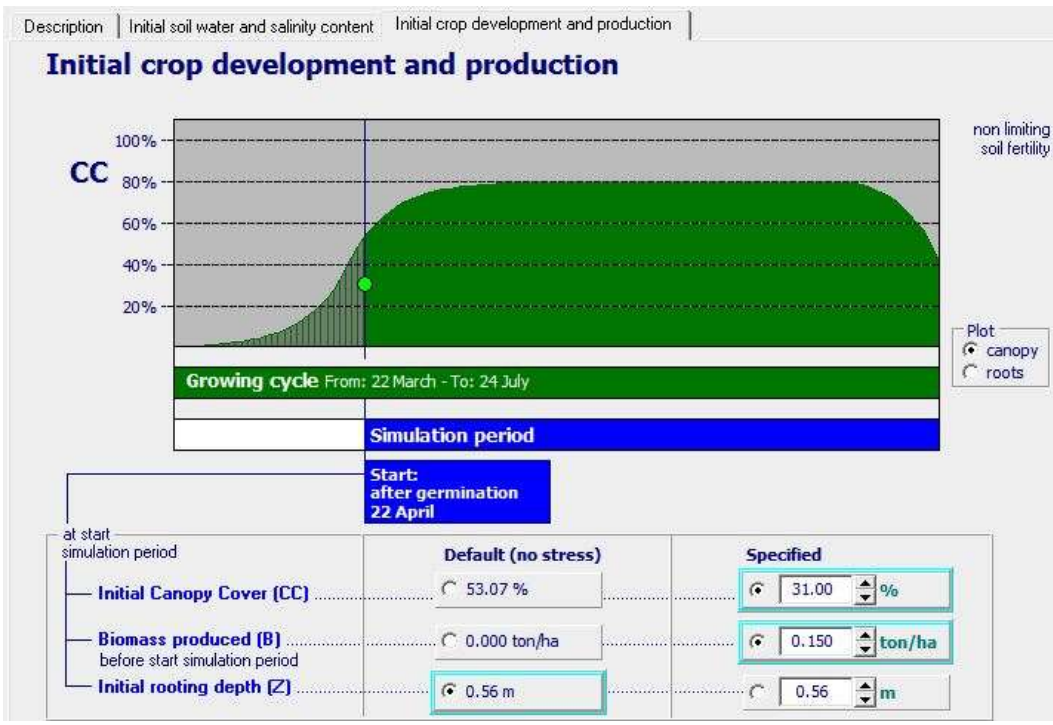


Table 2.23u – 5. – Example of initial conditions one month after planting, with indication of the observed soil water content at particular depths, the canopy cover and the biomass already produced at that day

```
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
```



2.23.11 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 1st 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	 Integer Integer String of characters

	growing period (if any) For the 1st irrigation event (if any) after the growing period: - 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 Repeat for each successive irrigation event after the growing period (if any) 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.	 Integer Integer String of characters

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 %

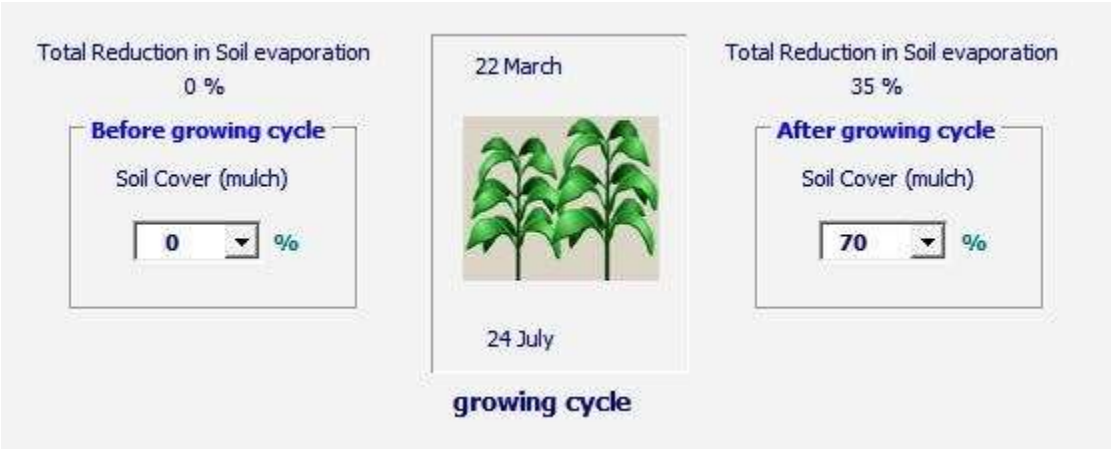
Table 2.23v – 3. – Indicative values for soil surface wetted for various irrigation methods

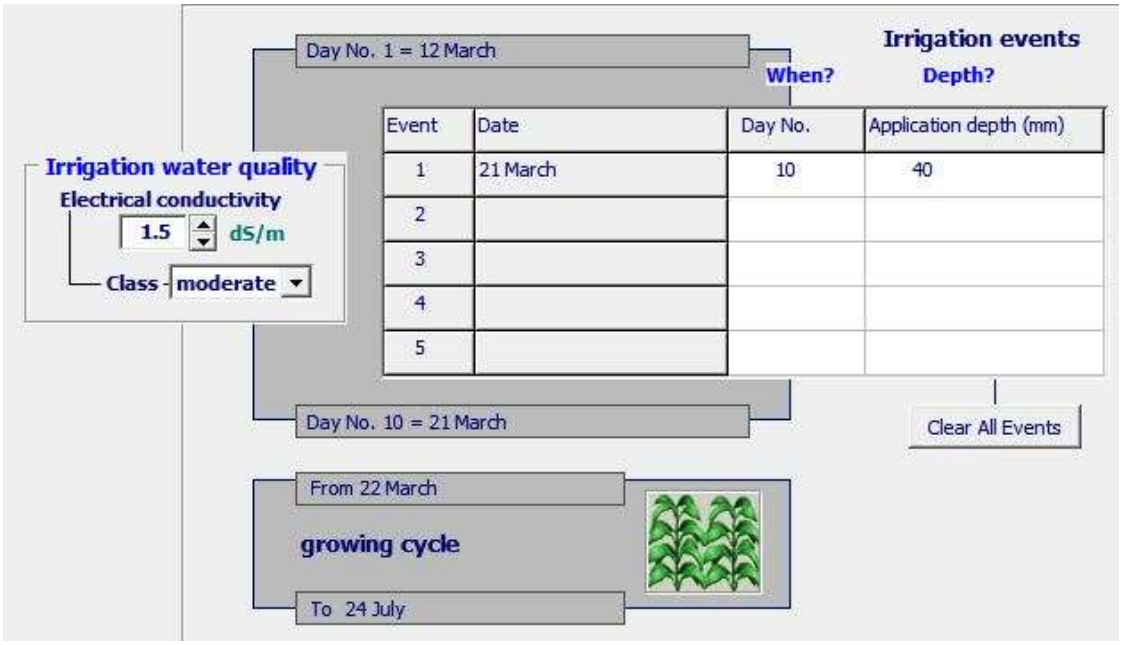
Irrigation method	Soil surface wetted (%)
Sprinkler irrigation	100
Basin irrigation	100
Border irrigation	100
Furrow irrigation (every furrow), narrow bed	60 – 100
Furrow irrigation (every furrow), wide bed	40 – 60
Furrow irrigation (alternated furrows)	30 – 50
Trickle/Drip - Micro irrigation	15 – 40
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
     7.1        : AquaCrop Version (August 2023)
     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
```





2.23.12 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 is a text file which contains
(a) information about the project,
(b) the year number of cultivation and the start and end dates of the simulation and cropping period, and
(c) the names of files (climate, calendar, crop, irrigation and field management, soil profile and ground water, initial and off-season conditions and field data).
The structure of the project file is presented in Table 2.23w - 1. An example is provided in Table 2.23w – 6.

The settings for the program parameters are saved in another text file which has the same file name as the project, but with the filename extension 'PP1' (for single projects) and 'PPn' (for multiple projects). Its structure is given in Table 2.23w – 5 and an example is provided in Table 2.23w – 7.

Table 2.23w – 1. – Structure of a project file (file with extension PRO or PRM)

Line Number	Description
a. – Information	
1	Description of the project
2	AquaCrop version number
b. – Simulation and the growing cycle for the first run	
3	Year number of cultivation (always 1 for annual crops; and 1, 2, 3 … for perennials), with 1 being the Seeding/planting year
4	Day number(1) for the first day of the simulation period
5	Day number(1) for the last day of the simulation period
6	Day number(1) for the first day of the growing cycle
7	Day number(1) for the last day of the growing cycle
c. – The names(2) and directories(3) for the 14 files containing the characteristics of the crop, crop calendar, environmental (climate, management and soil), initial and off-season conditions, and field data	
8 up to 49	11. Climate (CLI) file and the enveloped: 1.1 air temperature (Tnx or TMP) file,

	1.2 reference ET (ETo) file, 1.3 rain (PLU) file, and 1.4 atmospheric CO_2 concentration (CO2) file; 12. Calendar (CAL) file; 13. Crop (CRO) file; 14. Irrigation management (IRR) file; 15. Field management (MAN) file; 16. Soil profile (SOL) file; 17. Groundwater table (GWT) file; 18. Initial conditions (SW0) file; 19. Off-season conditions (OFF) file; 20. Field Data (OBS) file.
In case of **multiple projects**, section 'b' (5 lines for the simulation and growing cycle) and section 'c' (42 lines for the 14 files) are specified for each of the successive runs, in successive blocks of (5 + 42 =) 47 lines.	
(4) Day number: The day number refers to the days elapsed since 0th January 1901 at 0 am (see Table 2.23w-3 and 2.23w-4 for the calculation procedure); (5) File name: in the absence of a file (None), the default conditions (see 2.3 Default settings at start) are considered; (6) Directory (path): in the absence of a file, (None) is specified as directory.	

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	(None)	No specific field management conditions are considered. It is

management		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

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 - 3 and the code in Table 2.23w – 4.

Table 2.23w-3 – 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: - 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-4 – 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 *)
```

Table 2.23w-5 – Structure of program file parameters (file with extension PP1 or PPn)

Line No.	Description	Format	Example
Settings for crop program parameters (12 parameters)			
1	Evaporation decline factor for stage II	Integer	4
2	Ke(x) Soil evaporation coefficient for fully wet and non-shaded soil surface	XXX.XX	1.10
3	Threshold for green CC below which HI can no longer increase (% cover)	Integer	5
4	Starting depth of root zone expansion curve (% of Zmin)	Integer	70
5	Maximum allowable root zone expansion (fixed at 5 cm/day)	XXX.XX	5.00
6	Shape factor for effect water stress on root zone expansion	Integer	-6
7	Required soil water content in top soil for germination (% TAW)	Integer	20
8	Adjustment factor for FAO-adjustment soil water depletion (p) by ETo	XXX.X	1.0
9	Number of days after which deficient aeration is fully effective	Integer	3
10	Exponent of senescence factor adjusting drop in	XXX.XX	1.00

	photosynthetic activity of dying crop		
11	Decrease of p(sen) once early canopy senescence is triggered (% of p(sen))	Integer	12
12	Thickness top soil (cm) in which soil water depletion has to be determined	Integer	10
Settings for field program parameters (1 parameter)			
13	Depth [cm] of soil profile affected by water extraction by soil evaporation	Integer	30
Settings for soil parameters (5 parameters)			
14	Considered depth (m) of soil profile for calculation of mean soil water content for CN adjustment	XXX.XX	0.30
15	Adjustment of CN to Antecedent Moisture Class (0 = Not adjusted; 1 = Adjusted)	0 or 1	1
16	Salt diffusion factor (capacity for salt diffusion in micro pores) [%]	Integer	20
17	Salt solubility [g/liter]	Integer	100
18	Shape factor for effect of soil water content gradient on capillary rise	Integer	16
Settings for temperature program parameters (3 parameters)			
19	Default minimum temperature (°C) if no temperature file is specified	XXX.X	12.0
20	Default maximum temperature (°C) if no temperature file is specified	XXX.X	28.0
21	Default method for the calculation of growing degree days	Integer	3
Settings for 10-day or monthly rain program parameters (4 parameters)			
22	Procedure to estimate daily rainfall (when input is 10-day/monthly rainfall) 0 : 100 % effective 1 : USDA-SCS procedure 2 : Fixed percentage	0, 1 or 2	1
23	Percentage of 10-day or monthly rainfall which is effective (when Procedure (option 2) is a fixed percentage)	Integer	70
24	Number of showers in a decade for run-off estimate (when input is 10-day/monthly rainfall)	Integer	2

25	Parameter for reduction of soil evaporation (when input is 10-day/monthly rainfall)	Integer	5

Table 2.23w-6 – Example of a (multiple) project file

```
5 years of alfalfa
      7.1       : AquaCrop Version (august 2023)
```

```
      1         : Year number of cultivation (Seeding/planting year)
  36281         : First day of simulation period - 1 May 2000
  36515         : Last day of simulation period - 21 December 2000
  36281         : First day of cropping period - 1 May 2000
  36515         : Last day of cropping period - 21 December 2000
```

```
-- 1. Climate (CLI) file
   Bru76-05.CLI
   C:\FAO\AquaCrop7\DATA\
   1.1 Temperature (Tnx or TMP) file
   Bru76-05.TMP
   C:\FAO\AquaCrop7\DATA\
   1.2 Reference ET (ETo) file
   Bru76-05.ETo
   C:\FAO\AquaCrop7\DATA\
   1.3 Rain (PLU) file
   Bru76-05.PLU
   C:\FAO\AquaCrop7\DATA\
   1.4 Atmospheric CO2 concentration (CO2) file
   MaunaLoa.CO2
   C:\FAO\AquaCrop7\SIMUL\
-- 2. Calendar (CAL) file
   1May.CAL
   C:\FAO\AquaCrop7\DATA\
-- 3. Crop (CRO) file
   alfalfa.CRO
   C:\FAO\AquaCrop7\DATA\
-- 4. Irrigation management (IRR) file
   (None)
   (None)
-- 5. Field management (MAN) file
   (None)
   (None)
-- 6. Soil profile (SOL) file
   Loam.SOL
   C:\FAO\AquaCrop7\DATA\
-- 7. Groundwater table (GWT) file
   (None)
   (None)
-- 8. Initial conditions (SW0) file
   (None)
   (None)
-- 9. Off-season conditions (OFF) file
   (None)
   (None)
-- 10. Field data (OBS) file
   (None)
   (None)
```

```
      2         : Year number of cultivation (Non-seeding/planting
```

```
year)
  36516         : First day of simulation period - 22 December 2000
  36845         : Last day of simulation period - 16 November 2001
  36565         : First day of cropping period - 9 February 2001
  36845         : Last day of cropping period - 16 November 2001
-- 1. Climate (CLI) file
   Bru76-05.CLI
   C:\FAO\AquaCrop7\DATA\
   1.1 Temperature (Tnx or TMP) file
   Bru76-05.TMP
   C:\FAO\AquaCrop7\DATA\
   1.2 Reference ET (ETo) file
   Bru76-05.ETo
   C:\FAO\AquaCrop7\DATA\
   1.3 Rain (PLU) file
   Bru76-05.PLU
   C:\FAO\AquaCrop7\DATA\
   1.4 Atmospheric CO2 concentration (CO2) file
   MaunaLoa.CO2
   C:\FAO\AquaCrop7\SIMUL\
-- 2. Calendar (CAL) file
   1May.CAL
   C:\FAO\AquaCrop7\DATA\
-- 3. Crop (CRO) file
   alfalfa.CRO
   C:\FAO\AquaCrop7\DATA\
-- 4. Irrigation management (IRR) file
   (None)
   (None)
-- 5. Field management (MAN) file
   (None)
   (None)
-- 6. Soil profile (SOL) file
   Loam.SOL
   C:\FAO\AquaCrop7\DATA\
-- 7. Groundwater table (GWT) file
   (None)
   (None)
-- 8. Initial conditions (SW0) file
   KeepSWC
   Keep soil water profile of previous run
-- 9. Off-season conditions (OFF) file
   (None)
   (None)
-- 10. Field data (OBS) file
   (None)
   (None)
Etc.
```

Table 2.23w-7 – Example of a Program Parameter file

```
  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) 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 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     : Daily rainfall is estimated by USDA-SCS procedure (when input is 10-day/monthly rainfall)
 70     : Percentage of effective rainfall (when input is 10-day/monthly rainfall)
  2     : Number of showers in a decade for run-off estimate (when input is 10-day/monthly rainfall)
  5     : Parameter for reduction of soil evaporation (when input is 10-day/monthly rainfall)
```

2.23.13 File with field data (*.OBS)

A file with field data (Tab. 2.23x - 1 and 2.23x - 2) contains observed field data which can 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	
	- The day number at which the observation was made (with reference to the date specified in line 4 (DD), 5 (MM) and 6 (YYYY));	Integer
	- The mean value of sampled green Canopy Cover (%) on that day (-9.0 if no field data was collected)	Real (1 digit)
	- The standard deviation (%) for the various CC observations made during the sampling on that day (-9.0 if not available or non-applicable)	Real (1 digit)
	- The mean value of sampled dry above ground biomass (ton/ha) on that day (-9.0 if no field data was collected)	Real (3 digits)
	- The standard deviation for the various B observations made during the sampling on that day (-9.0 if not available or non-applicable)	Real (1 digit)
	- 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)	Real (1 digit)
	- The standard deviation for the various SWC observations made during the sampling on that day (-9.0 if not available or non-applicable)	Real (1 digit)
	Repeat for each successive day with observations	

Table 2.23x – 2. – Example of a file with field data.

```
measurements of CC, B and SWC at particular days
     7.1   : AquaCrop Version (August 2023)
     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
```

2.23.14 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;
- Biomass and yield at multiple cuttings

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	Total above-ground dry biomass	ton/ha
23	HI	Harvest Index adjusted for failure of pollination, inadequate photosynthesis and water stress	%
24	Y(dry)	Dry crop yield (HI x Biomass)	ton/ha
25	Y(fresh)	Fresh crop yield	ton/ha
26	Brelative	Relative biomass (Reference: no water, no soil fertility, no soil salinity stress, no weed infestation)	%
27	WPet	ET Water productivity for yield part (kg yield produced per m3 water evapotranspired)	kg/m^3
28	Bin	Daily mass of assimilates mobilized form root system at start of season	ton/ha

29	Bout	Daily mass of assimilates stored in root system at end of season	ton/ha

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/Ex	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 evapotranspriation (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 Biomass and Yield at multiple cuttings

(Default file name: ProjectHarvest.OUT)

Biomass and Yield at Multiple cuttings

** Run number: 1

Nr	Day	Month	Year	DAP	Interval days	Biomass ton/ha	Sum(B) ton/ha	Dry-Yield ton/ha	Sum(Y) ton/ha	Fresh-Yield ton/ha	Sum(Y) ton/ha
0	1	5	2004				0.000		0.000		0.000
1	22	5	2004	22	22	4.447	4.447	3.144	3.144	20.960	20.960
2	13	6	2004	44	22	3.603	8.050	3.063	6.207	20.418	41.378
3	5	7	2004	66	22	3.603	11.653	3.063	9.270	20.419	61.798
4	27	7	2004	88	22	3.603	15.257	3.063	12.332	20.419	82.217
5	18	8	2004	110	22	3.603	18.860	3.063	15.395	20.419	102.635
6	9	9	2004	132	22	3.603	22.463	3.063	18.458	20.419	123.054
7	1	10	2004	154	22	3.387	25.850	3.061	21.520	20.410	143.464
9999	28	10	2004				26.903		23.290		155.268

Legend

```
DAP          : Days after planting
Interval     : Number of days between events
Nr = 0       : At start of season
Nr = 1 to n  : Harvest event
Nr = 9999    : At end of season
```

2.25.10 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	Total above-ground dry biomass	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	Y(dry)	Dry crop yield (HI x Biomass)	ton/ha
34	Y(fresh)	Fresh crop yield	ton/ha
35	WPet	ET Water Productivity for yield part (kg yield produced per m3 water evapotranspired)	kg/m^3
36	Bin	Total mass of assimilates mobilized from root system at start of season	ton/ha

37	Bout	Total mass of assimilates stored in root system at end of season	ton/ha
38	DayN	End day of simulation run	-
39	MonthN	End month of simulation run	-
40	YearN	End year of simulation run	-

2.25.11 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 7.1 (August 2023) - Output created on (date) : ….
Evaluation of simulation results - Statistics


  ASSESSMENT OF CANOPY COVER -------------------------------------
              --------- Canopy Cover (%) ---------
    Nr        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          47.2       9 July

  Valid observations/simulations sets (n) ....... :     5
  Average of observed Canopy Cover ............. :    38.0   %
  Average of simulated Canopy Cover ............ :    41.6   %

  Pearson Correlation Coefficient (r) ........... :     0.95
  Root mean square error (RMSE) ................ :     7.3   % CC
  Normalized root mean square error  CV(RMSE).... :    19.1   %
  Nash-Sutcliffe model efficiency coefficient (EF):     0.86
  Willmotts index of agreement (d) ............. :     0.97
  ----------------------------------------------------------------


  ASSESSMENT OF BIOMASS PRODUCTION -------------------------------
              --------- Biomass (ton/ha) ---------
    Nr        Observed    +/- St Dev     Simulated    Date
  ----------------------------------------------------------------
     1          1.000         0.300         0.940      20 April
     2          4.000         0.200         3.964       1 June
     3          4.400         0.300         4.618      19 June
     4          5.000         0.500         5.129       9 July
     5          5.500         0.500         5.209      19 July

  Valid observations/simulations sets (n) ....... :     5
  Average of observed Biomass production ........ :     3.980   ton/ha
  Average of simulated Biomass production ....... :     3.972   ton/ha
```

```
Pearson Correlation Coefficient (r) ........... :     0.99
Root mean square error (RMSE) ................ :     0.175   ton/ha
Normalized root mean square error  CV(RMSE).... :     4.4   %
Nash-Sutcliffe model efficiency coefficient (EF):     0.99
Willmotts 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         124.7       9 July
   5         100.0          10.0         122.1      19 July

Valid observations/simulations sets (n) ....... :     5
Average of observed Soil water content ........ :   180.0   mm
Average of simulated Soil water content ....... :   180.6   mm

Pearson Correlation Coefficient (r) ........... :     0.99
Root mean square error (RMSE) ................ :    23.3   mm
Normalized root mean square error  CV(RMSE).... :    13.0   %
Nash-Sutcliffe model efficiency coefficient (EF):     0.92
Willmotts index of agreement (d) ............. :     0.97
---------------------------------------------------------------
```