Chapter 2
Users guide

AquaCrop
Version 4.0

Reference Manual
June 2012

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

FAO, Land and Water Division
Rome, Italy

Copyright

Disclaimer

Acknowledgments

List of principal symbols

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

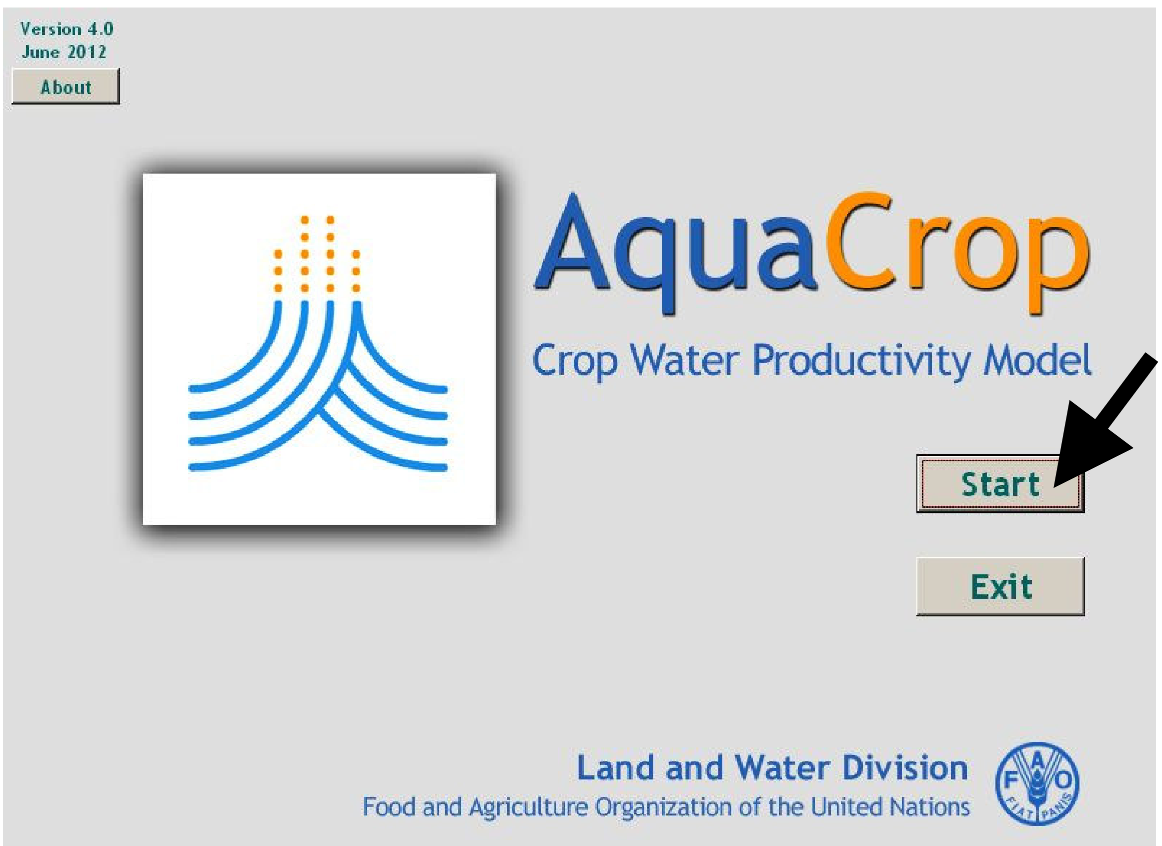
Chapter 2. Users guide

Running AquaCrop

Menu reference

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

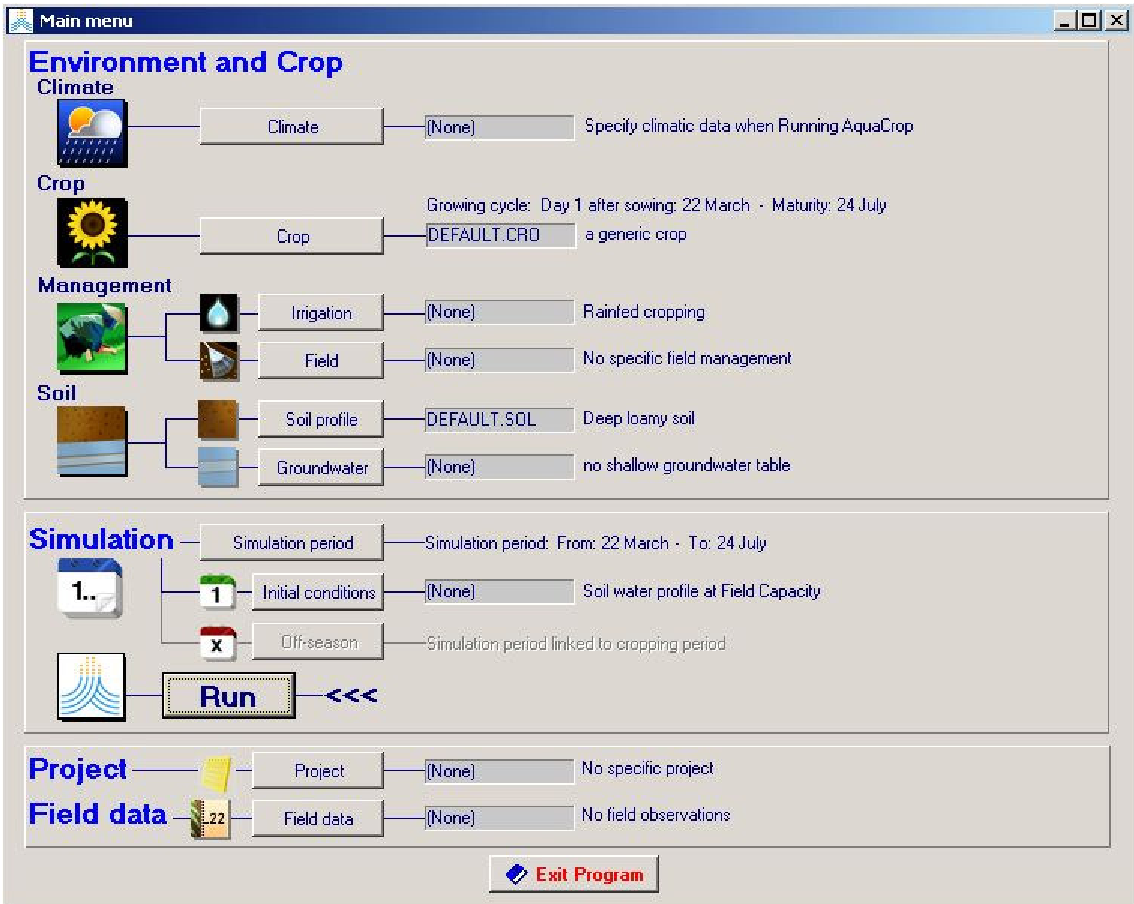


Figure 2.2
Main menu of AquaCrop

The ***Main Menu*** consists of 3 panels where the names and descriptions of the selected input files are displayed (Figure 2.2):

A. Environment panel: where the user:

(1) selects or creates Climate (Temperature, ETo, Rain, CO_2), Crop, Management (Irrigation and Field), Soil profile and Groundwater files and updates the corresponding data;
(2) specifies the start of the growing cycle;

B. Simulation panel: where the user:

(3) specifies: (i) the simulation period, (ii) the initial conditions for a simulation run, and (iii) the off-season conditions when the simulation period exceeds the growing period;
(4) runs a simulation for the specified environment, period and conditions.

C. Project and Field data panel: where projects and field data files can be selected, created or updated.

2.3 Default settings at start

2.3.1 Selected input

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

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

Environment	**File**	**Remarks**
Climate	(None)	A default minimum and maximum air temperature (see Climate), an ETo of 5 mm/day, no rainfall and an average atmospheric CO_2 concentration of 369.47 ppm are assumed throughout the growing cycle. When running a simulation without a climate file, the user has still the option to specify other than the default ETo and rainfall data. This climatic data can be specified for each day of the simulation period in the Input panel of the ***Simulation run*** menu
Crop	Default	Generic crop data
Irrigation management	(None)	Rainfed cropping is assumed. When running a simulation in this mode, irrigation can still be scheduled. The quality of the irrigation water and the irrigation application amount can be specified for each day of the simulation period in the Input panel of the ***Simulation run*** menu
Field management	(None)	No specific field management conditions are considered. It is assumed that soil fertility is unlimited, and that field surface practices does not affect soil evaporation or surface run-off
Soil	Default	Deep loamy soil
Groundwater	(None)	Absence of a shallow groundwater table
Simulation	**File**	**Remarks**
Period		The simulation period covers the growing cycle completely
Initial conditions	(None)	At the start of the simulation it is assumed that in the soil profile (i) the soil water content is at field capacity and (ii) salts are absent
Off-season conditions	(None)	No specific field management conditions are considered outside the growing period. When running a simulation there are no irrigation events and mulches does not cover the field surface in the off-season
Project/ Field data	**File**	**Remarks**
Project	(None)	
Field data	(None)	

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

2.3.2 Program settings

2.4 Selecting input files and undoing the selection

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

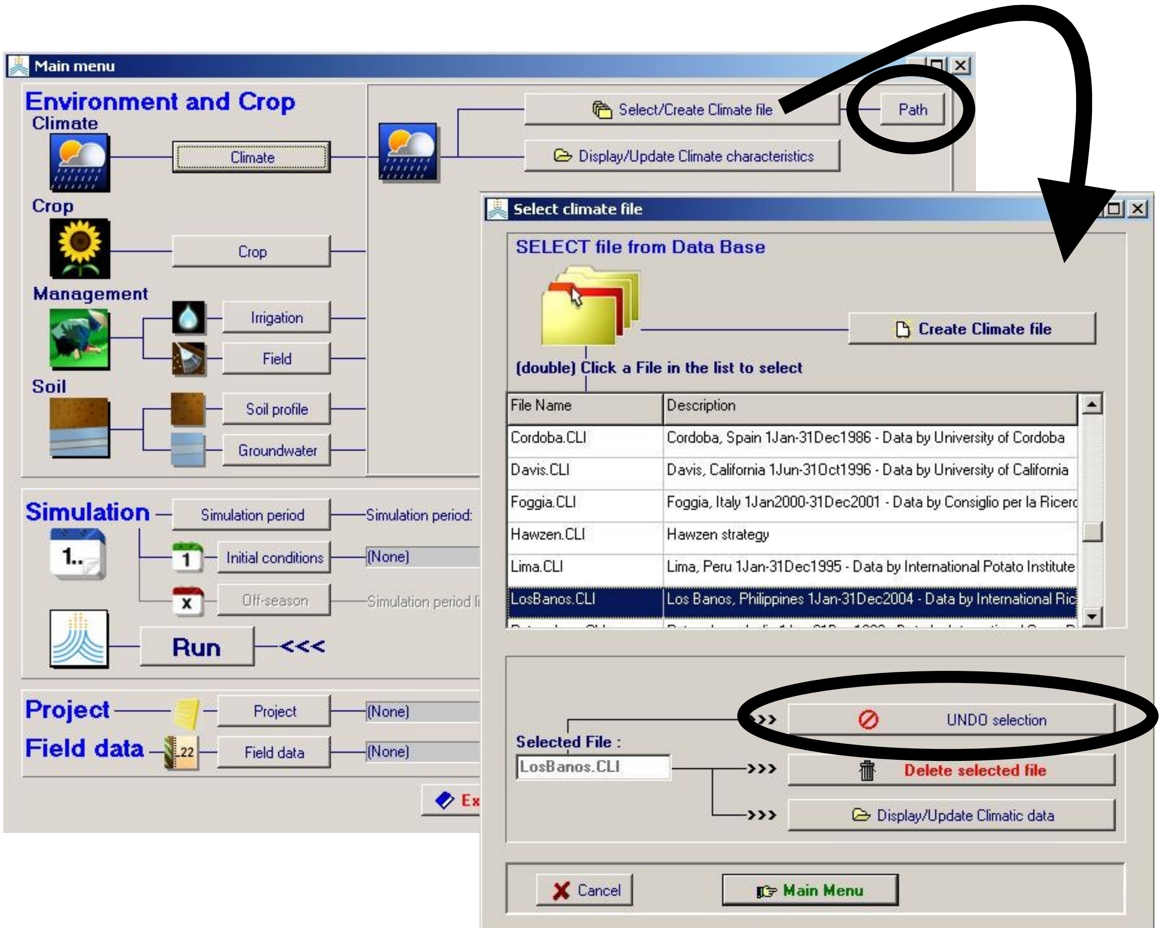


Figure 2.4
Access to the *Select climate file* menu where input files can be selected from the data base and where the selection can be undone with the <UNDO selection> command

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 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***.

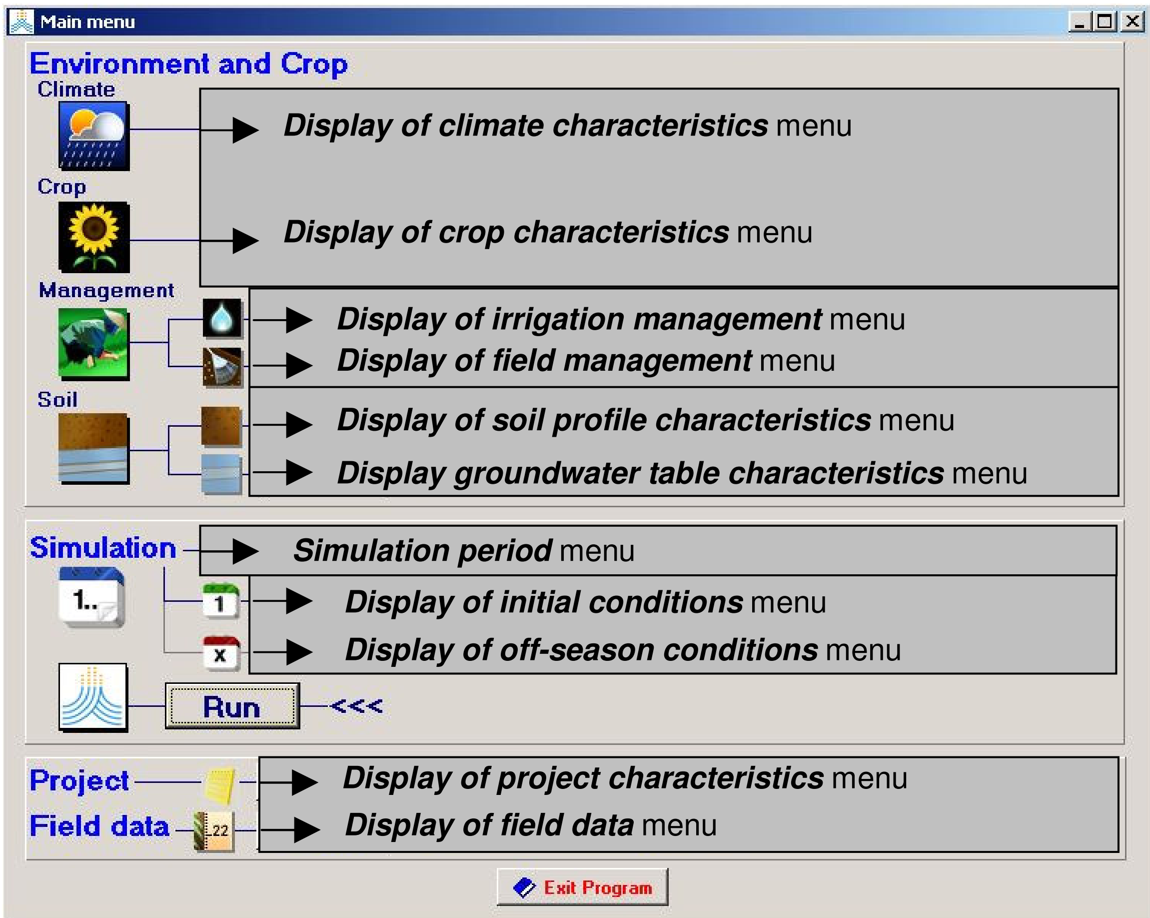


Figure 2.5a
By clicking on the Icons (or file names) in the *Main menu*
the specified input data is displayed in a set of *Display* menus

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).

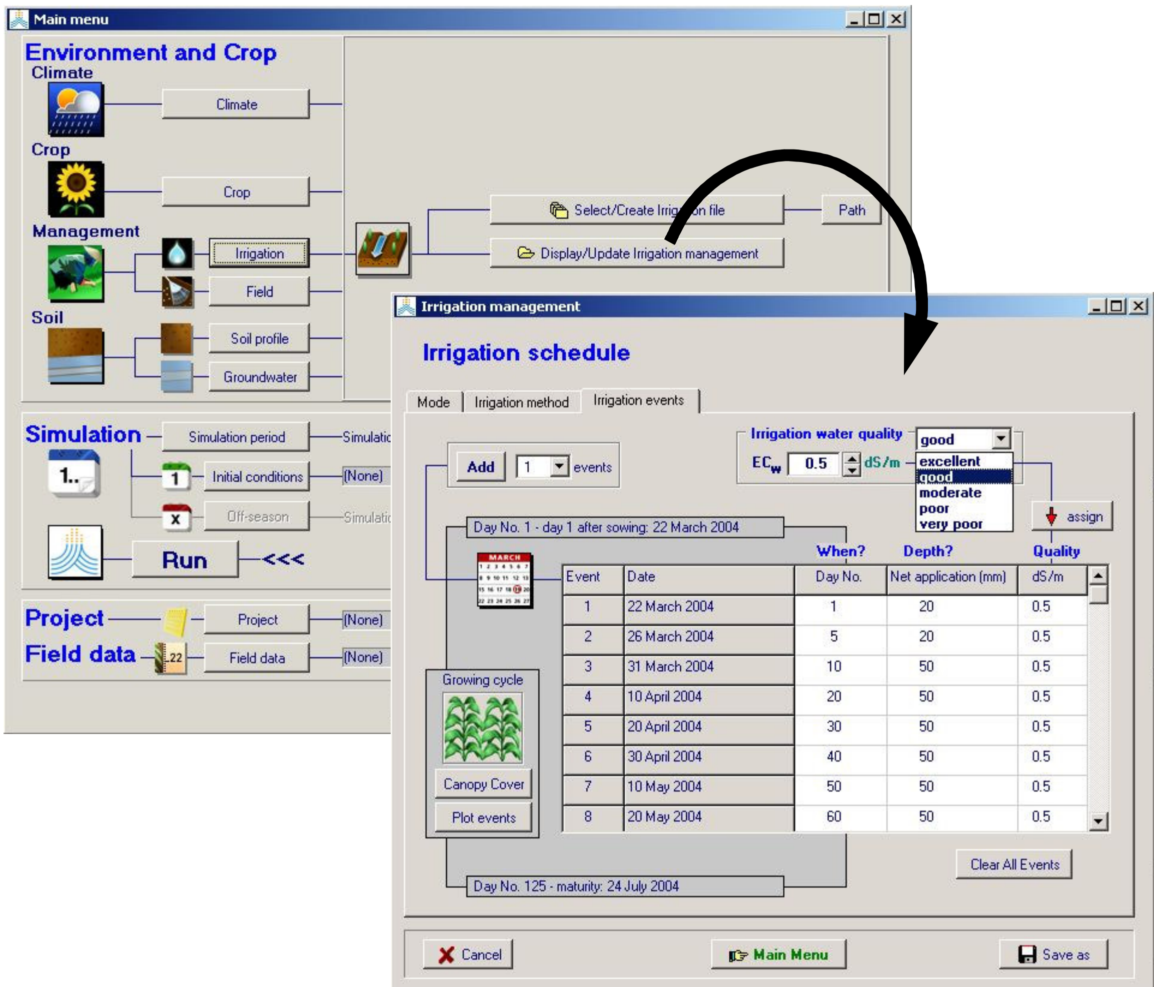


Figure 2.5b
Access to the *Irrigation management* menu
where the displayed input data can be updated

In the Menu reference of this Chapter the Display/Update menus are described (sections 2.8 to 2.20).

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).

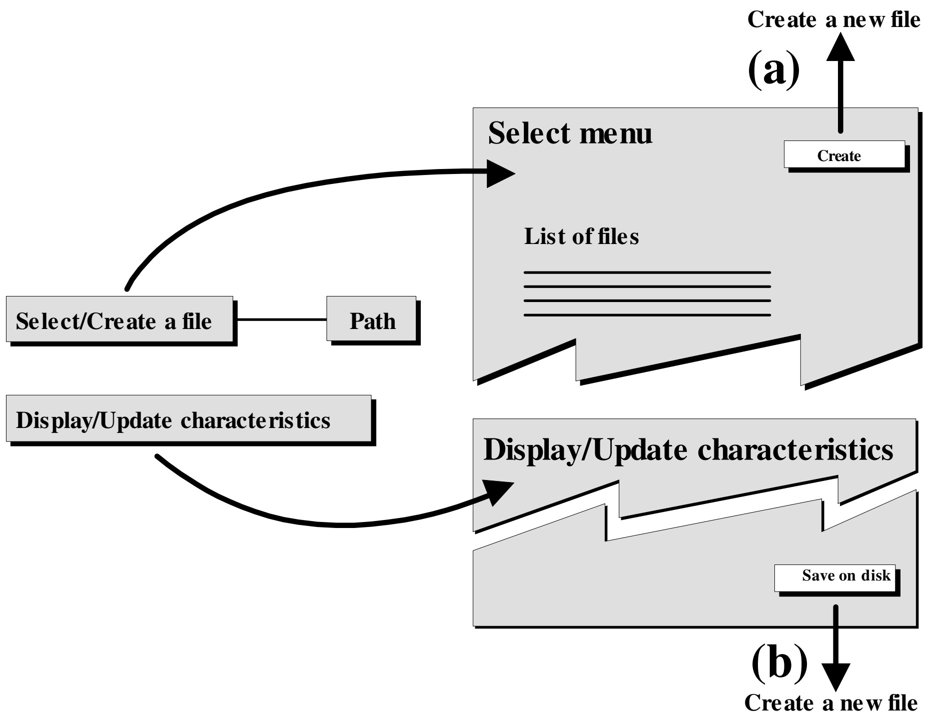


Figure 2.6a
Options available to create input files by means of the user interface

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 management, soil profile, groundwater, 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)

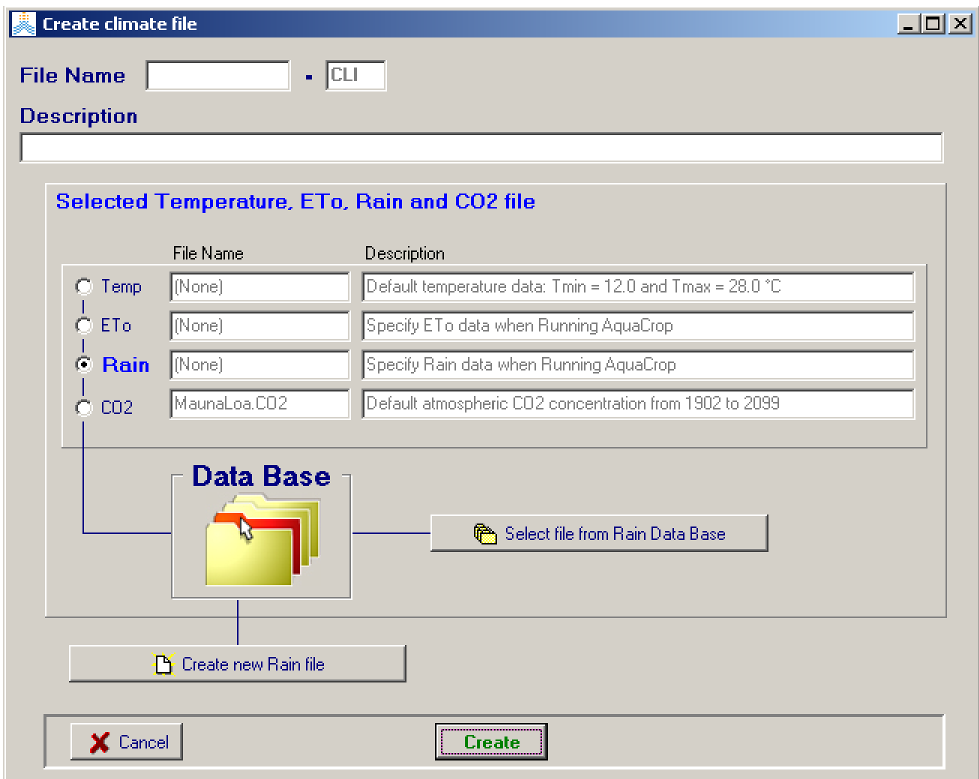


Figure 2.6b
***Create climate file* menu**

- **Create 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 2.21.2 Temperature, ETo and Rainfall files).

- **Create crop file**

When creating a crop file, the user selects the type of crop (Fruit/Grain producing crops, Leafy vegetable crops, Roots and tubers, or Forage crops) and specifies a few parameters (Fig. 2.6c). With the help of this information AquaCrop generates the complete set of required crop parameters. The parameters are displayed and the values can be adjusted in the ***Crop characteristics*** menu (see 2.9).

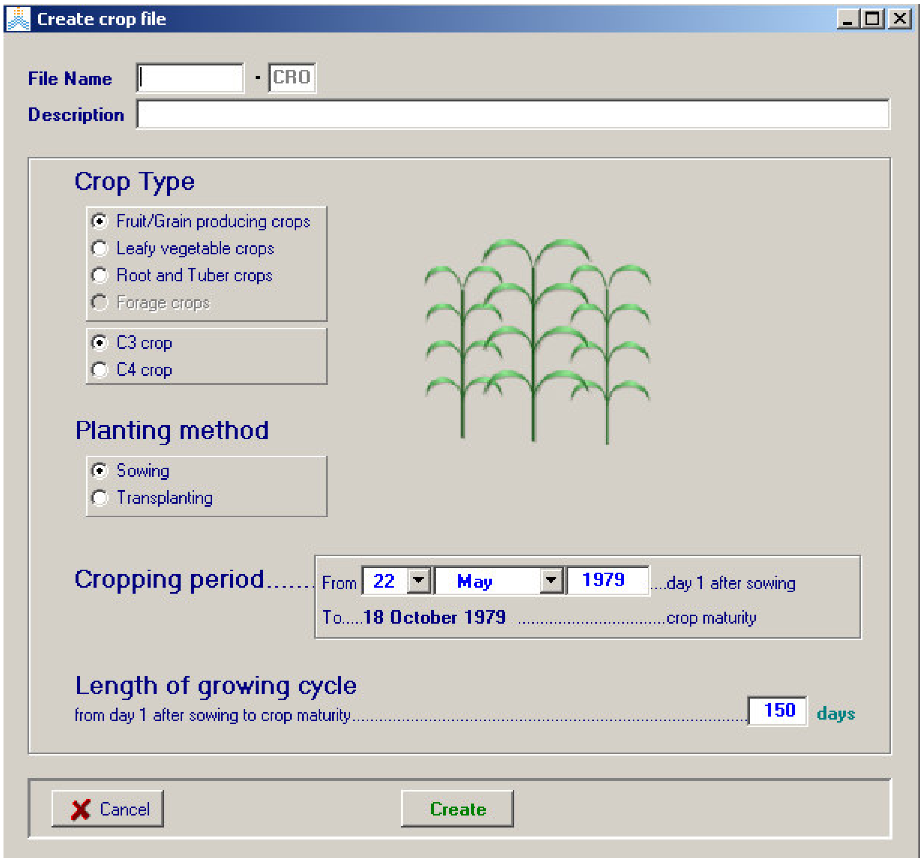


Figure 2.6c
***Create crop file* menu**

- **Create irrigation file**

When creating an irrigation file, the type of file has first to be selected:
1. Net irrigation water requirement;
2. Irrigation schedule; or
3. Generation of irrigation schedule.

Subsequently the user specifies 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; or
3. the irrigation water quality, and the time and depth criteria to generate irrigation events.

- **Create soil profile file**

When creating a soil profile file, the user has to specify only a few characteristics (Fig. 2.6d). 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 2.13).

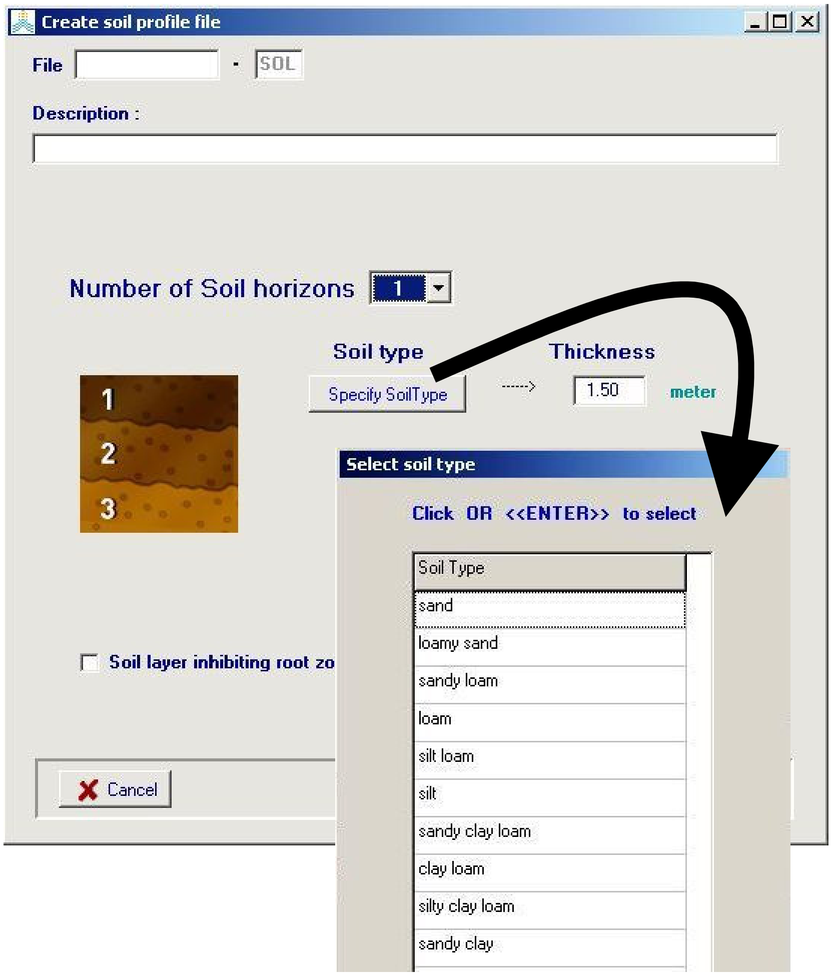


Figure 2.6d
***Create soil profile file* menu**

- **Create groundwater file**

When creating a groundwater file, the type of file has first to be selected:

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 characteristics*** menu (see 2.14)

- **Create project file**

When creating a project file, the type of file has first to be selected (Fig. 2.18b):

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 2.18.2 Selecting and creating a project). The characteristics can be updated in the ***Project Characteristics*** menu (see 2.18.3 Updating project characteristics).

- **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 2.19).

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.

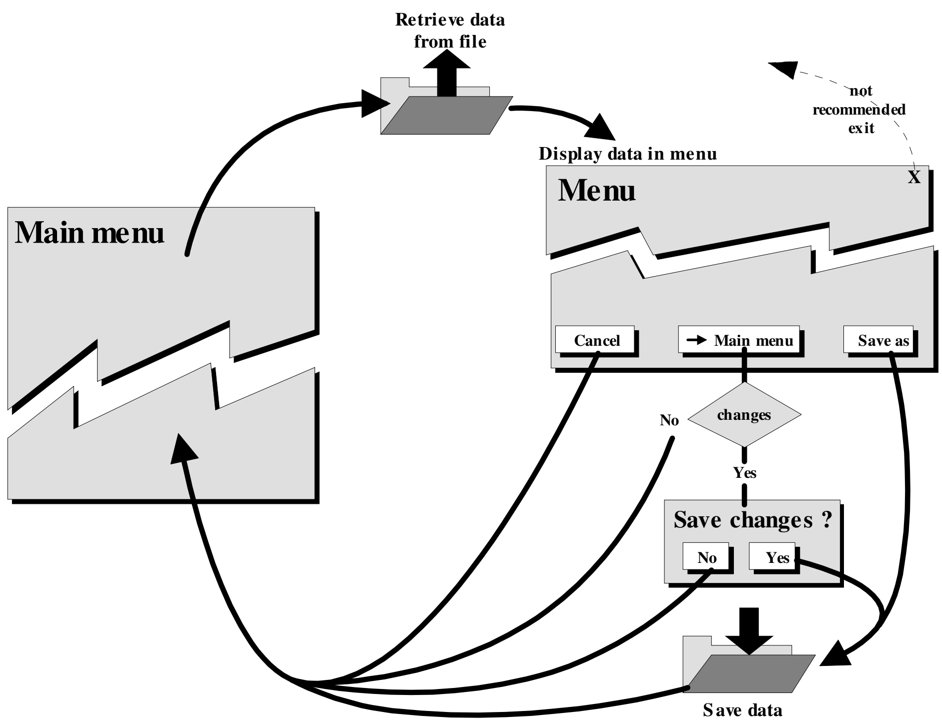


Figure 2.7
Options to exit and close a menu

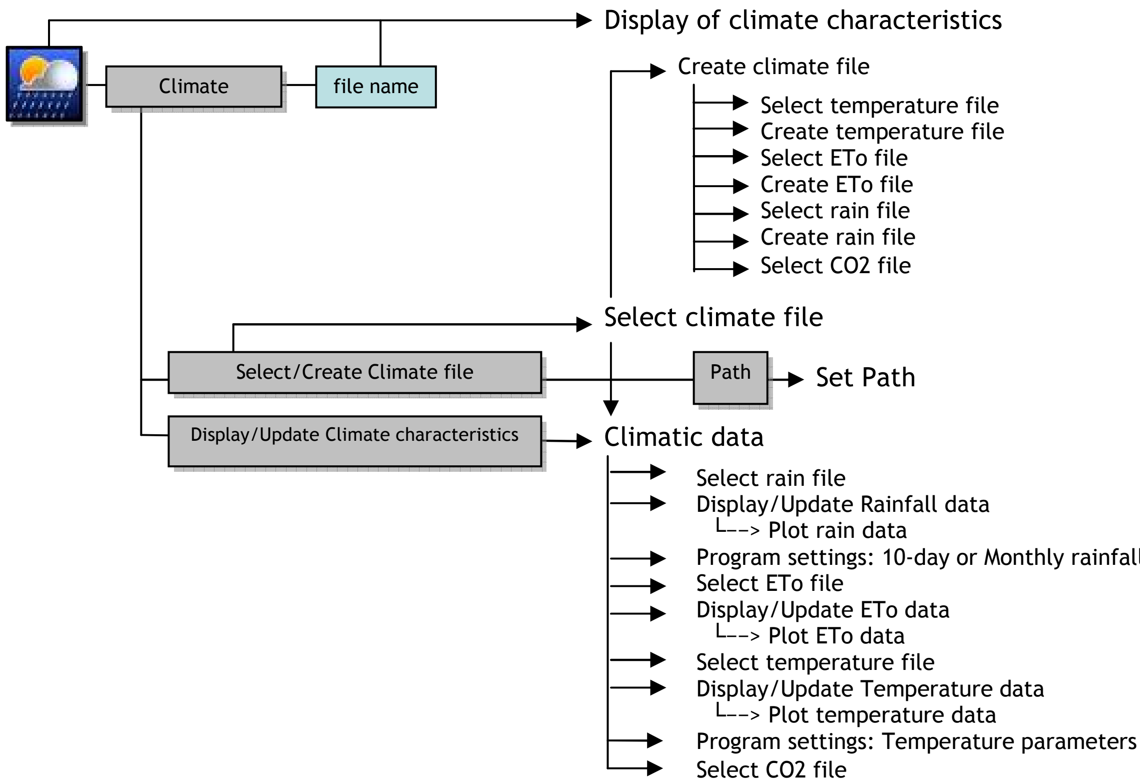
Menu reference

Hierarchical structure of the menus

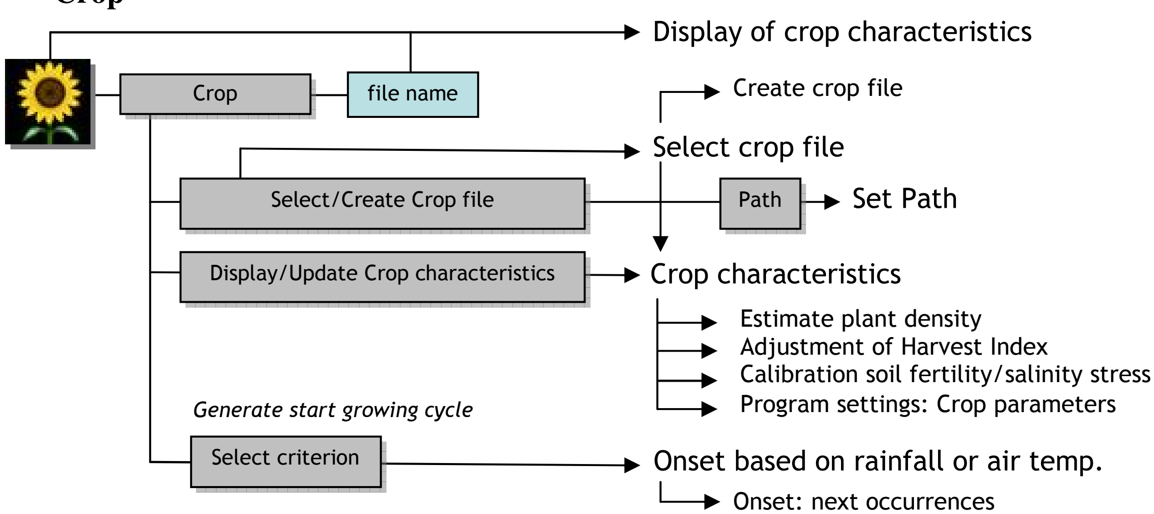
Main Menu

Environment panel

- **Climate**



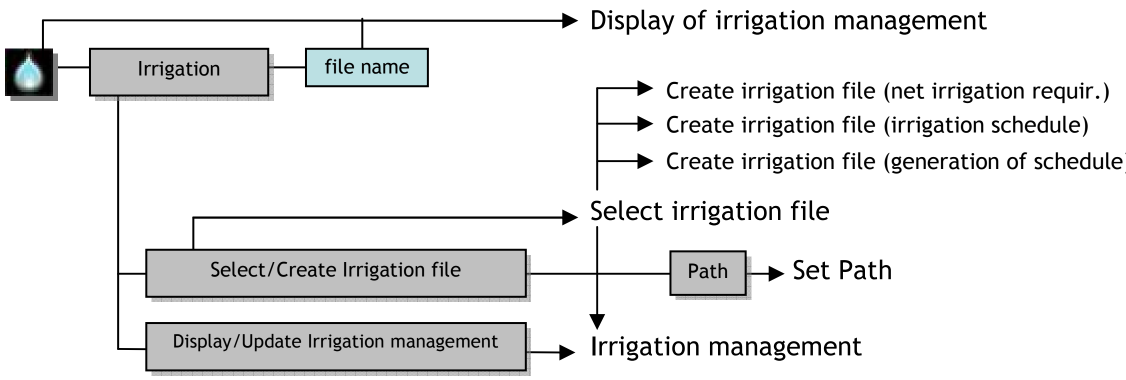
- **Crop**



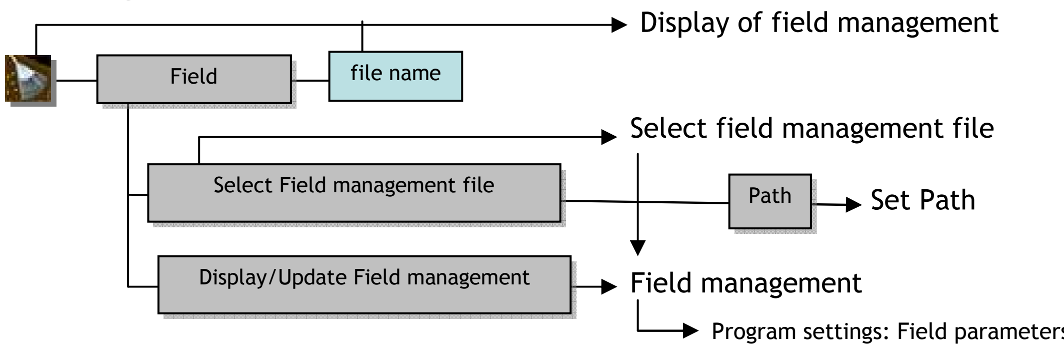
Environment panel (continued)

- **Management**

- irrigation management

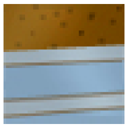


- field management

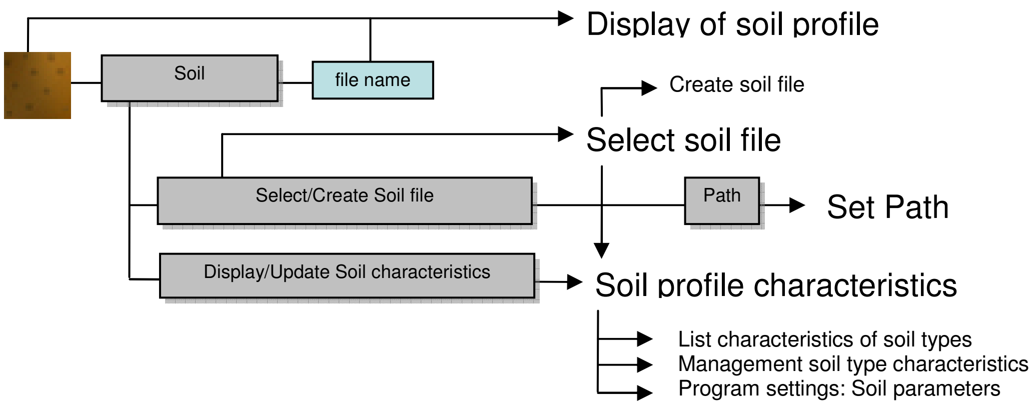


Environment panel (continued)

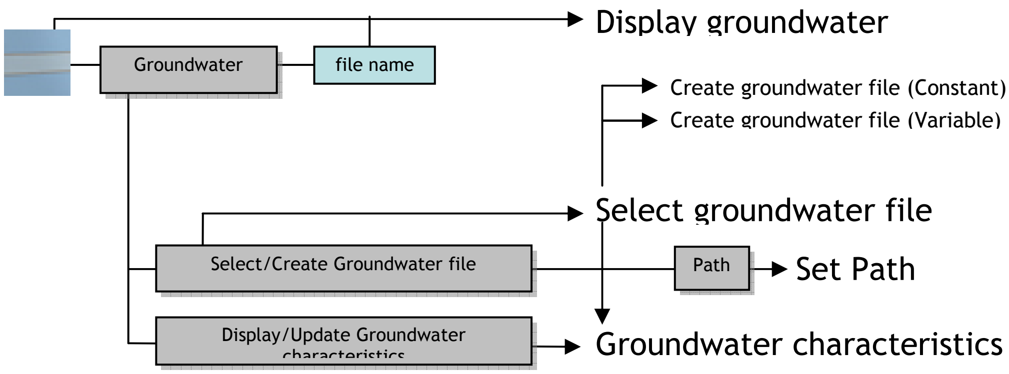
▪Soil



- soil profile

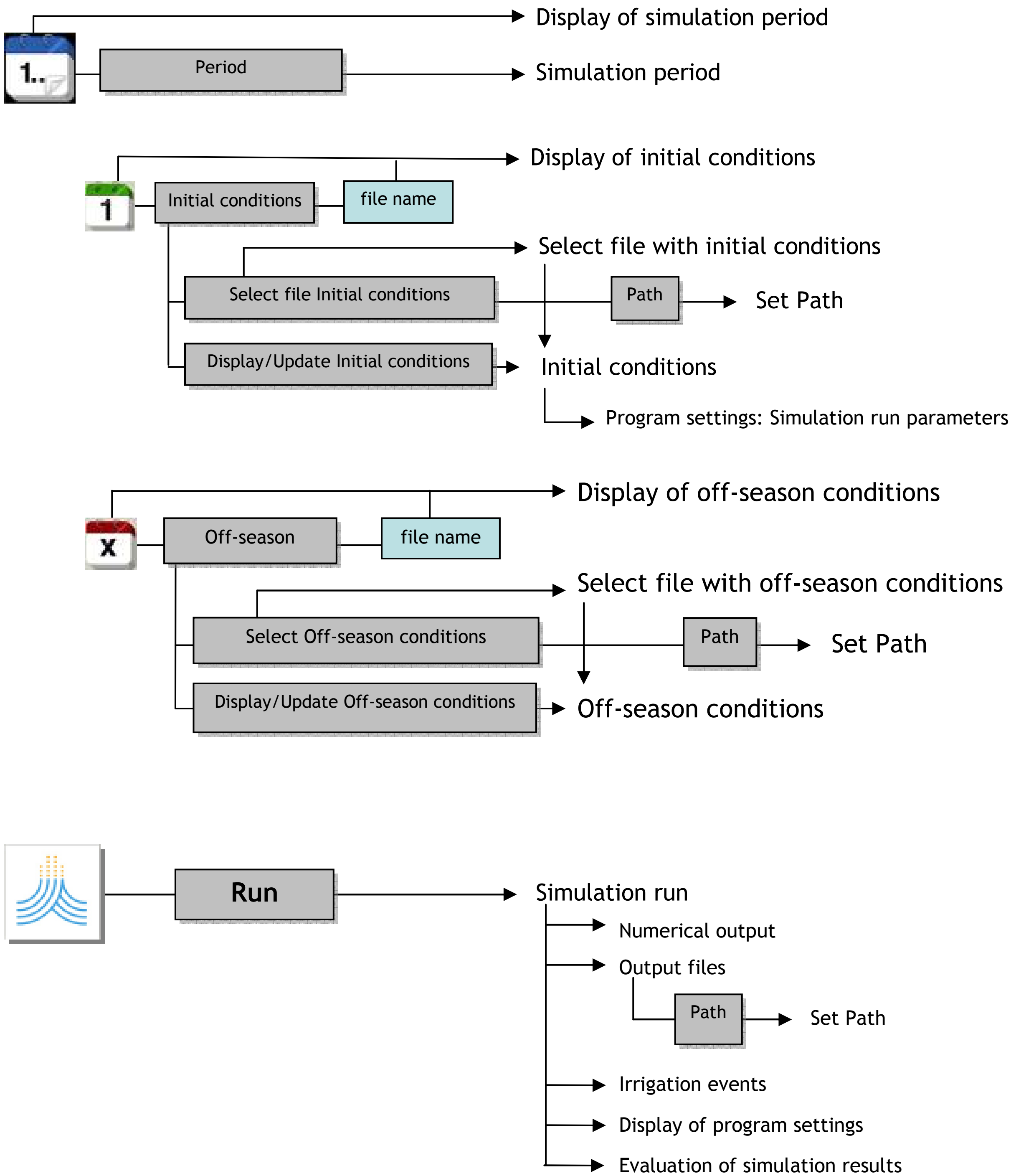


- groundwater



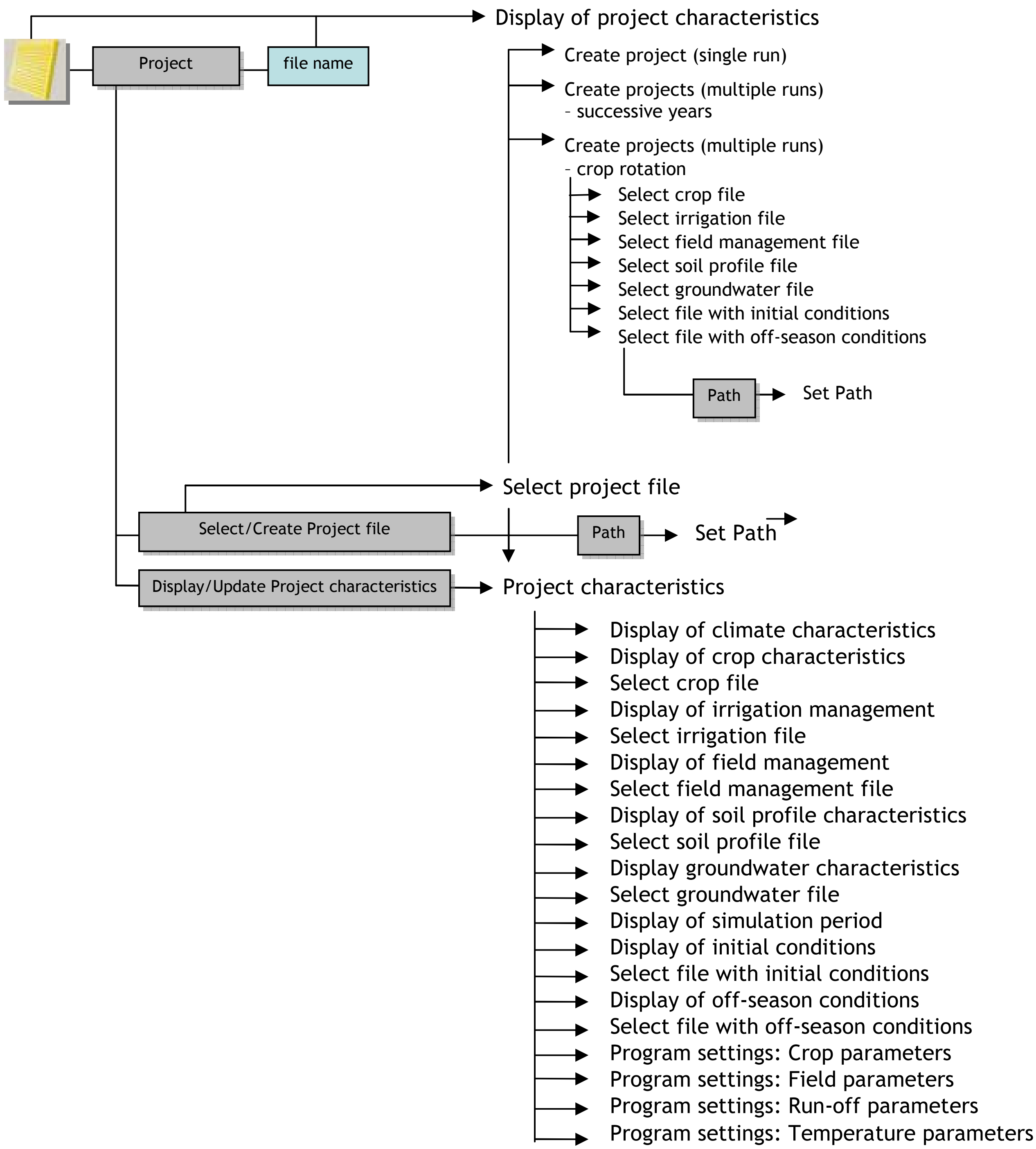
Main menu

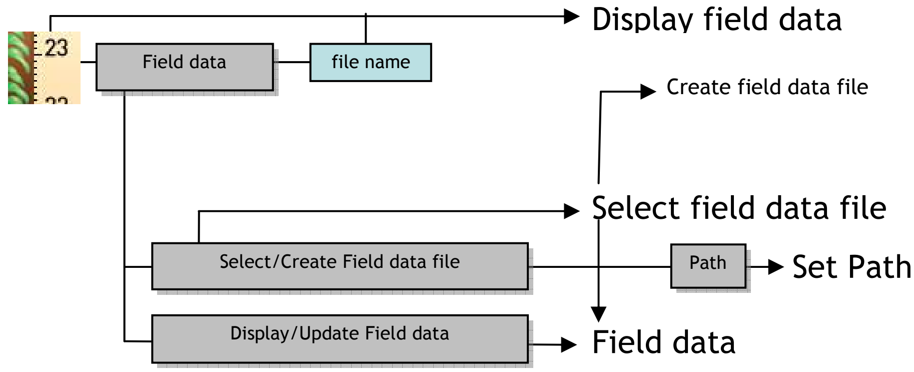
Simulation panel



Main Menu

Project/Field data panel




Display field data
23
Field data
file name
Create field data file
Select field data file
Select/Create Field data file
Path
Set Path
Display/Update Field data
Field data

2.8 Climatic data

For each day of the simulation period, AquaCrop requires minimum and maximum air temperature, reference evapotranspiration (ET_o), rainfall and the mean annual atmospheric CO_2 concentration. The climatic data are retrieved from files containing daily, 10-daily or monthly data. The selected climatic data can be displayed in the ***Display of climate characteristics*** menu and updated in the ***Climatic data*** menu (Fig. 2.8).

Figure 2.8
***Climatic data* menu**

2.8.1 Minimum and maximum air temperature

Temperature data are used to calculate growing degree day, which determines crop development and phenology (see 2.9.2), and also for making adjustment in biomass production during damaging cold periods (see 2.9.8). 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.

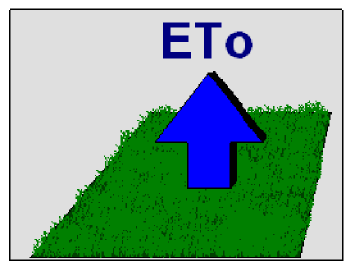
2.8.2 Reference evapotranspiration (ETo)

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 available for that purpose (Box 2.8). In the calculator, the data from a weather station can be specified in a wide variety of units, meteorological data can be imported, procedures are available to estimate missing climatic data and the calculated ETo can be exported to AquaCrop.

Box 2.8.
The ETo Calculator (Land and water Digital Media Service N° 36, FAO, 2009).

The ETo Calculator is public domain software, and an installation disk (1.5 Mb) and a software copy of the Reference Manual can be obtained from:



Land and Water Development Division
FAO, Viale delle Terme di Caracalla
00100 Rome, Italy
e-mail: Land-and-Water@fao.org
Fax: (+39) 06 570 56275

web page: http://www.fao.org/nr/water/ETo.html

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.

2.8.3 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.

2.8.4 Mean annual atmospheric CO_2

AquaCrop considers 369.47 parts per million by volume as the reference. It is the average atmospheric CO2 concentration for the year 2000 measured at Mauna Loa Observatory in Hawaii. Other CO2 concentrations will alter canopy expansion and crop water productivity (Chapter 3). AquaCrop uses as default the data from the MaunaLoa.CO2 (stored in the SIMUL subdirectory) which contains the mean annual atmospheric CO2 concentration measured at Mauna Loa Observatory since 1958. 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). 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 2.19.3).

2.8.5 Program settings

From the ***Climatic data*** menu the user has access to the program settings listed in Table 2.8. Distinction is made in program settings for 10-day or monthly rainfall, and for Temperature parameters.

Table 2.8
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)	Method 3
	▪ Default minimum (T_n) and maximum (T_x) air temperature in the absence of a temperature file	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	USDA-SCS
	▪ Effective rainfall: percentage (fraction of rainfall)	70
	▪ Surface runoff: showers per 10-day	2
	▪ Soil evaporation: root number	5

[1] David Etheridge et al. (1996), J. Geophys. Research vol. 101, 4115-4128

2.9 Crop characteristics

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 2.9a). The number and type of crop parameters vary slightly with the crop types selected when creating a new crop in AquaCrop (see 2.6.3). Distinction is made between

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

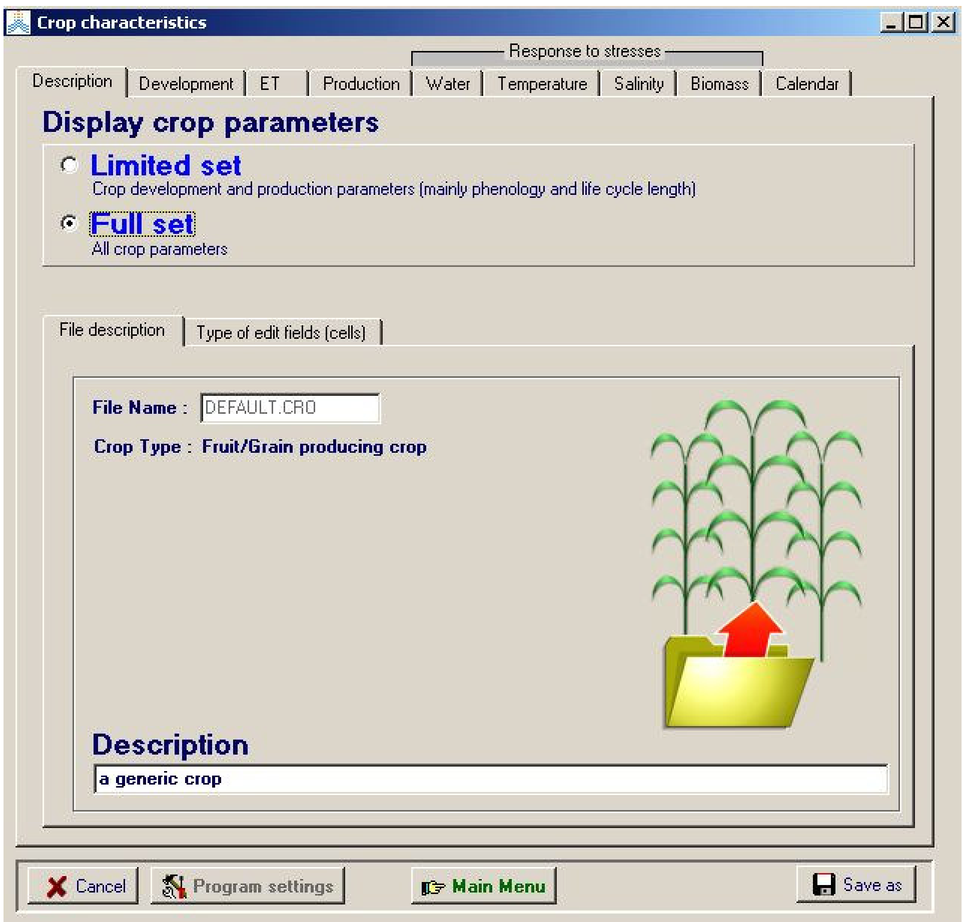


Figure 2.9a
First page of the *Crop characteristics* menu
showing the two options for the display mode

The crop characteristics are grouped in 9 different folders (tab sheets):

- **Description**
  - File description
  - Type of edit fields (cells)
  - Protected file (if applicable)

<table>
<tr>
<td>

- **Development**
  - Initial canopy cover
  - Canopy development
  - Flowering and yield formation
  - Root deepening
  - Temperatures
- **ET**
  - Coefficients
  - Water extraction pattern
- **Production**
  - Crop water productivity
  - Harvest Index
- **Water stress**
  - Canopy expansion
  - Stomatal closure
  - Early canopy senescence
  - Aeration stress
  - Harvest Index
    - Before flowering
    - During flowering
    - During yield formation
    - Overview
- **Temperature stress**
  - Biomass production
  - Pollination
- **Salinity stress**
- **Biomass - stress**
  - Canopy
  - Water productivity
  - Transpiration
  - Biomass
  - Biomass – stress relationship
  - Ks curves
  - Crop parameters

</td>
<td>7 Folders (tab sheets)
displaying crop characteristics</td>
</tr>
</table>

- **Calendar**

2.9.1 Description

- **Display modes of crop parameters**

Two types of display mode of crop parameters can be selected (Fig. 2.9a):

- ***Limited set:*** Crop parameters describing mainly phenology and life cycle length are displayed. They are

Planting	
Type of planting method (direct sowing or transplanting)	
Canopy size of the transplanted seedling (method of planting: transplanting)	
Phenology (cultivar specific)	
Time to flowering or the start of yield formation	
Length of the flowering stage	
Time to start of canopy senescence	
Time to maturity (i.e. the length of crop cycle)	
Time to reach full canopy (only if crop cycle is expressed in calendar days)	
Management dependent	
Plant density	
Time to emergence	
Maximum canopy cover (depends on plant density and cultivar)	
Soil dependent	
Maximum rooting depth	
Time to reach maximum rooting depth	
Soil and management dependent	
Response to soil fertility and/or soil salinity stress	

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 or when the planting method is altered. The displayed parameters are cultivar specific or might be affected by the field management, conditions in the soil profile, or the climate (especially when simulating in calendar day mode).

- ***Full set:*** All crop parameters are displayed (Table 2.9a).

- **Type of edit fields (cells)**

Crop parameters are displayed in edit-fields (cells). The color 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 favorable 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 2.9a.

- **Protected files**

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.

Table 2.9a.
List of the crop parameters and their type

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

(1) Conservative generally applicable
(2) Conservative for a given specie but can or may be cultivar specific
(3) Dependent on environment and/or management
(4) Cultivar specific

Table 2.9a. **continued.**

Symbol	Description	Type (1), (2), (3), (4)
2. Crop transpiration		
$Kc_{Tr?x}$	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)
3.2 Harvest Index		
HI_o	Reference harvest index (%)	Cultivar (4)
	Excess of potential fruits (%)	Conservative (2)
	Possible increase (%) of HI due to water stress before flowering	Conservative (1)
	Coefficient describing positive impact of restricted vegetative growth during yield formation on HI	Conservative (1)
	Coefficient describing negative impact of stomatal closure during yield formation on HI	Conservative (1)
	Allowable maximum increase (%) of specified HI	Conservative (1)

(1) Conservative generally applicable
(2) Conservative for a given specie but can or may be cultivar specific
(3) Dependent on environment and/or management
(4) Cultivar specific

Table 2.9a. continued.

Symbol	Description	Type [(1), (2), (3), (4)]
4. Stresses		
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 stress period to be exceeded before senescence is triggered	Conservative [(1)]
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/salinity 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)]
	Shape factor for the stress coefficient for stomatal closure	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 biomass production (°C - day)	Conservative [(1)]

(1) Conservative generally applicable
(2) Conservative for a given specie but can or may be cultivar specific
(3) Dependent on environment and/or management
(4) Cultivar specific

Table 2.9a. 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)

(1) Conservative generally applicable
(2) Conservative for a given specie but can or may be cultivar specific
(3) Dependent on environment and/or management
(4) Cultivar specific

2.9.2 Development

In figure 2.9b1 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 5 folders:

- Initial canopy cover (initial canopy cover at 90% emergence);
- Canopy development (canopy expansion and decline);
- Flowering and Yield formation (or Root/Tuber formation);
- Root deepening;
- Temperatures (required for the calculation of growing degree days).

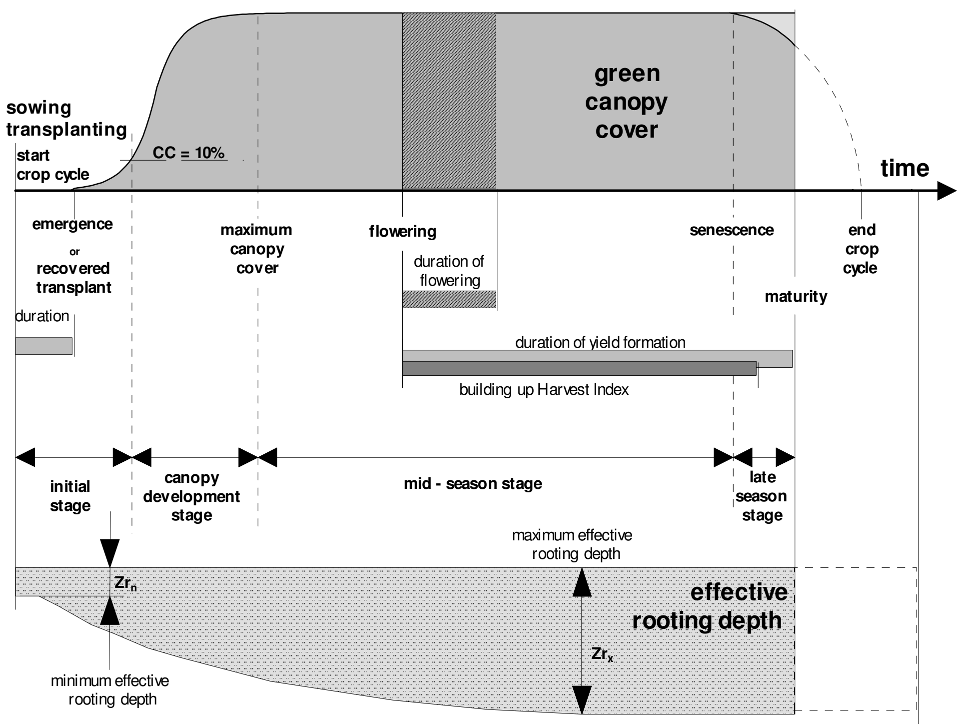


Figure 2.9b1
Schematic representation of crop development for fruit/grain producing crops

- **Initial canopy cover**

The initial canopy cover (CC_o) is required to describe canopy expansion (Chapter 3 – Section 3.3.2 Canopy development). 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

- 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. 2.9b2).

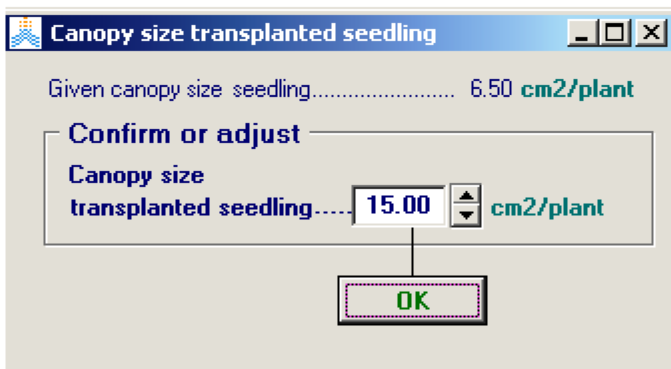


Figure 2.9b2
Confirming the canopy size of the transplanted seedling when altering the planting method from direct sowing to transplanting in the *Canopy size seedling* menu

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. 2.9b3);
- selecting one of the classes ranging from very small to very high cover (Tab. 2.9b1);
- specifying directly the percentage in the ***Crop characteristic*** menu, which might be required for transplanted seedlings.

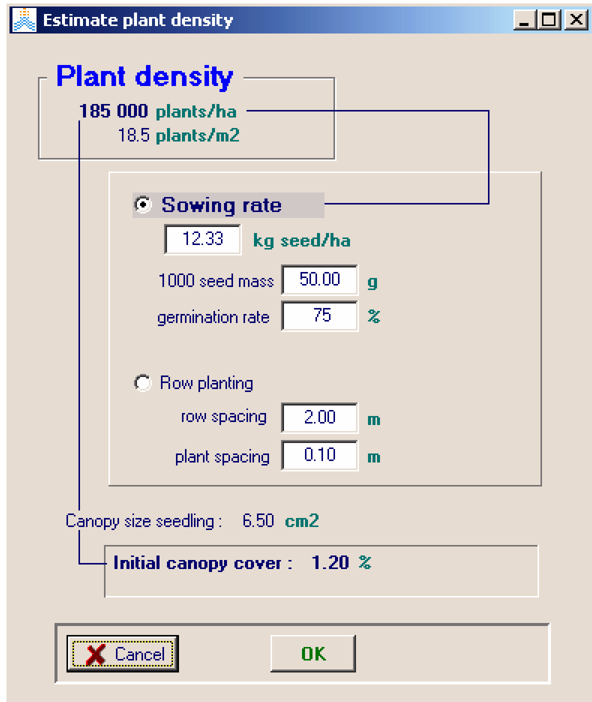


Figure 2.9b3
Estimation of plant density from sowing rate or plant density in the *Estimate plant density* menu

Table 2.9b1
Classes, corresponding default values, and ranges for the initial canopy cover (CC_o)

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

- **Canopy development**

Canopy expansion for no stress condition is described by two equations (see Chapter 3 – section 3.3.2 Canopy development) 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. 2.9b4).

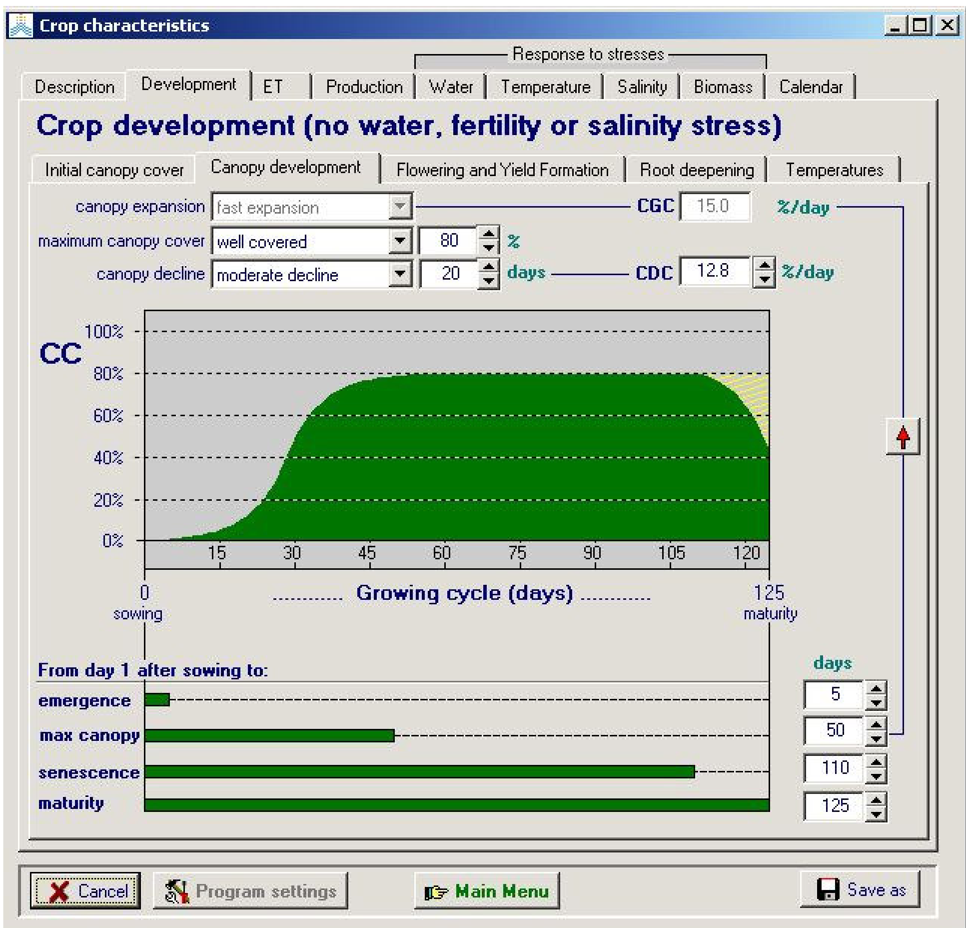


Figure 2.9b4
Specification of canopy development in the *Crop characteristics* menu

***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. 2.9b4) 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. 2.9b2).

Table 2.9b2
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. 2.9b3). AquaCrop displays the corresponding ground cover at maximum canopy. CC_x can also be specified by entering directly the percentage.

Table 2.9b3
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. 2.9b4), 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 2.9b4
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. 2.9b5). These parameters are mainly cultivar specific.

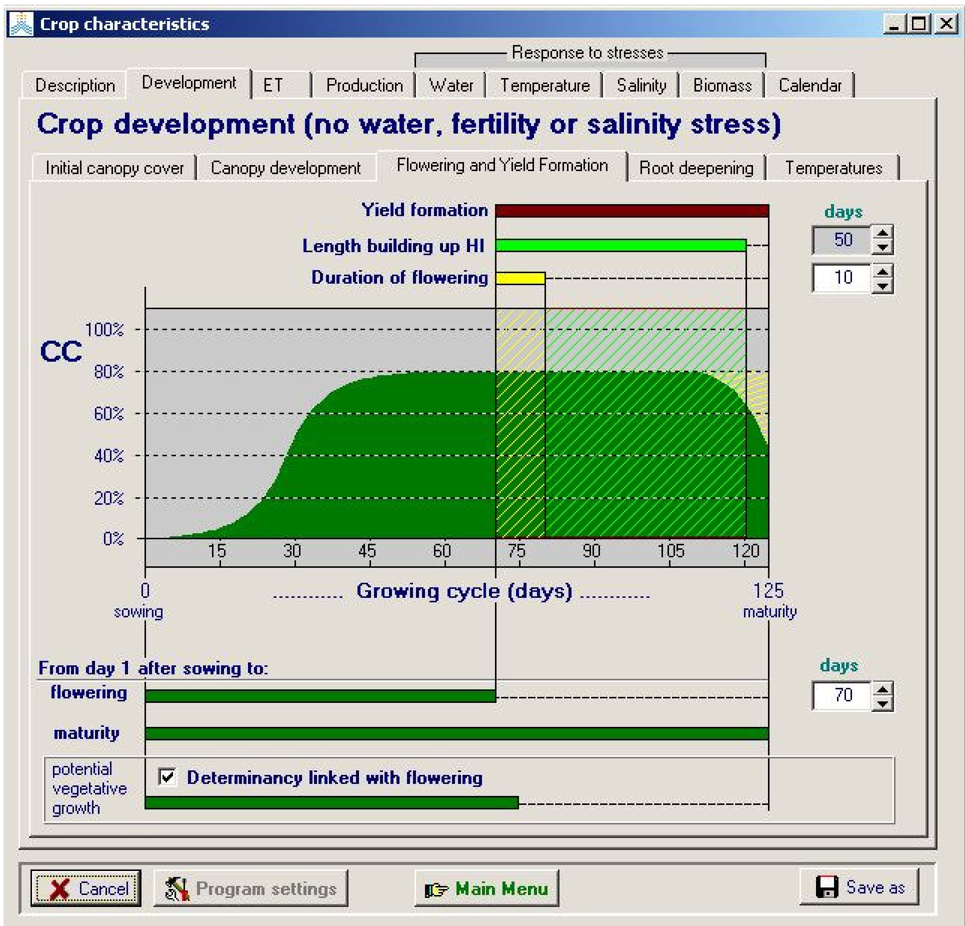


Figure 2.9b5

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. 2.9b5), 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. 2.9b6) the canopy development can stretch till canopy senescence. The corresponding period for potential vegetative growth is displayed.

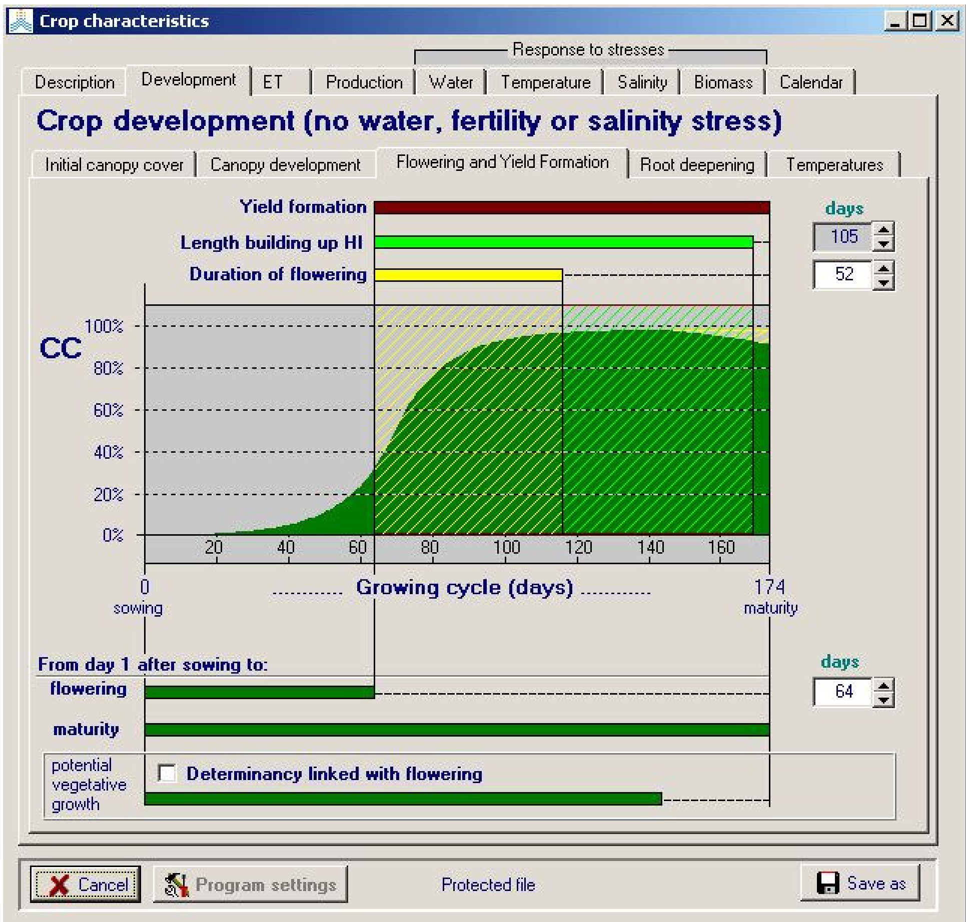


Figure 2.9b6
Specification of flowering and time required to build up the Harvest Index for fruit/grain producing crops in the *Crop characteristic* menu for a crop where determinancy is not linked with flowering, such as cotton.

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. 2.9b7). These parameters are mainly cultivar specific.

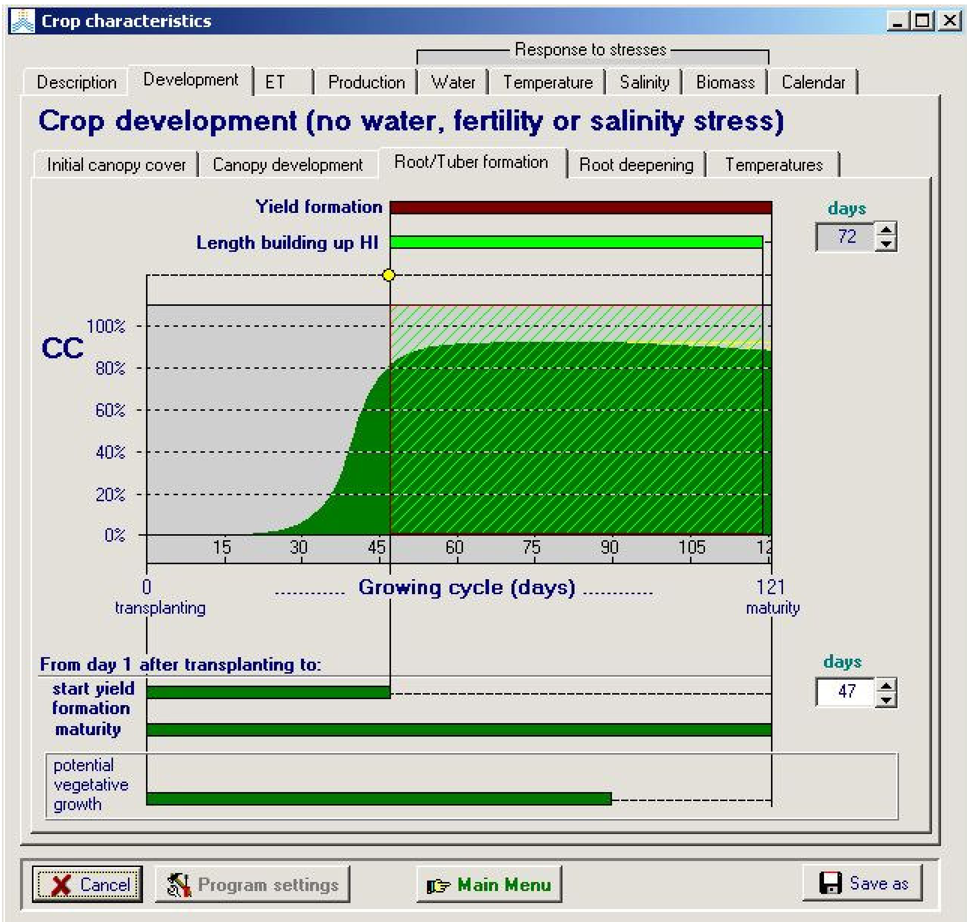


Figure 2.9b7

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 to be specified 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. 2.9b8). These parameters are user specific as root development is strongly impacted by local soil conditions and the life cycle length of the crop.

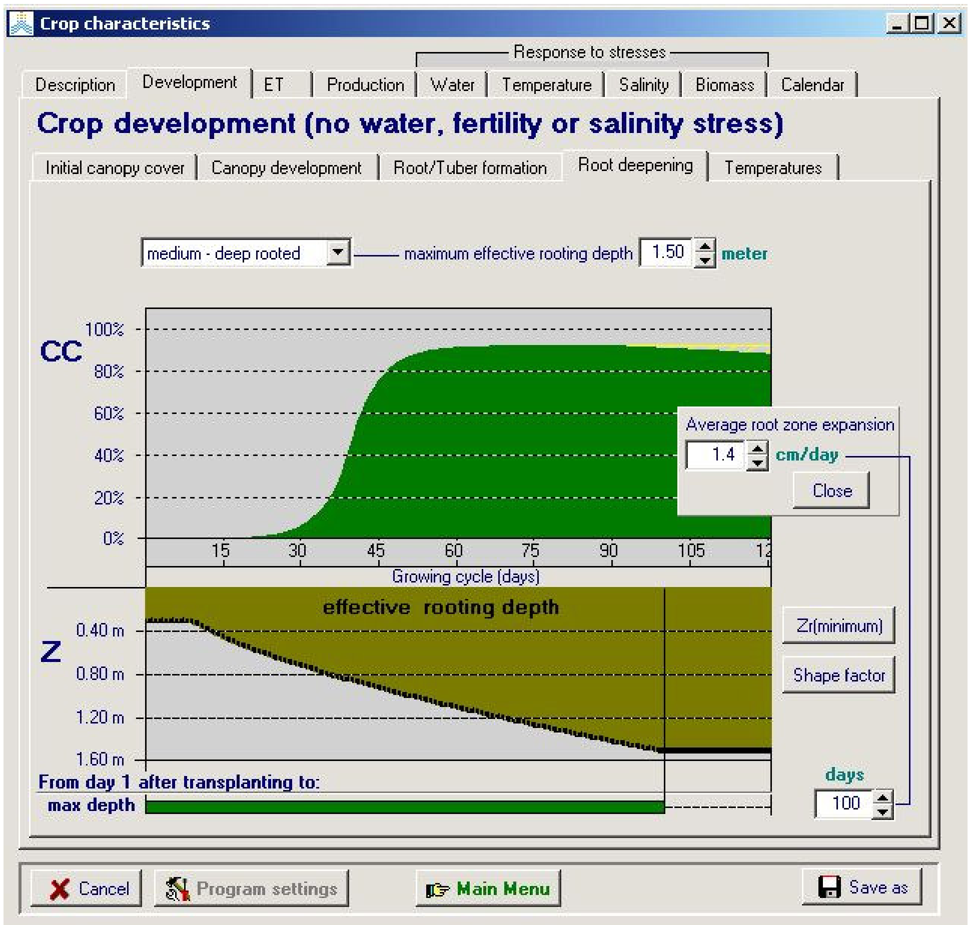


Figure 2.9b8
Specification of root deepening in the *Crop characteristic* menu

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.

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. 2.9b5). 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. The rooting depth can also be specified by entering directly the numeric value in meter. As a general rough guide for field crops in general, the roots deepening rate is about 2 cm per day when the environment is optimal for growth, the soil is not cold and soil layers that limits growth are absent.

Table 2.9b5
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	0.35 m	0.10 … 0.39
Shallow – medium rooted	0.60 m	0.40 … 0.99
Medium – deep rooted	1.00 m	1.00 … 1.99
Deep rooted crops	1.35 m	2.00 … 2.99
Very deep rooted crops (perennial)	2.00 m	3.00 … 10.0

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 might not reach its maximum value if an impermeable soil layer blocks 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 layer, the expansion is halted (Fig. 2.9b9).

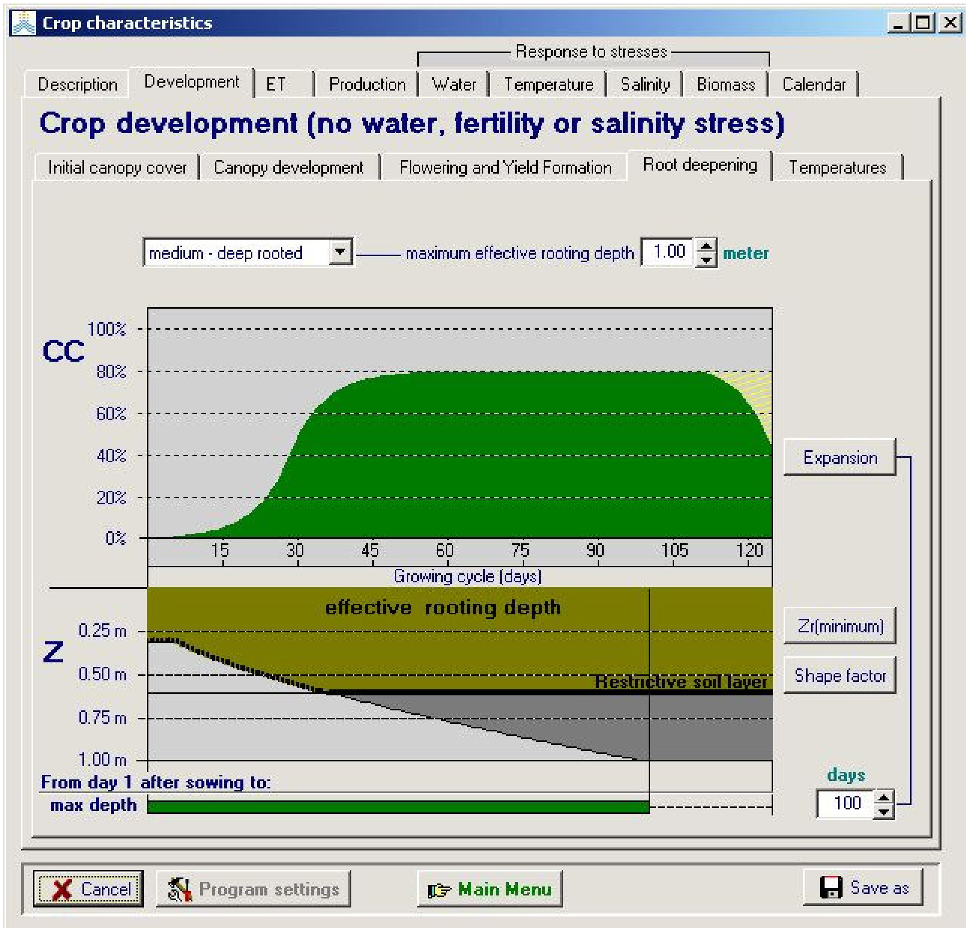


Figure 2.9b9
Effect of a restrictive soil layer on root development

- **Temperatures for growing degree days (GDD)**

Crop development can be specified in calendar days or growing degree days (GDD). 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 Temperatures folder (Fig.2.9b10).

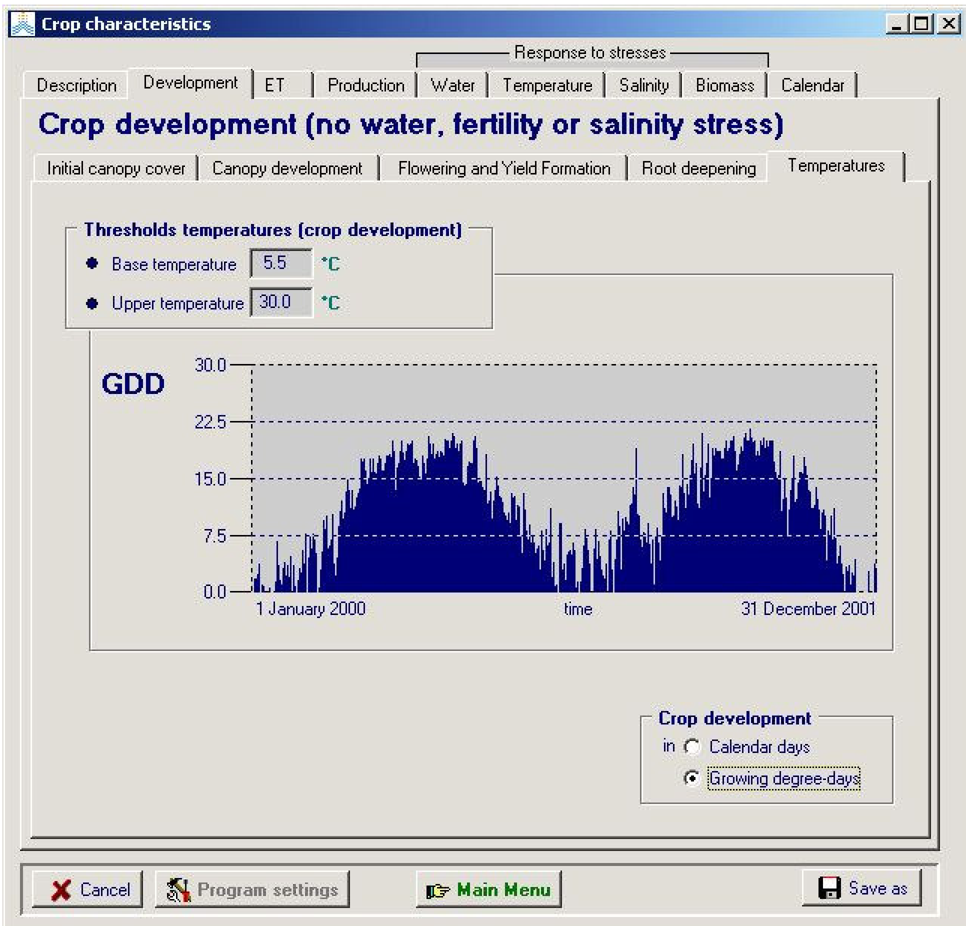


Figure 2.9b10
Specification of the base and upper temperature threshold in the *Crop characteristics* menu

2.9.3 Evapotranspiration

- **Coefficients**

The soil water evaporation coefficient (Ke) and the crop transpiration coefficient (Kc_{Tr}) are plotted from sowing to maturity (Fig. 2.9c1).

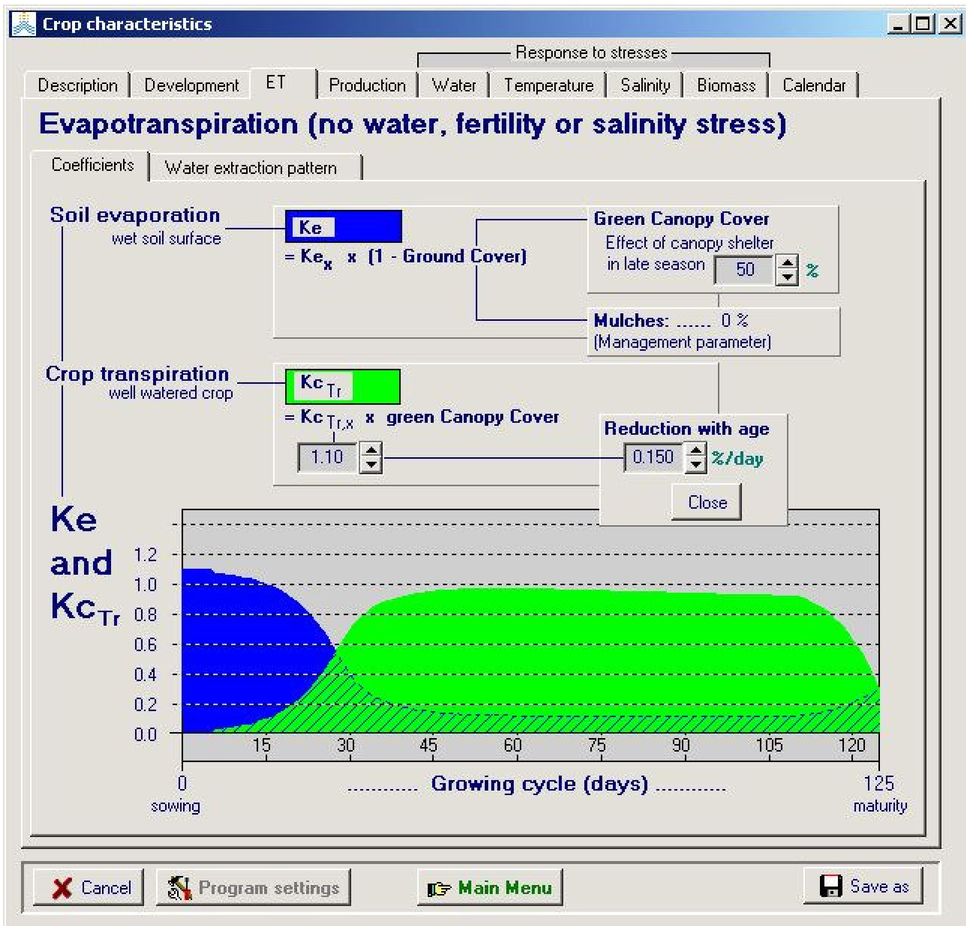


Figure 2.9c1

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

Evaporation from a fully wet soil surface is inversely proportional to the effective canopy cover. The proportional factor is the soil evaporation coefficient for fully wet and unshaded soil surface (Ke_x) which is a program parameter (see 2.9.11 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 senescening canopy retains more or less of its dead leaves.

Crop transpiration from a well water soil is proportional to the effective canopy cover. 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. 2.9c1).

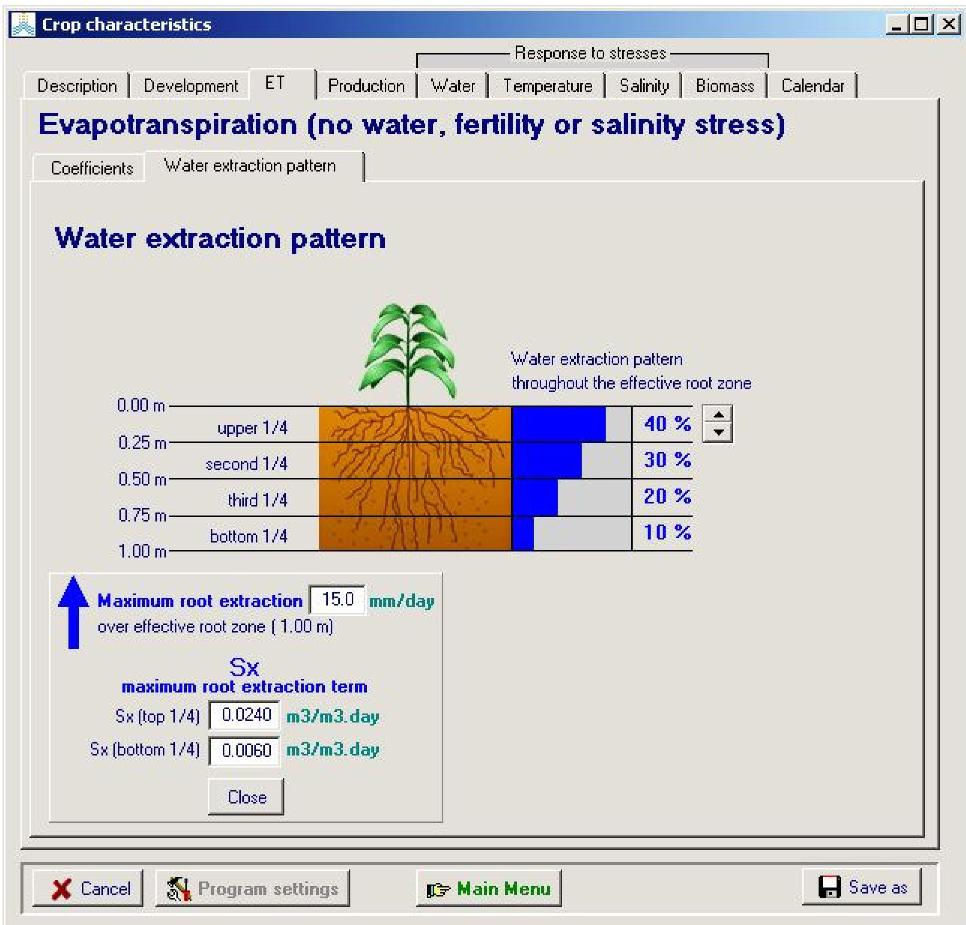


Figure 2.9c2
Derived maximum extraction terms (S_x) at the top and bottom of the root zone after the specification of the water extraction pattern and the maximum root extraction

- **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). S_x at the top of the soil profile is generally different from S_x at the bottom of the root zone. By specifying the maximum root extraction of a well developed crop (a default value of 15 mm/day for root zones deeper than 0.5 m is considered), and the water extraction pattern throughout the root zone, S_x values are derived in AquaCrop for different depths in the root zone (Fig. 2.9c2).

If a soil layer blocks the root zone expansion, the maximum root extraction term at the bottom of the root zone increases when the roots continue to develop. This simulates the concentration of roots above the restrictive soil layer. When a restrictive layer in the soil profile is present, the adjustment of the extraction terms can be displayed in AquaCrop (Fig. 2.9c3).

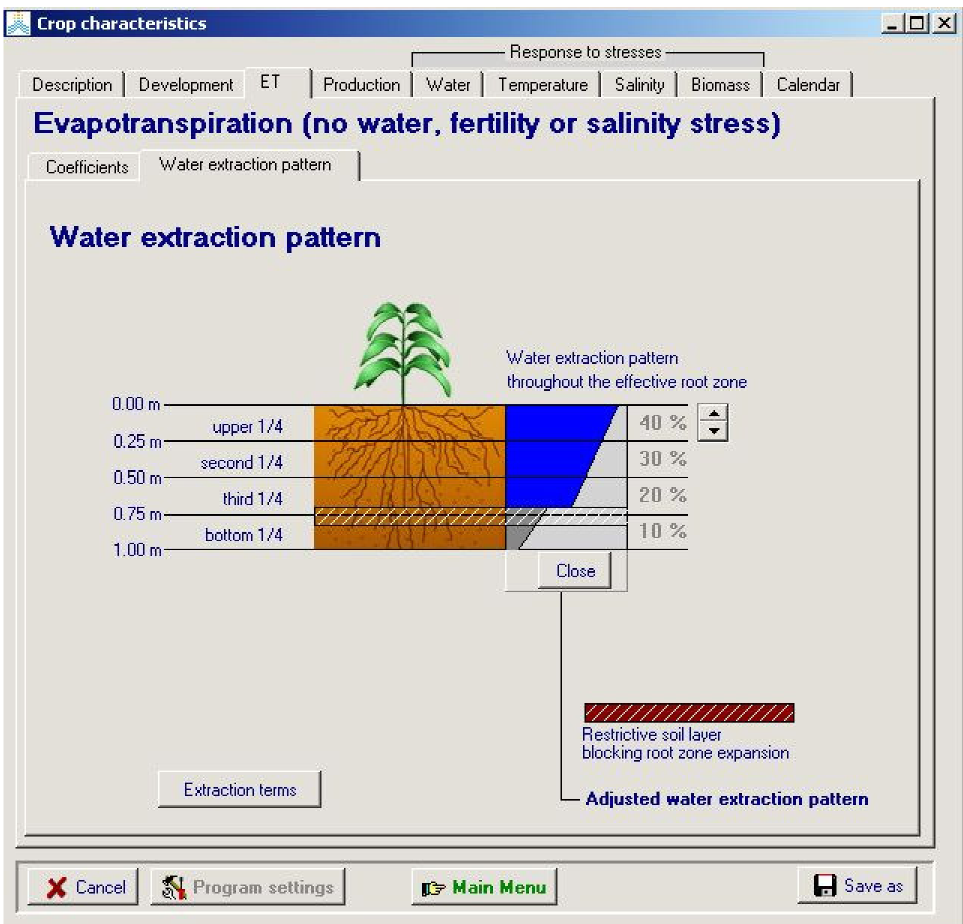


Figure 2.9c3
Adjustment of the water extraction pattern
in the presence of a restrictive soil layer blocking root zone expansion

2.9.4 Production

- **Crop water productivity normalized for climate and CO_2 (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. 2.9d1).

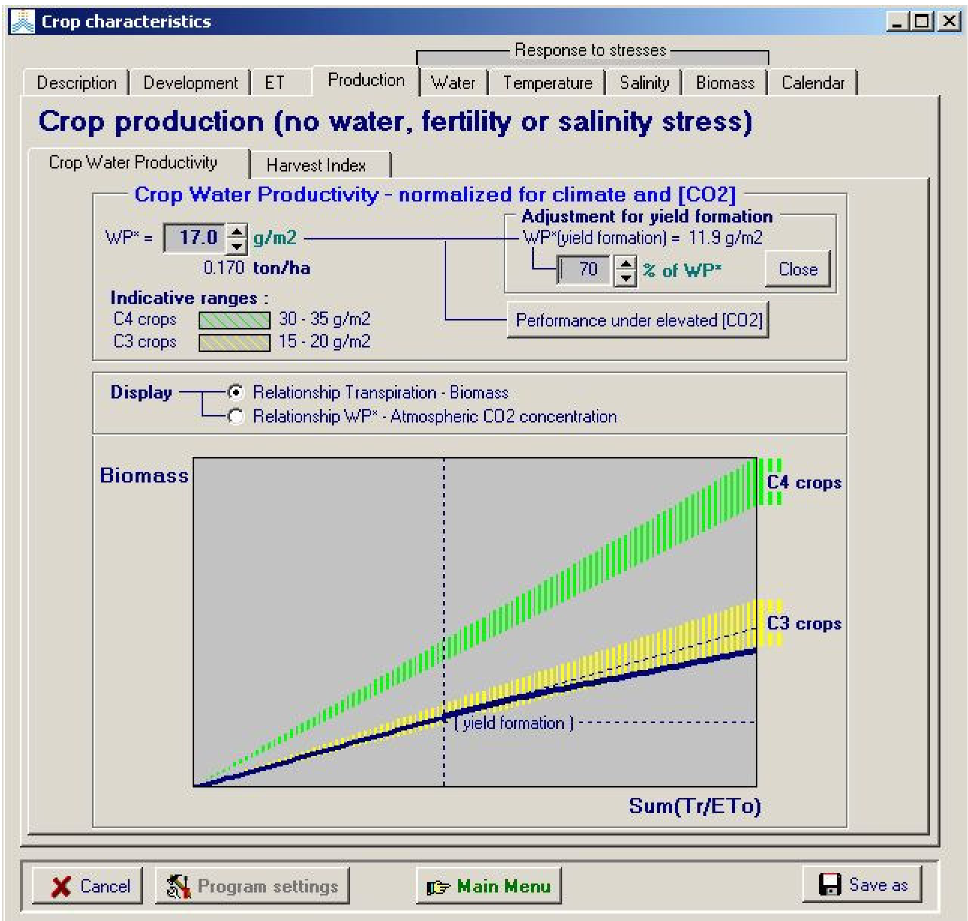


Figure 2.9d1
The water productivity normalized for climate and atmospheric CO_2 and its adjustment if the harvestable organs are rich in oil and/or proteins

- **Performance under elevated atmospheric CO_2 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 Above ground biomass). The theoretical adjustment might not be entirely valid when (i) soil fertility is not properly adjusted to the higher productivity under elevated 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. 2.9d2).

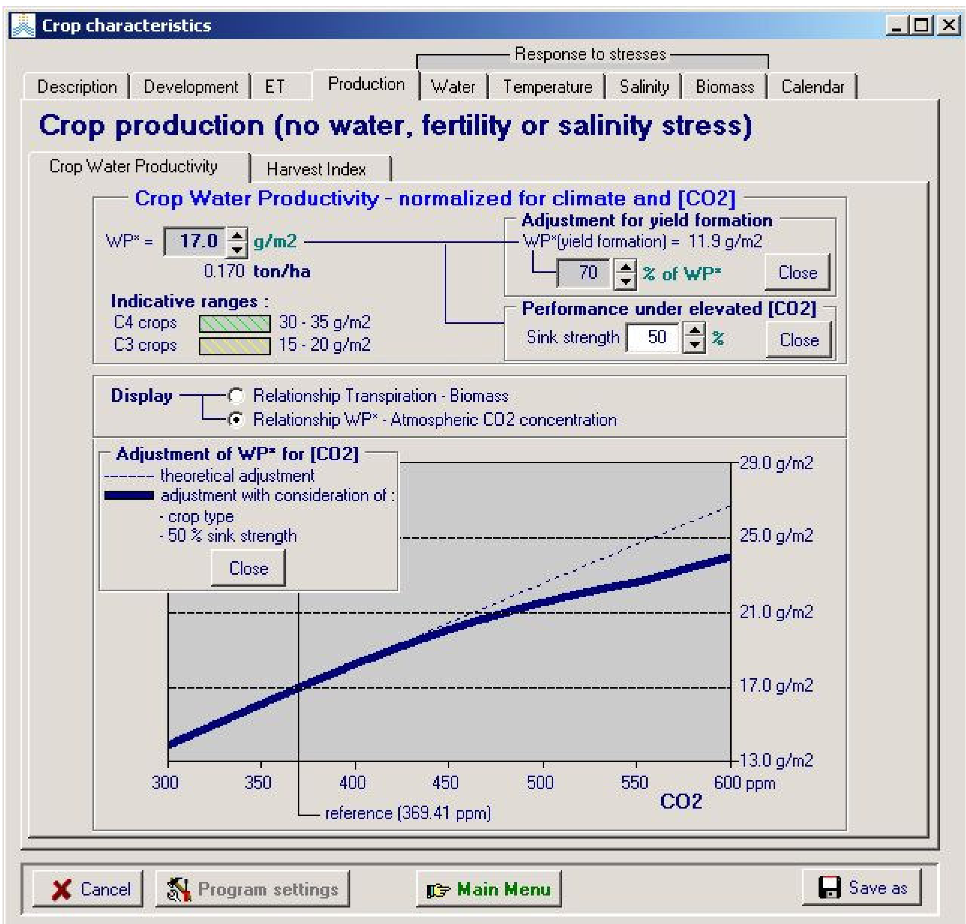


Figure 2.9d2
The water productivity adjusted to atmospheric CO_2 concentration by considering crop type and crop sink strength

- **Reference Harvest Index (HI_o)**

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

Fruit or grain producing crops

Beginning at the start of flowering HI increases linearly after a lag phase until physiological maturity is reached (Fig. 2.9d3). The value reached at maturity under non-stress conditions is taken as HI_o for that species.

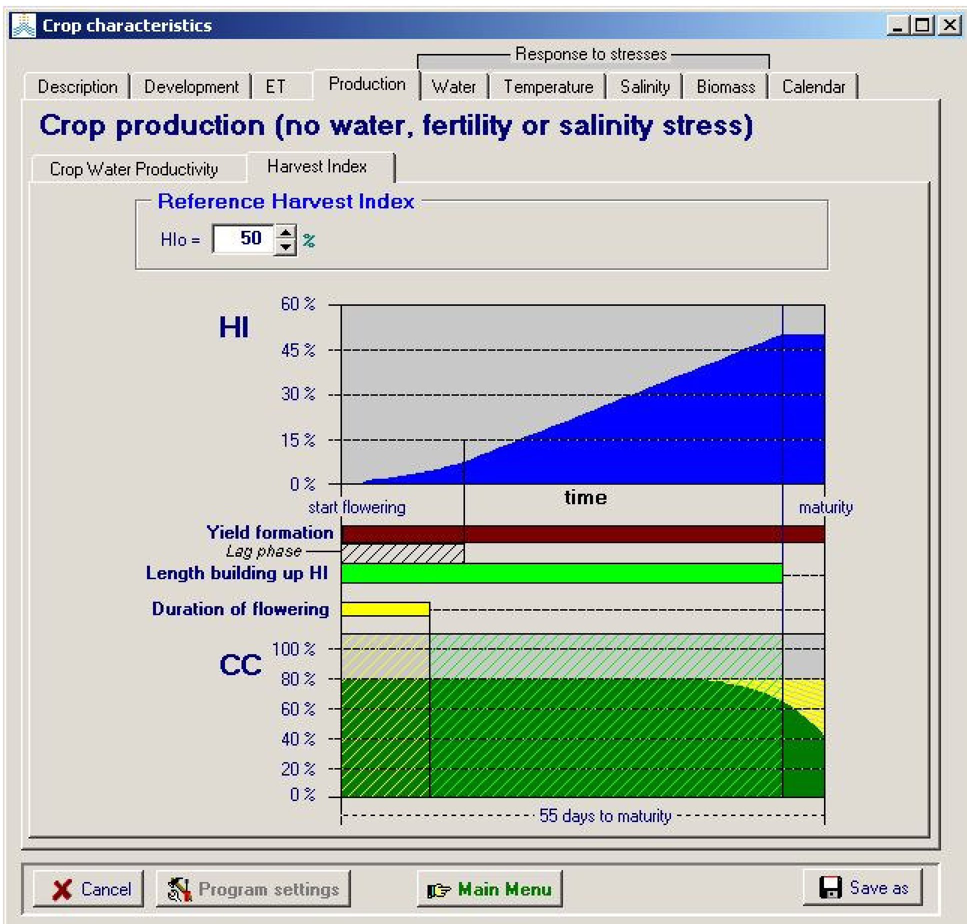


Figure 2.9d3
Specification of the reference harvest index (HI_o)
and the display of the building up of the Harvest Index from flowering to physiological maturity for a fruit or grain producing crop

Root and tubers

Beginning at tuber formation or root enlargement HI increases until physiological maturity (Fig. 2.9d4). 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.

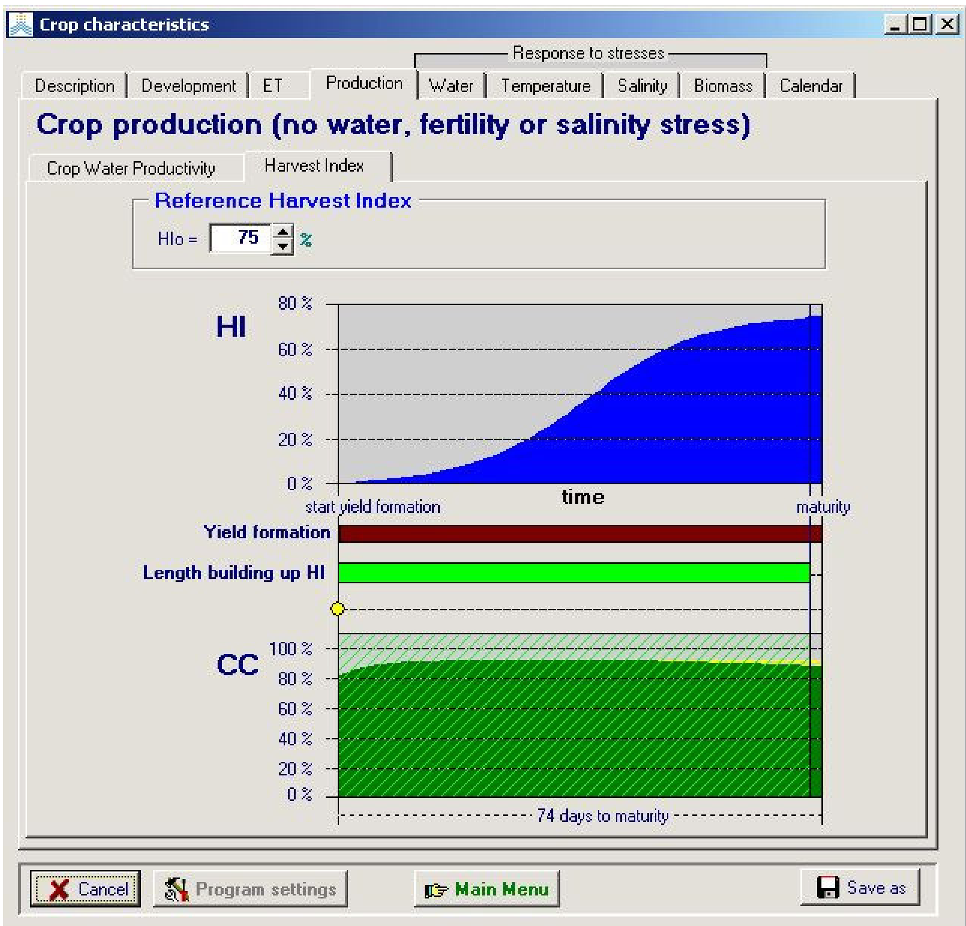


Figure 2.9d4
Specification of the reference harvest index (HI_o)
and the display of the building up of the Harvest Index from the tuber formation or root enlargement to physiological maturity for roots and tubers

Leafy vegetable crops
Beginning at germination, HI increases with a logistic equation till the reference harvest indeed (HIo) is reached (Fig. 2.9d5). For leafy vegetable crops, the time to reach HI_o is expressed as a percentage of the growing cycle.

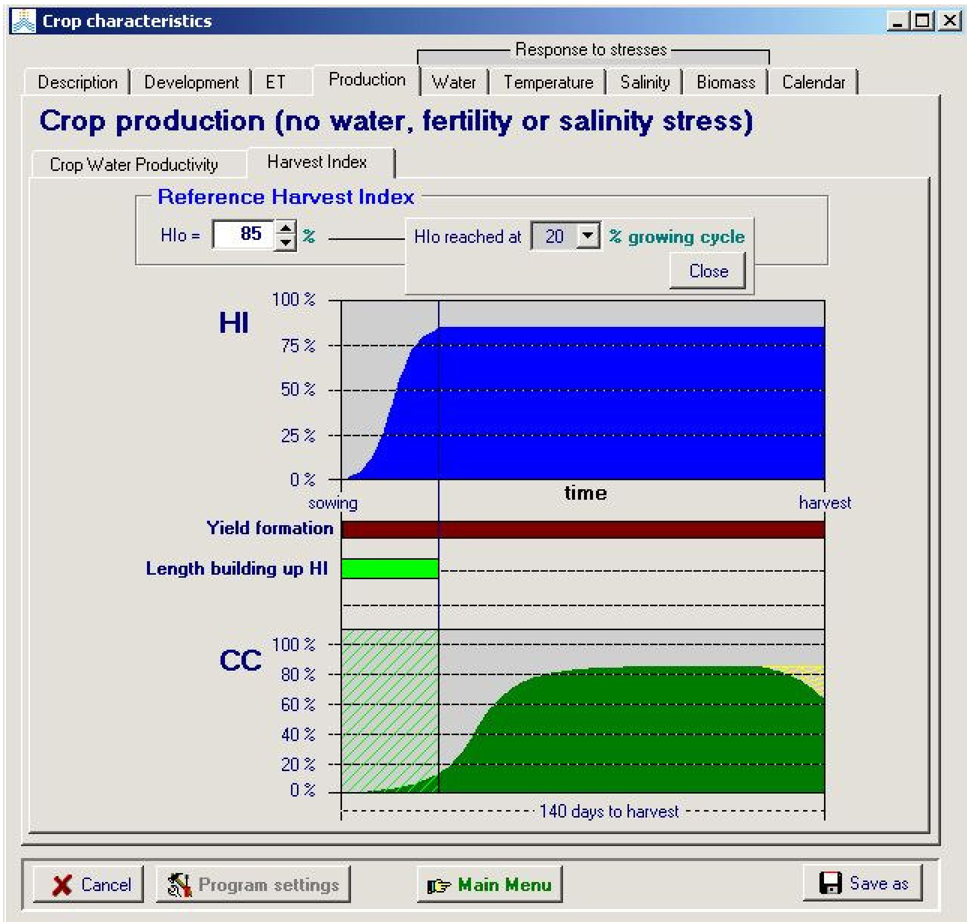


Figure 2.9d5
Specification of the reference harvest index (HI_o) and the time to reach HI_o for leafy vegetable crops

2.9.5 Water stress

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

Effects of water stress on canopy expansion, stomatal conductance, and early canopy senescence are described by water stress coefficients Ks. Above an upper threshold of soil water content, 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. 2.9e1). 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.

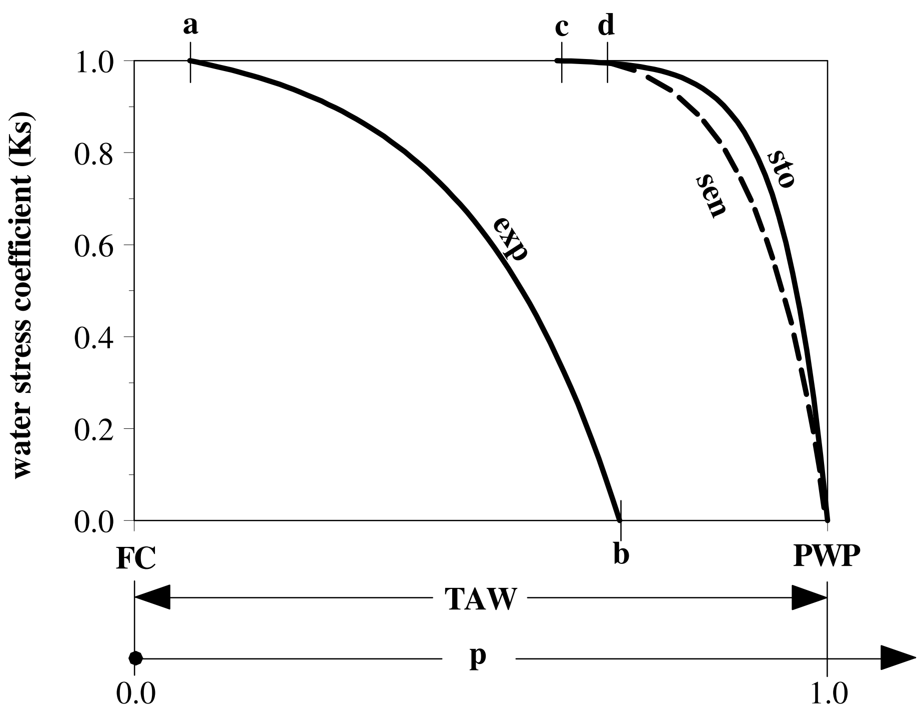


Figure 2.9e1
Examples of the variation of the water stress coefficient for leaf expansion (exp), stomatal conductance (sto) and canopy senescence (sen) for various soil water depletions

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). 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. 2.9e2). 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).

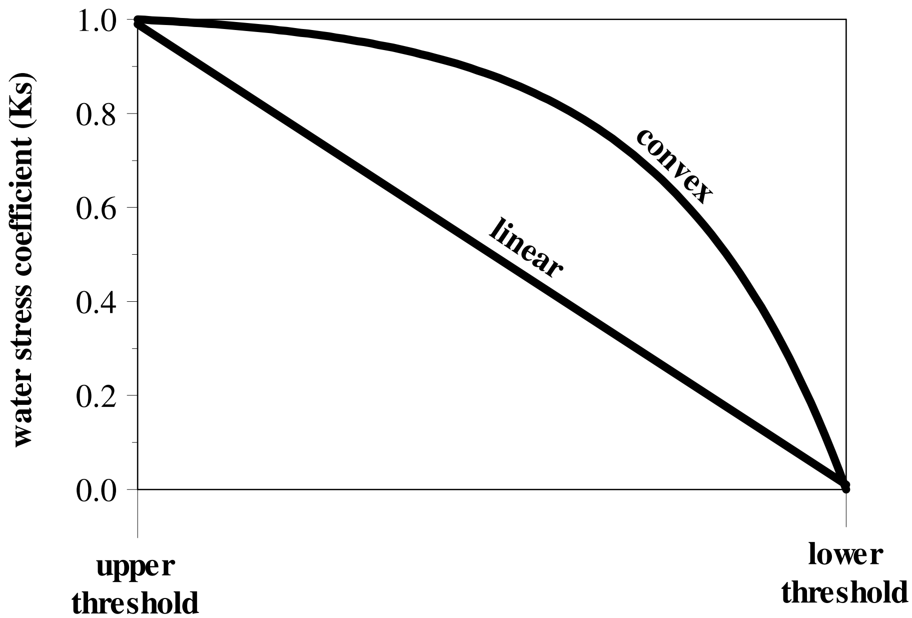


Figure 2.9e2
Convex and linear shapes of the Ks curve

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. 2.9e3), 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. 2.9e1, Fig. 2.9e3) 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 2.9e1
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

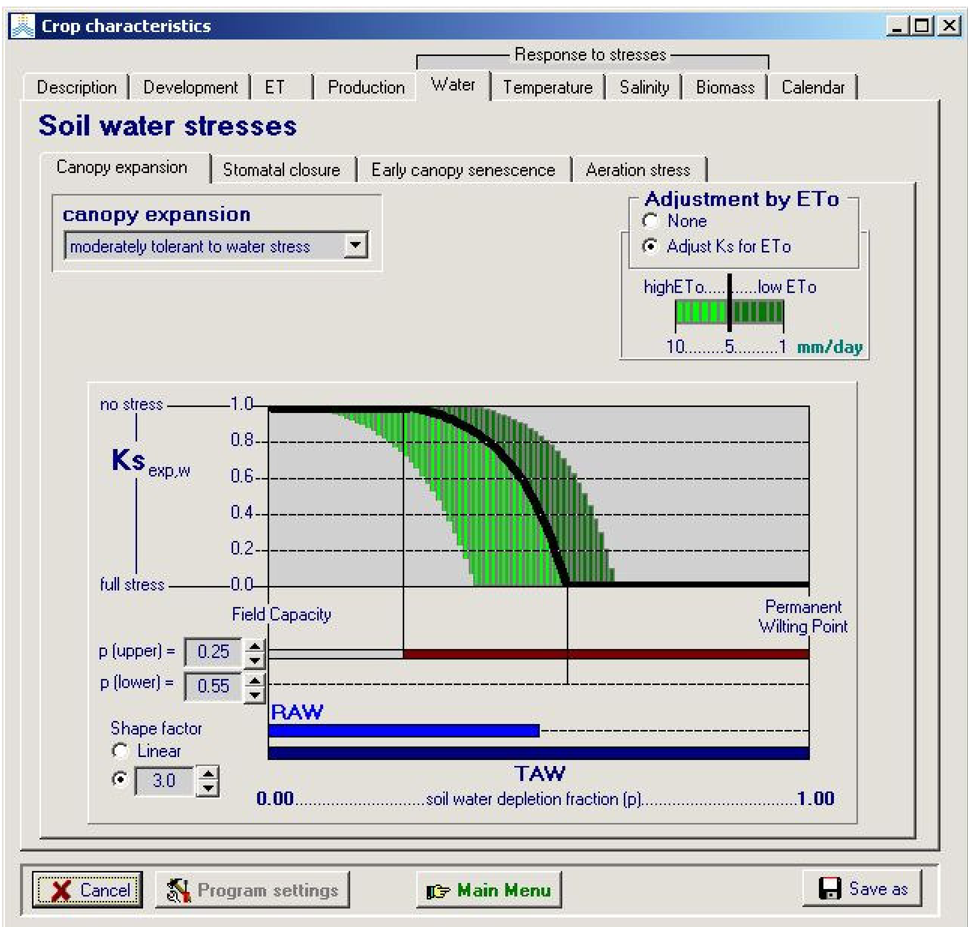


Figure 2.9e3
Specification of the upper and lower thresholds and the shape of the Ks curve for the effect of water stress on canopy expansion ($Ks_{exp,w}$)

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 2.9e2) 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 2.9e2
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. 2.9e3) 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 2.9e3
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

- **Effect of soil salinity stress on the thresholds for soil water depletion**

If soil salinity affects crop development, the thresholds for leaf expansion, stomatal conductance and early canopy senescence might shift upwards due to a decrease in soil water potential. By means of the Program settings the user can switch on or off the effect of soil salinity on the thresholds (Fig. 2.9e4).

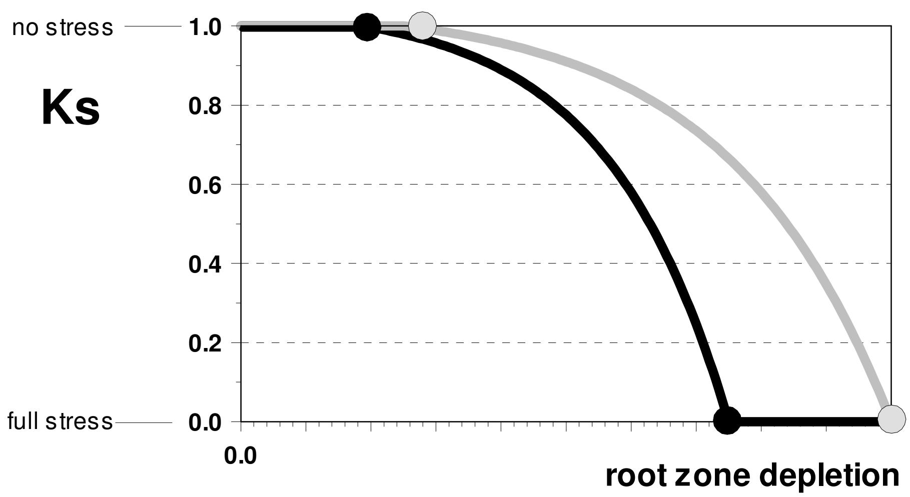


Figure 2.9e4 – Shift of the thresholds (circles) for root zone depletion and its effect on Ks (lines) with (black) and without (gray) the effect of soil salinity on the thresholds.

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 2.9e5), the aeration of the root zone will be deficient, resulting in a decrease of crop transpiration.

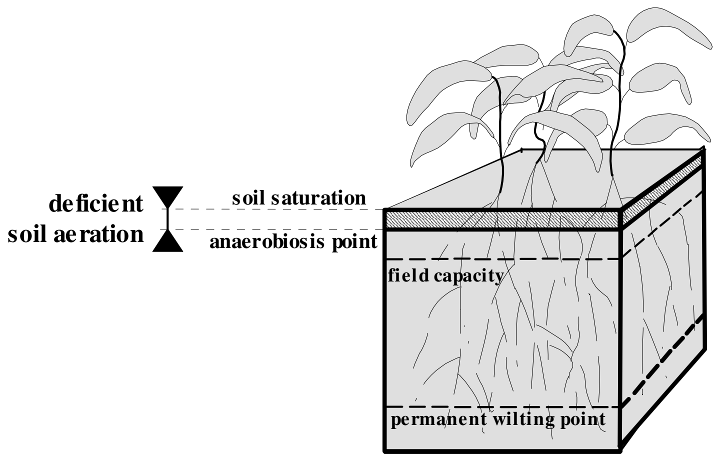


Figure 2.9e5
Zone (dark area) of restricted soil water extraction as a result of deficient soil aeration

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. 2.9e6). The user specifies the sensitivity of the crop to water logging by selecting an aeration stress class (Tab. 2.9e4) or by specifying the anaerobiosis point (volume percent below soil saturation).

Table 2.9e4
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

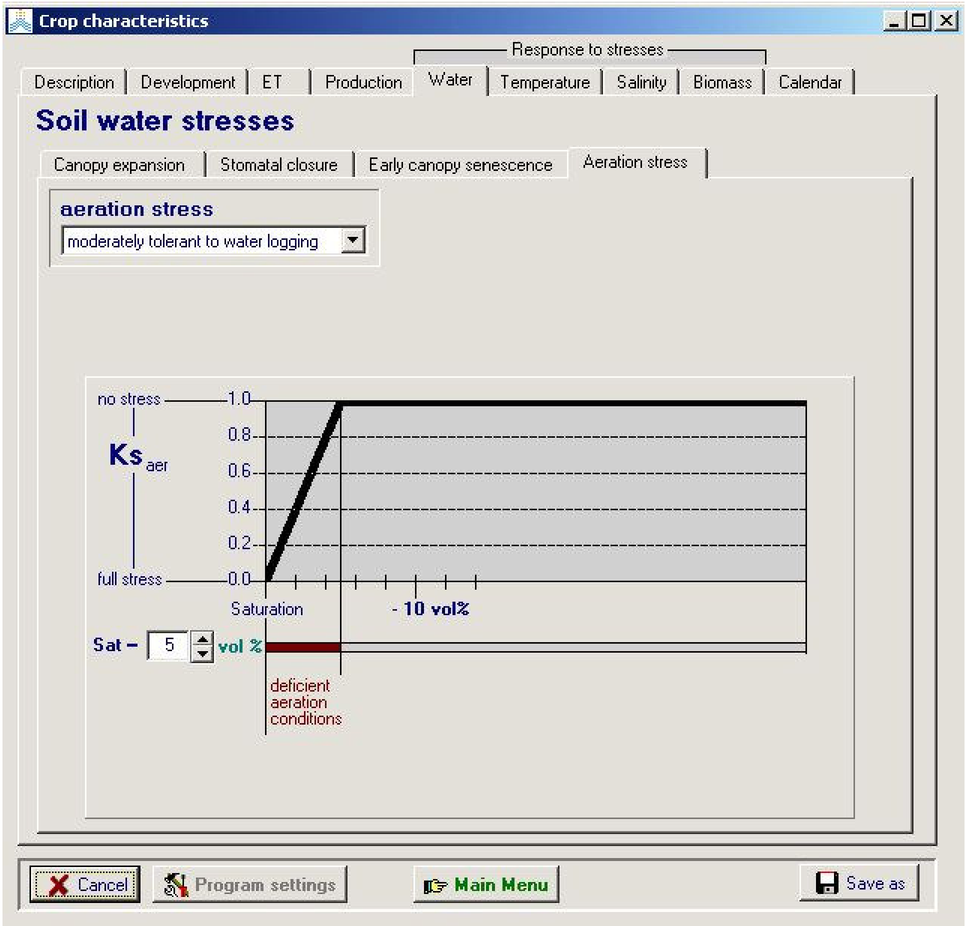


Figure 2.9e6
Specification of the soil water content below saturation at which poor aeration no longer limits transpiration

- **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. 2.9e7) or select a class graded for the effect of pre-anthesis water stress (Tab. 2.9e5).

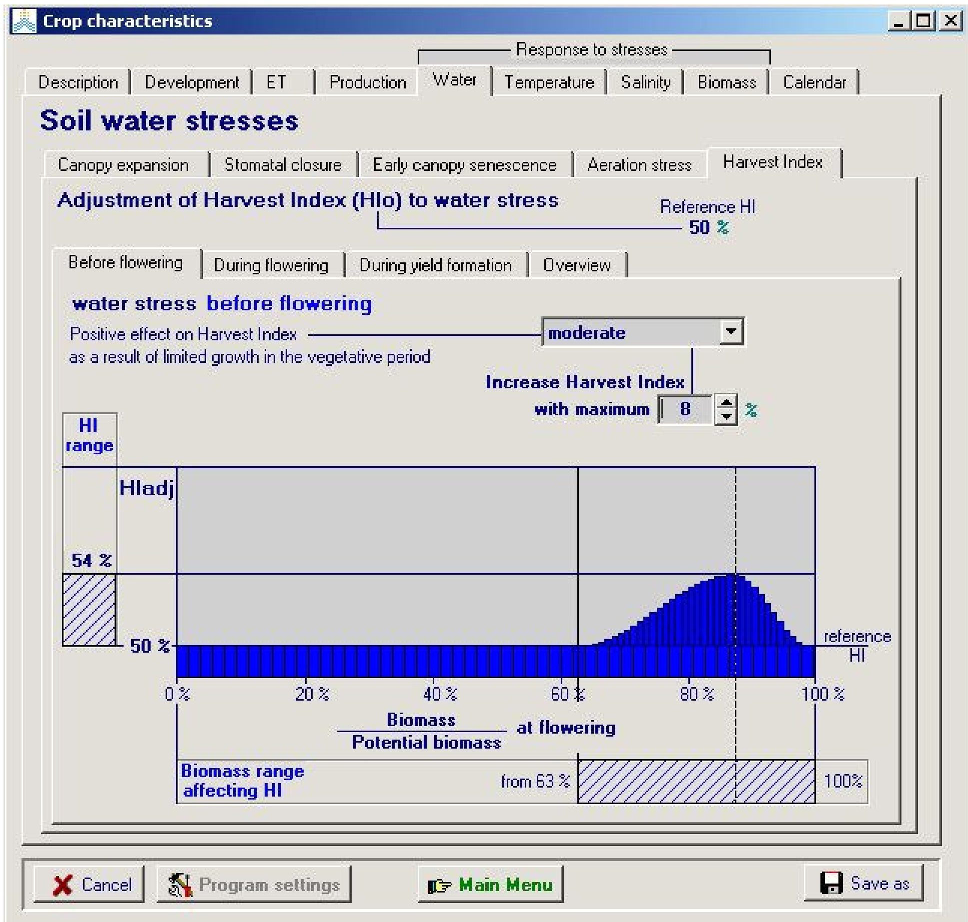


Figure 2.9e7
Positive effect on Harvest Index of pre-anthesis water stress affecting biomass production

Table 2.9e5
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. 2.9e8, Tab 2.9e6).

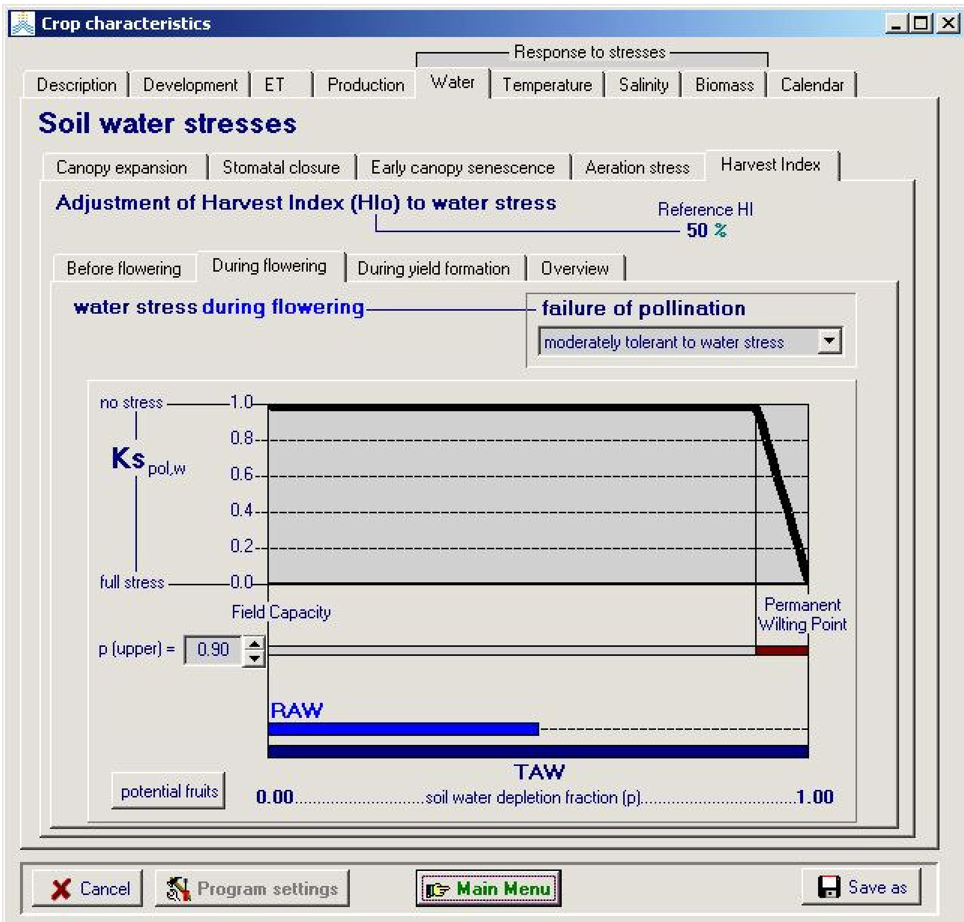


Figure 2.9e8
Specification of the upper thresholds
for the effect of water stress on failure of pollination

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. 2.9e7);

- 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. 2.9e8).

Table 2.9e6
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 2.9e7
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 2.9e8
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. 2.9e9). 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. 2.9e9).

Table 2.9e9
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

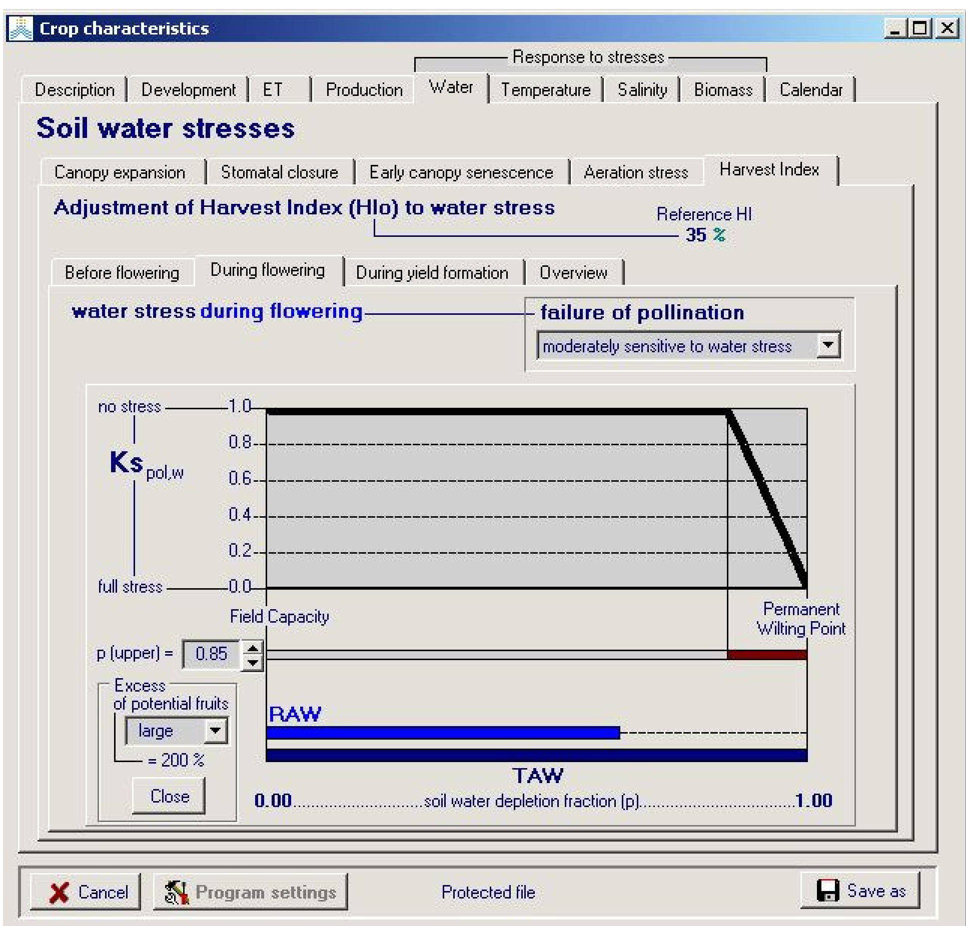


Figure 2.9e9
Specification of the extent of excessive potential fruits

The combined effect of water stress during yield formation is displayed in the corresponding tab sheet (Fig. 2.9e10).

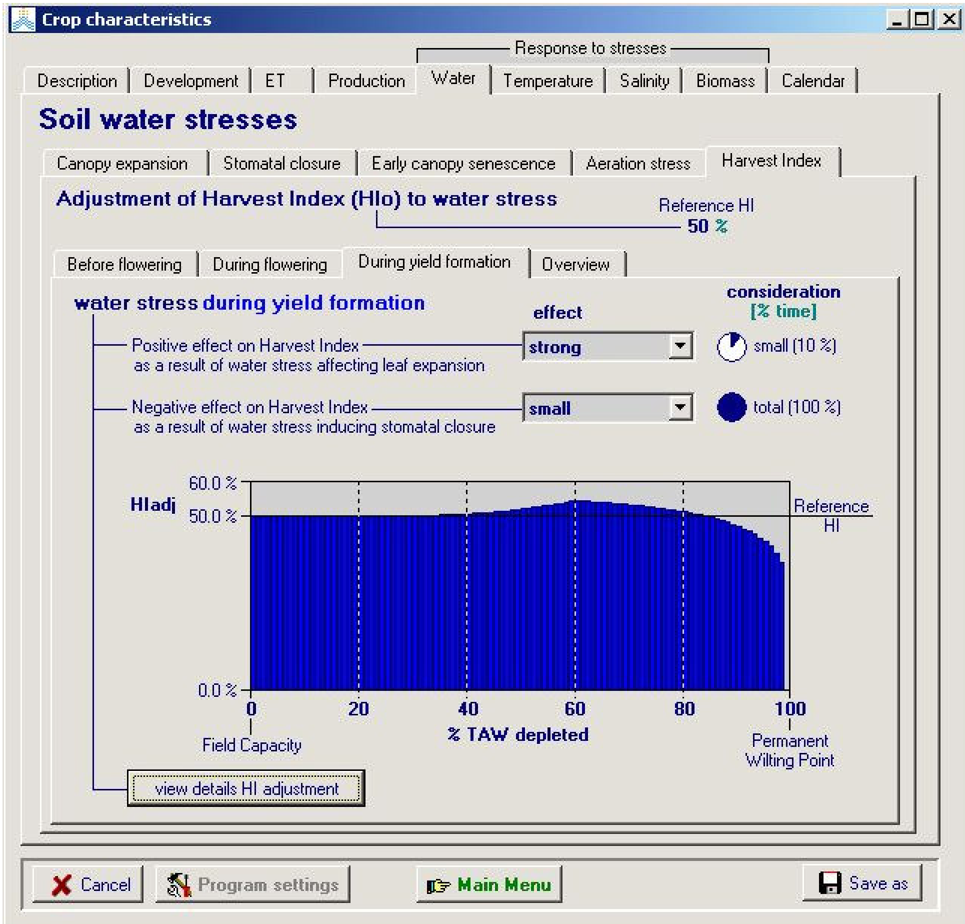


Figure 2.9e10
Effect on Harvest Index of post-anthesis water stress
for various degrees of root zone depletion (% TAW depleted)

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 2.9e11 and 2.9e12). The individual and combined effect on HI can be displayed for various root zone depletions and evaporative demands.

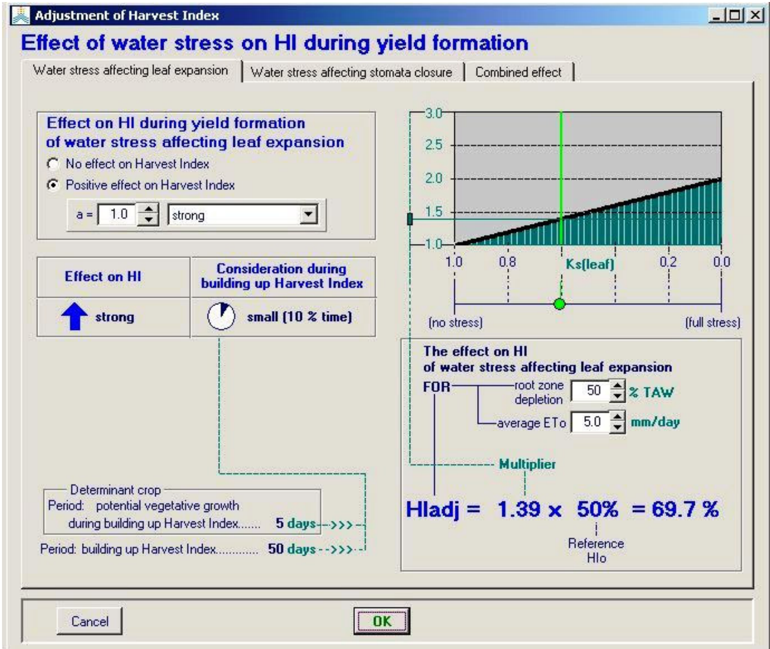


Figure 2.9e11

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

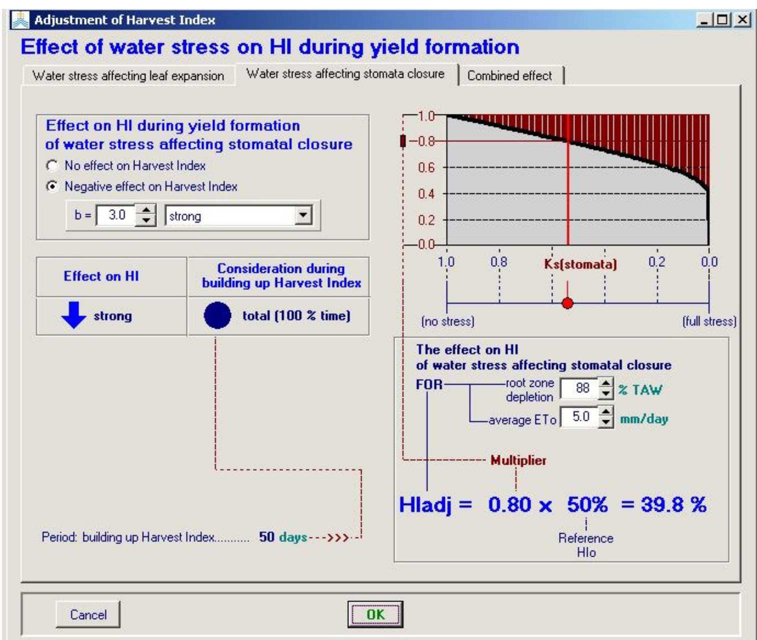


Figure 2.9e12

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 preset maximum. In the folder presenting the overview of water stress effects on Harvest Index, the user can adjust the maximum allowable increase (Fig. 2.9e13).

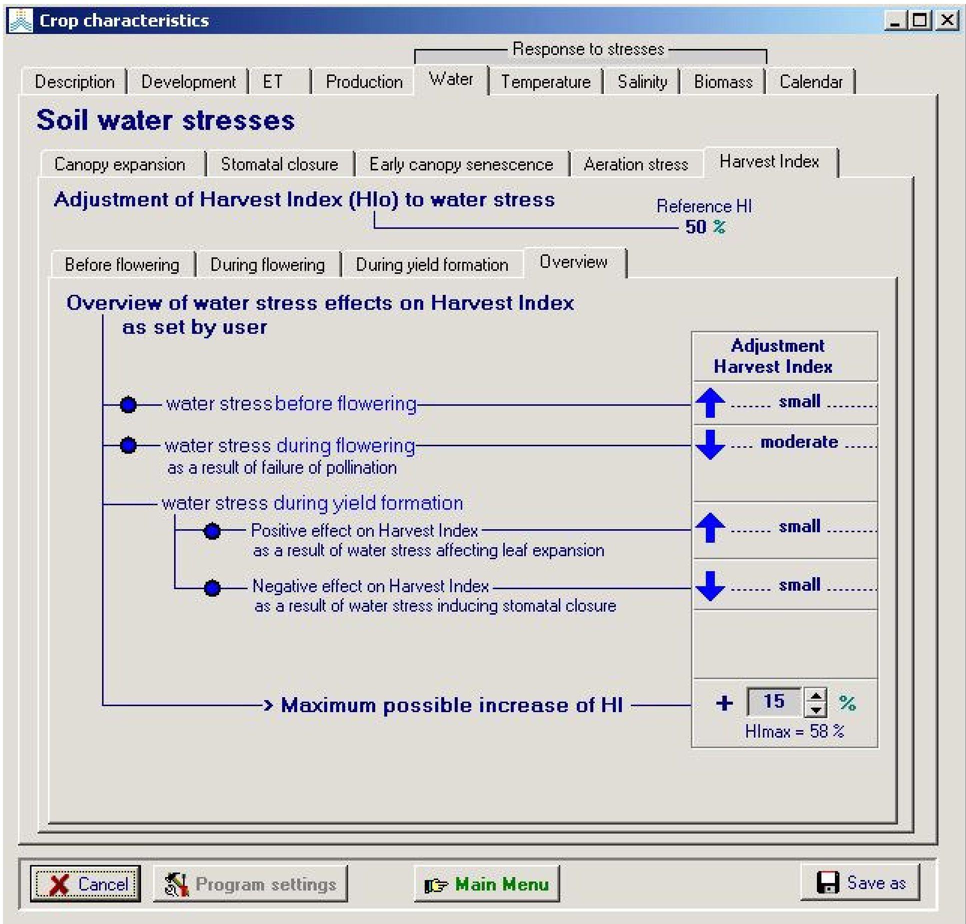


Figure 2.9e13
Combined effect of water stress on harvest index

2.9.6 Temperature stress

In AquaCrop temperature stress affecting biomass production and pollination is considered. The effects are described by temperature stress coefficients (Ks) which varies between 0 (full effect of temperature stress) and 1 (no effect).

- **Biomass production**

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 biomass production. 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. 2.9f1). The lower threshold is fixed at 0 °C-day. Between the upper and lower threshold the shape of the Ks curve is logistic.

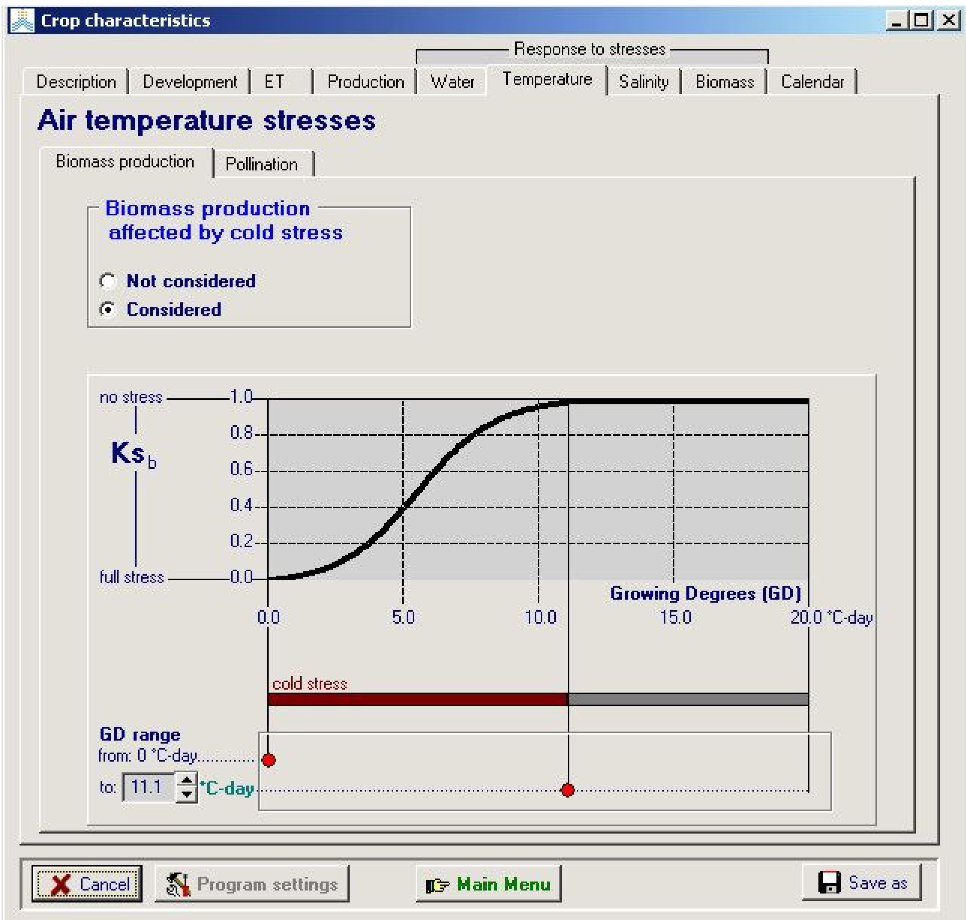


Figure 2.9f1
Specification of the threshold for temperature stress on biomass production

- **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. 2.9f2). Between the upper and lower thresholds the shapes of the Ks curves are logistic.

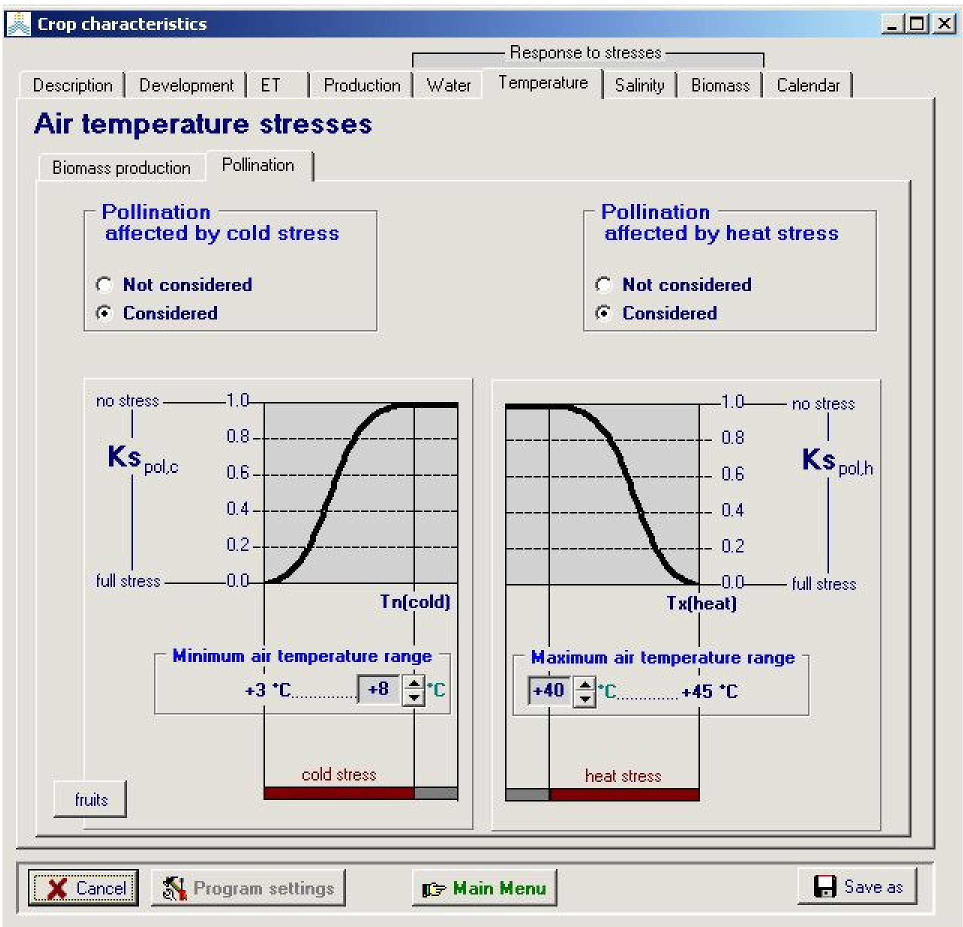


Figure 2.9f2
Specification of the thresholds for cold and heat stress on pollination

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.

2.9.7 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**

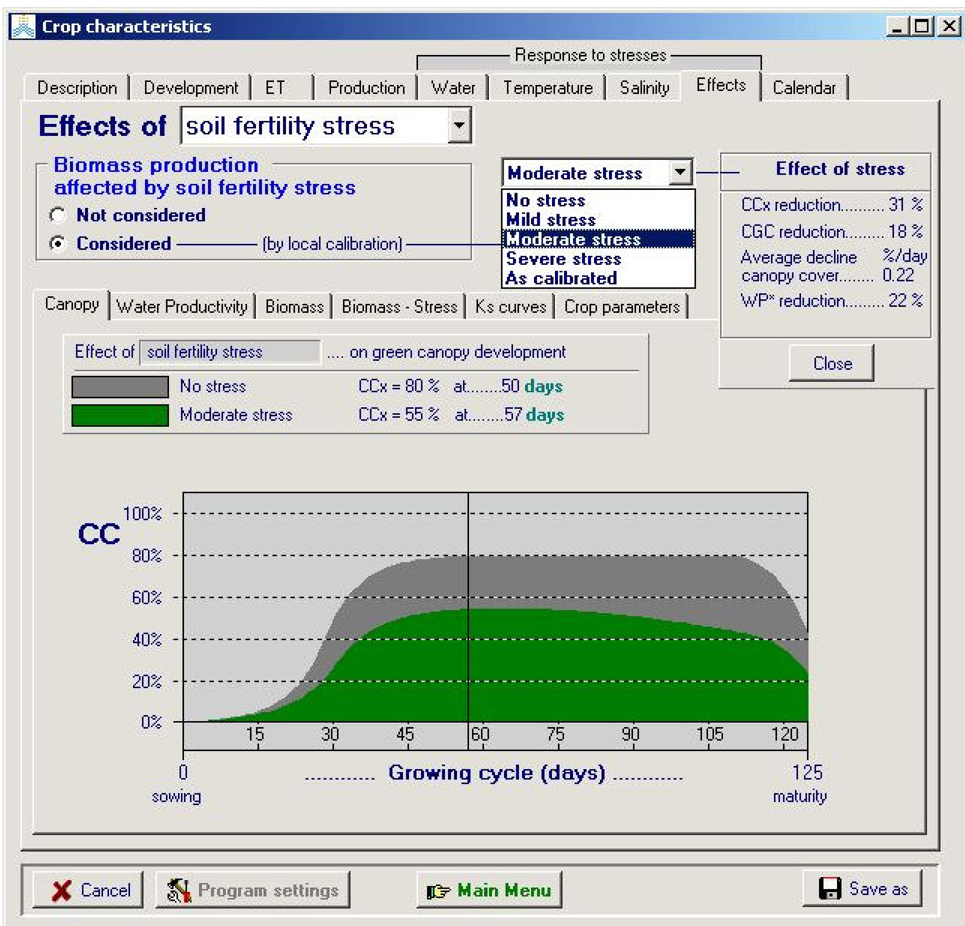


Figure 2.9g
The effect of moderate soil fertility stress on canopy development

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. 2.9g).

- **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 (see 2.12 Field management).

- **Calibration of the crop response**

Calibration of the crop response to soil fertility stress is done in the ***Crop characteristic*** menu (See 2.9.8 Calibration for soil fertility stress).

2.9.8 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**

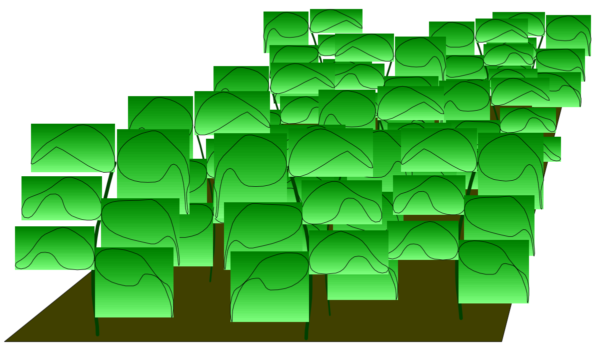
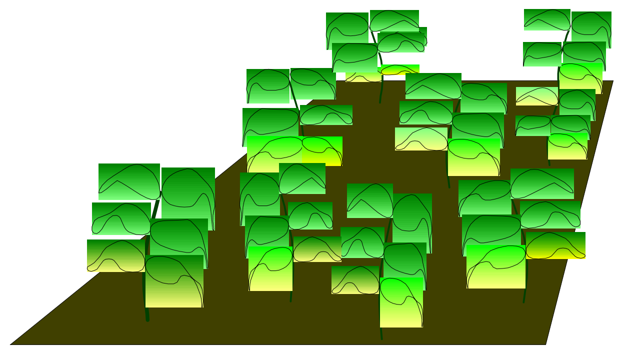
	
Reference field - well watered field - no soil fertility stress	**Stressed field** - well watered field - soil fertility stress
Observations: B_{ref} and CC_{ref}	**Observations:** B_{stress} and CC_{stress}

Figure 2.9h1 – 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. 2.9h1). 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 2.9h the stress coefficients (Ks) and decline coefficient (f) used for the simulation of the crop response to soil fertility stress are listed.

Table 2.9h – 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 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. 2.9h2).

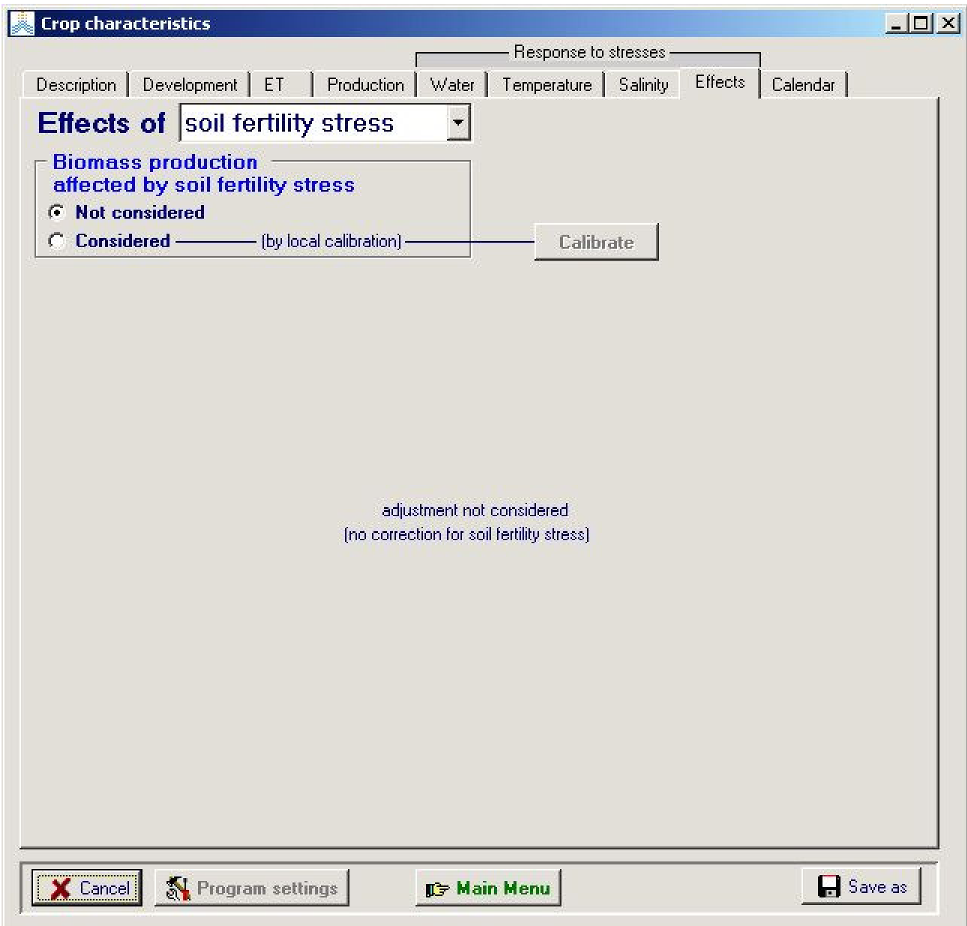


Figure 2.9h2 – Display in the ***Crop characteristics*** menu of a crop for which the effect of soil fertility stress on biomass is not considered

By selecting 'Considered' on the tab sheet in the ***Crop characteristics*** menu (Fig. 2.9h2), AquaCrop will display the ***Calibration soil fertility stress*** menu in which the calibration can be started (Fig. 2.9h3).

In the ‘Field observations’ tab sheet of the ***Calibration soil fertility stress*** menu (Fig. 2.9h3), the user specifies (with reference to Fig. 2.9h1) 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});
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’).

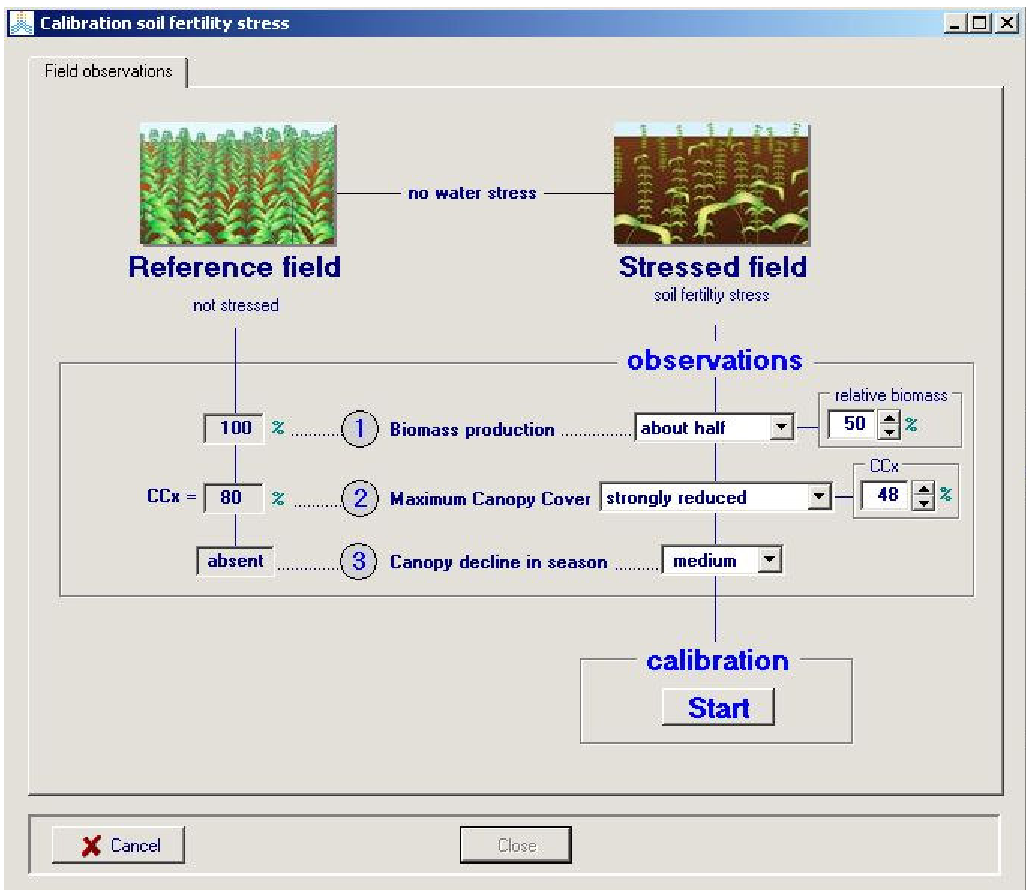


Figure 2.9h3 – Specification of field observations from the ‘Stressed field’ in the ***Calibration soil fertility stress*** menu

By clicking on the **<Start>** button in the ‘Field observations’ tab sheet of the ***Calibration soil fertility stress*** menu (Fig. 2.9h3), 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. 2.9h3), 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. 2.9h4).

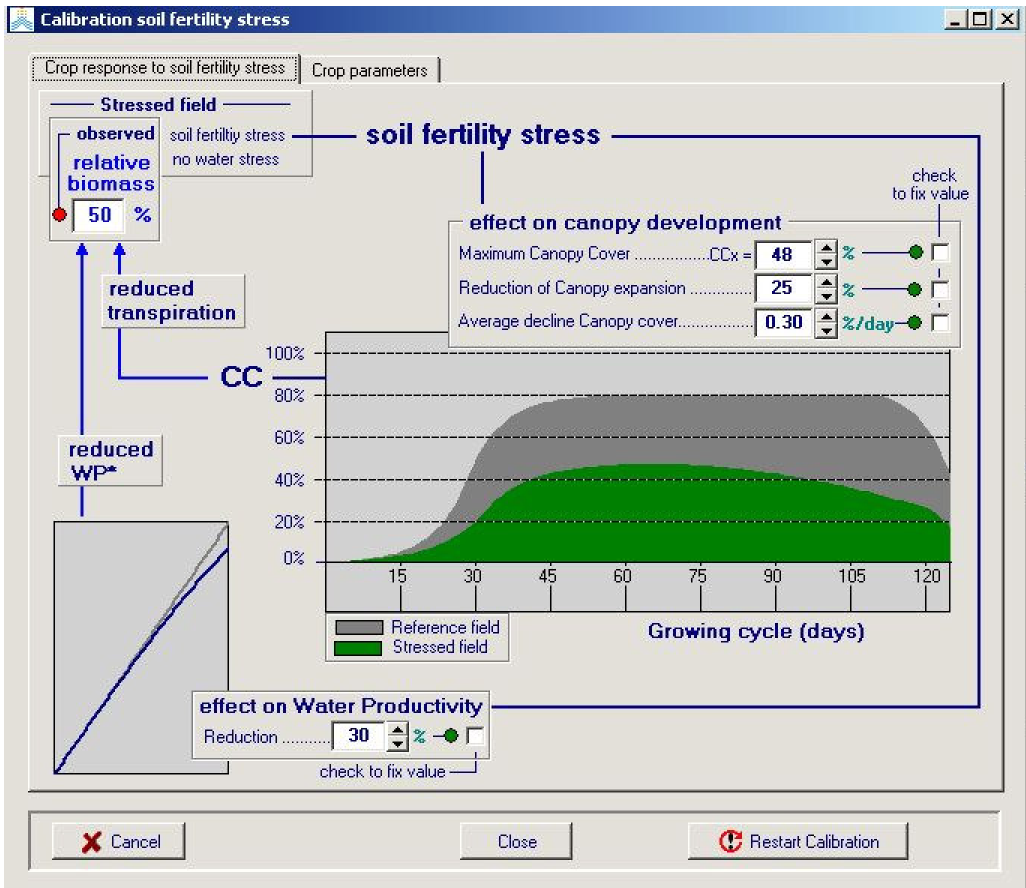


Figure 2.9h4 – The simulated relative biomass (similar as observed on the stressed field) obtained by considering the effect of soil fertility stress on (i) canopy development (maximum canopy cover, canopy expansion and canopy decline) and (ii) biomass Water Productivity (WP*), as displayed in the tab sheet 'Crop response to soil fertility stress' of the ***Calibration soil fertility stress*** menu.

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. 2.9h5).

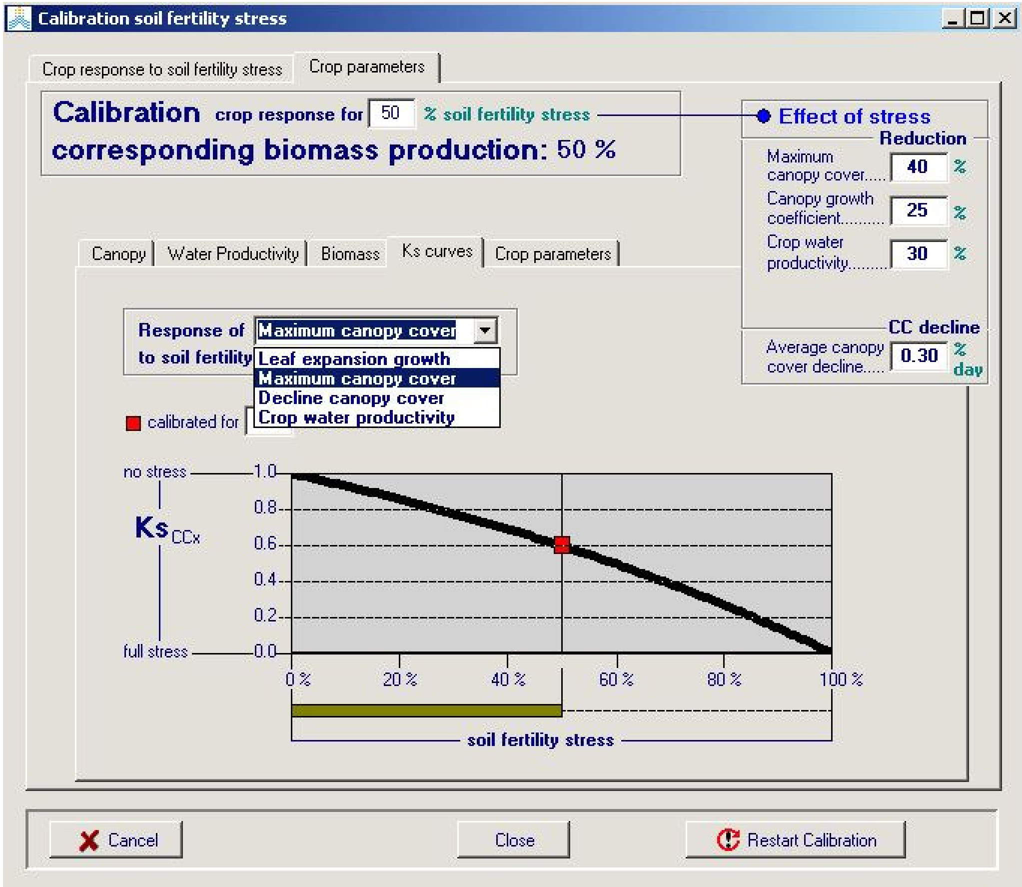


Figure 2.9h5 – The Ks curve for Maximum canopy cover as displayed in the tab-sheet 'Ks-curves' of the ***Calibration soil fertility stress*** menu

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

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

$$stress = 100\,(1 - B_{rel}) \qquad \text{(Eq. 2.9)}$$

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. 2.9h5).

Once a curve is calibrated, the Ks corresponding to other soil fertility/salinity stresses can be obtained from the curves. With reference to Fig. 2.9h5, 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. 2.9h4): (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. 2.9h4.

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. 2.9h3).

- **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. 2.9h6). 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. 2.9h5); 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. 2.9h5). 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. 2.9h6).

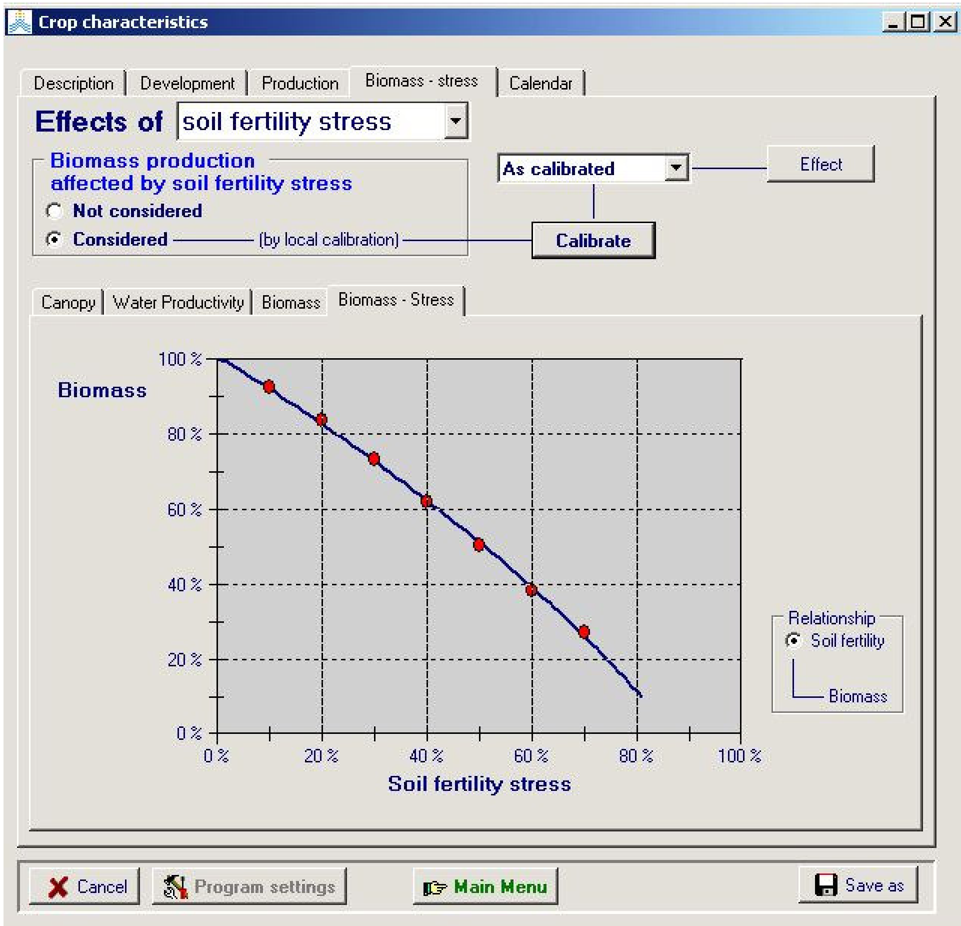


Figure 2.9h6 – Display of the relationship between Biomass and soil fertility stress in the 'Biomass-Stress' tab-sheet of the ***Crop characteristics*** menu.

<u>Fine tuning</u>

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. 2.9h4 and 2.9h5).

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. 2.9h3).

2.9.9 Soil salinity stress

- **Ks curve**

Biomass production might be affected by soil salinity stress. To describe this process a soil salinity stress coefficient (Ks_{salt}) is considered which varies between 0 (full effect of soil salinity stress) and 1 (no effect). The average electrical conductivity of the saturation soil-paste extract (ECe) from the root zone is the indicator for soil salinity stress.

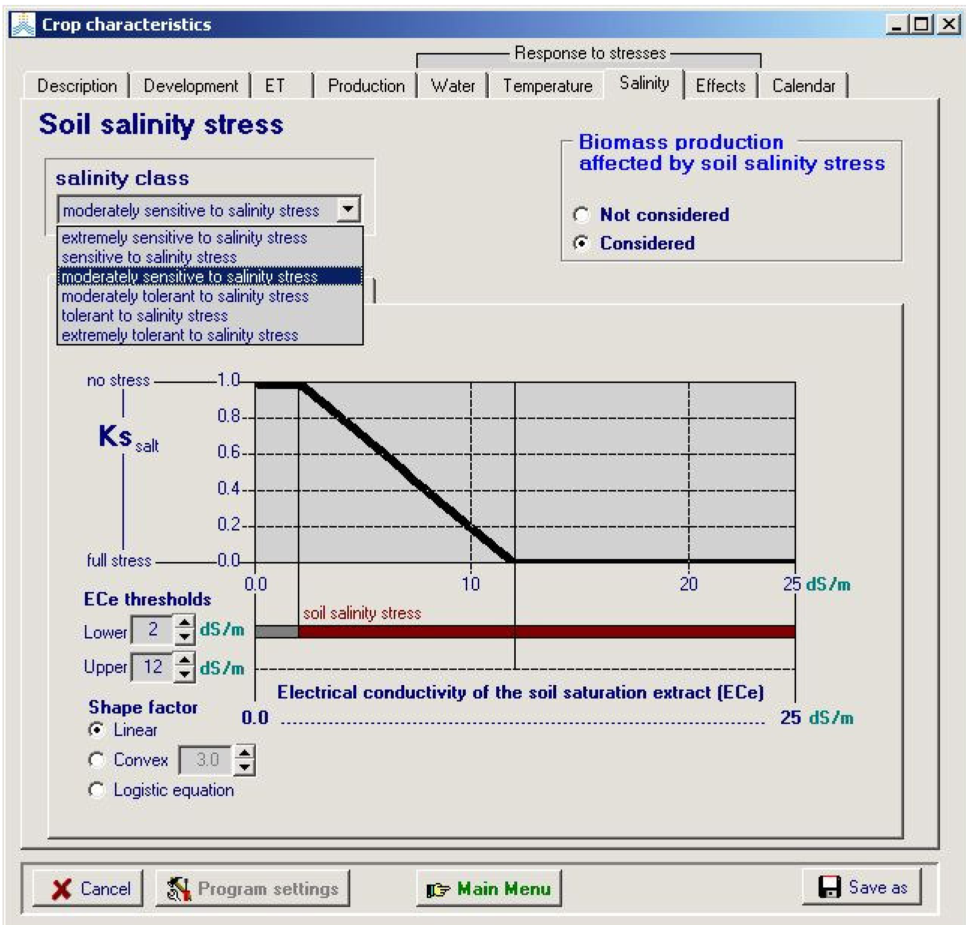


Figure 2.9i1
Specification of the upper and lower thresholds and the shape of the Ks_{salt} curve for the effect of soil salinity stress on biomass production

Thresholds: The user specifies the effect of soil salinity stress by selecting a sensitivity class or by specifying values for an upper and lower threshold for soil salinity in the root zone (Tab. 2.9i; Fig. 2.9i1). The thresholds are crop specific (see Annex III) and are given by electrical conductivities of saturated soil-paste extracts (ECe) and expressed in deciSiemens per meter (dS/m). 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 2.9i
Classes and corresponding default values for the lower (ECe_n) and upper (ECe_x) threshold of soil salinity stress

Class Sensitivity to water 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

Shape of Ks curve: Between the upper and lower threshold of the saturated soil-paste extracts, the shape of the Ks curve determines the magnitude of the effect of soil salinity stress on the biomass production. The shape can be linear, convex or logistic (Fig. 2.9i2). For the convex shapes, the shape factor can range from +6 (strongly convex) to 0 (linear).

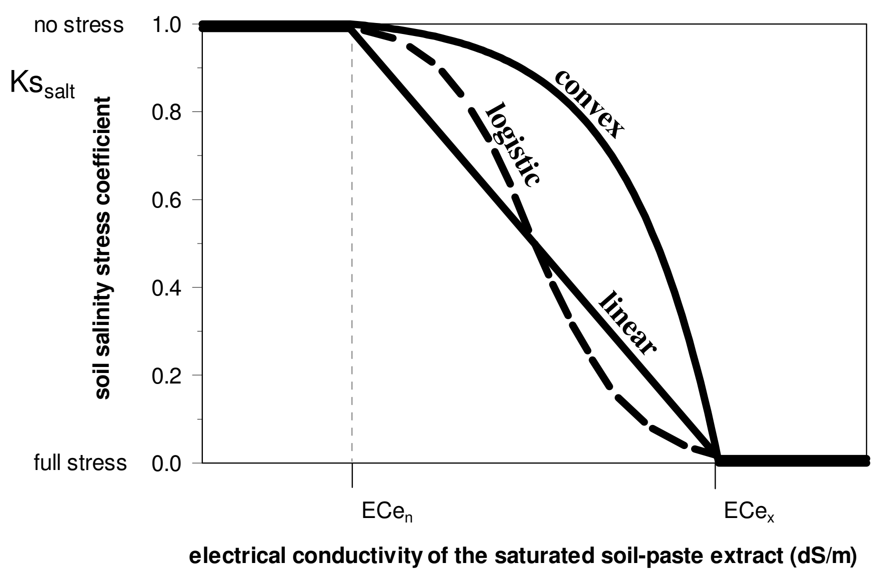


Figure 2.9i2
Linear, convex and logistic shapes of the Ks curve

- **Display of the effects of soil salinity stress**

Soil salinity stress can reduce canopy expansion and the maximum canopy cover that can be reached (CC_x). In addition, under long-term stress CC normally undergoes steady decline once the adjusted CC_x is reached at mid season. Further-on soil salinity stress induces stomatal closure.

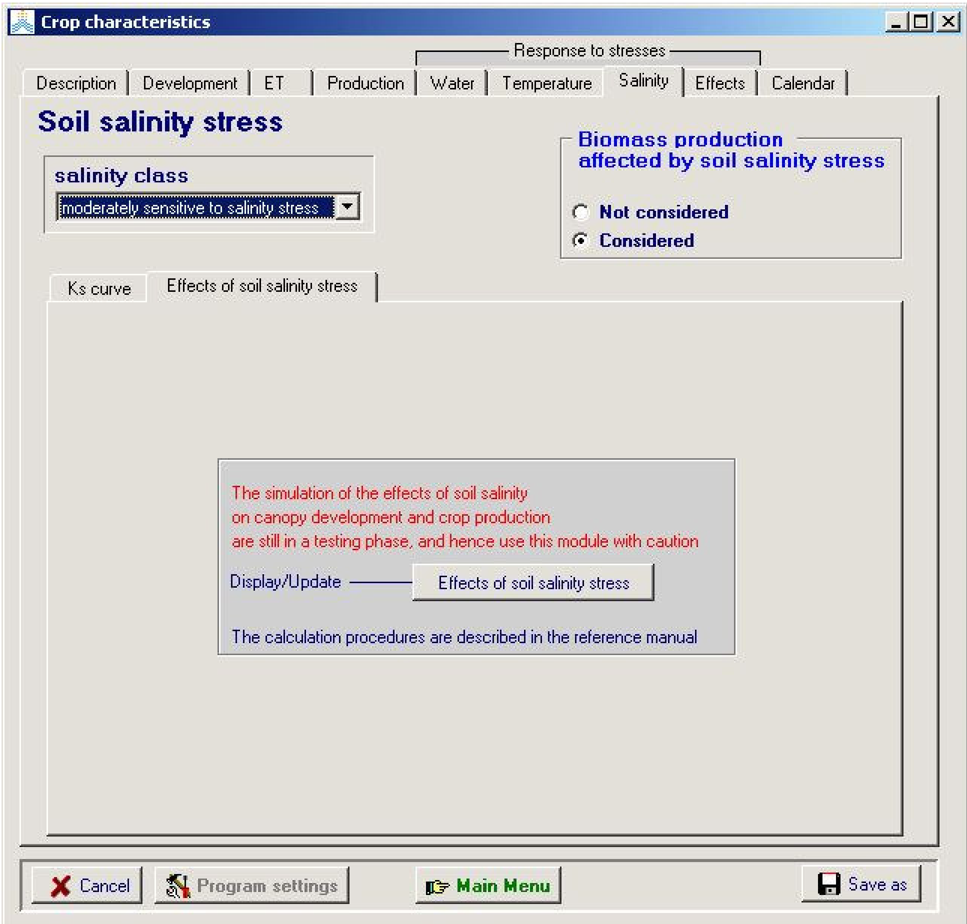


Figure 2.9i3
Information concerning the effect of soil salinity stress

As mentioned in the 'effects of soil salinity stress' tab sheet (Fig. 2.9i3), the simulation of the effects of soil salinity on canopy development and crop production are still in a testing phase. By clicking on the **<Effects of soil salinity stress>** button, the effects of soil salinity are displayed (Fig. 2.10j1). In this tab sheet the user can see the effect of various stress levels (if the crop response is calibrated for soil salinity stress), and/or calibrate the crop response for the stress.

- **Calibration of the crop response**

Calibration of the crop response to soil salinity stress is done in the ***Crop characteristic*** menu (See 2.9.10 Calibration for soil salinity stress).

2.9.10 Calibration for soil salinity stress

- **Crop response to soil salinity stress**

Soil salinity stress reduces biomass production (B). The electrical conductivity of the saturated soil-paste extract (ECe) from the root zone determines the value of the soil salinity stress coefficient, Ks_{salt} (Fig. 2.9i1). As explained in Chapter 3 (3.15 Simulation of the effect of soil salinity stress), Ks_{salt} expresses the degree of soil salinity stress and hence determines the total reduction in biomass production. The reduction in biomass production is the result of stomatal closure and a poor canopy development (slow canopy expansion, poor canopy cover and canopy decline during the crop cycle). Although the total reduction in biomass (given by Ks_{salt}) and the causes for its reduction are known, the individual effect of salinity stress on each of the processes is not yet sufficient documented for the simulation in AquaCrop.

In absence of extensive testing, the reduction in biomass production due to soil salinity stress is described in a similar way as the effect of soil fertility stress on B. The calibration for soil salinity stress is hence identical as the calibration for soil fertility stress (2.9.8 Calibration for soil fertility stress), and requires the access to observed green Canopy Cover (CC) and biomass production (B) in two well watered fields: one with and the other without soil salinity stress. The field with no stress is regarded as the 'Reference field', while the field with soil salinity stress 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 soil salinity stress (Fig. 2.9j1).

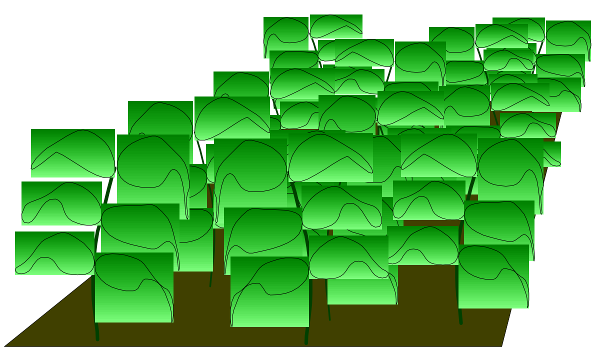
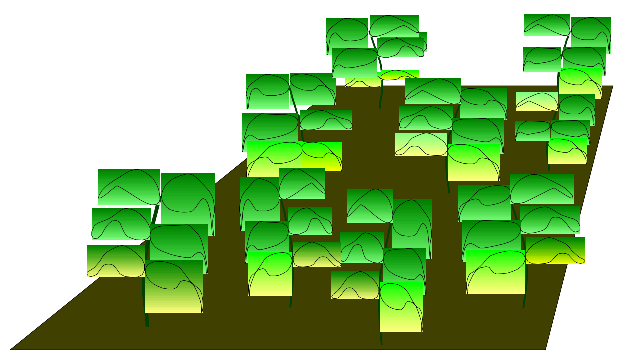
	
Reference field - well watered field - no soil salinity stress	**Stressed field** - well watered field - soil salinity stress
Observations: B_{ref} and CC_{ref}	**Observations:** B_{stress} and CC_{stress}

Figure 2.9j1 – The calibration of crop response to soil salinity stress is based on field observations of differences in Biomass production (B) and green Canopy Cover (CC) between a Reference and Stressed field.

The observed reduction in biomass is the result of an integration of effects of the stress on several processes. As explained in section 2.9.8 (Calibration for soil fertility stress) the soil fertility stress affects green canopy development (CC) and hence indirectly crop transpiration (Tr), and the biomass water productivity (WP*). The soil salinity stress affects in a similar way the green canopy development (CC) and hence indirectly crop transpiration (Tr), but it also affects crop transpiration directly by inducing stomatal closure. In Table 2.9j the stress coefficients (Ks) and decline coefficient (f) used for the simulation of the crop response to soil salinity stress are listed.

Table 2.9j – Stress coefficients for simulating crop response to soil salinity 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 salinity stress		
$Ks_{sto,salt}$	Stress coefficient for stomatal closure	Crop transpiration (Tr)

In absence of extensive testing, the effects of soil fertility stress and soil salinity stress on canopy development are assumed to be identical. Hence $Ks_{exp,f}$, Ks_{CCx} and $f_{CDecline}$ are used for simulating the effect of both soil fertility and soil salinity stress.

- **The effect of stress on biomass is not yet considered**

The calibration process

By selecting ‘Considered’ on the ‘Effects’ tab sheet in the ***Crop characteristics*** menu (Fig. 2.9j2), AquaCrop will display the ***Calibration soil salinity stress*** menu in which the calibration can be started (Fig. 2.9j3).

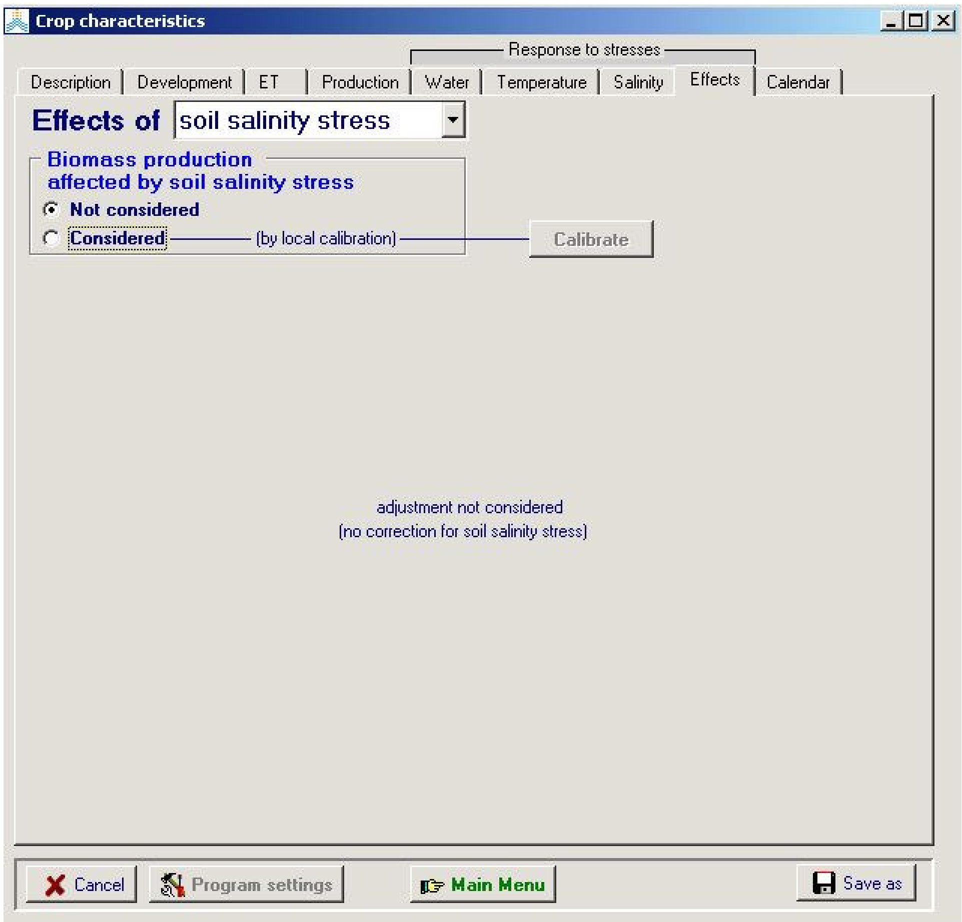


Figure 2.9j2 – Display in the ***Crop characteristics*** menu of a crop for which the effect of soil salinity stress on biomass is not considered

In the ‘Field observations’ tab sheet of the ***Calibration soil salinity stress*** menu (Fig. 2.9j3), the user specifies (with reference to Fig. 2.9j1) 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});

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').

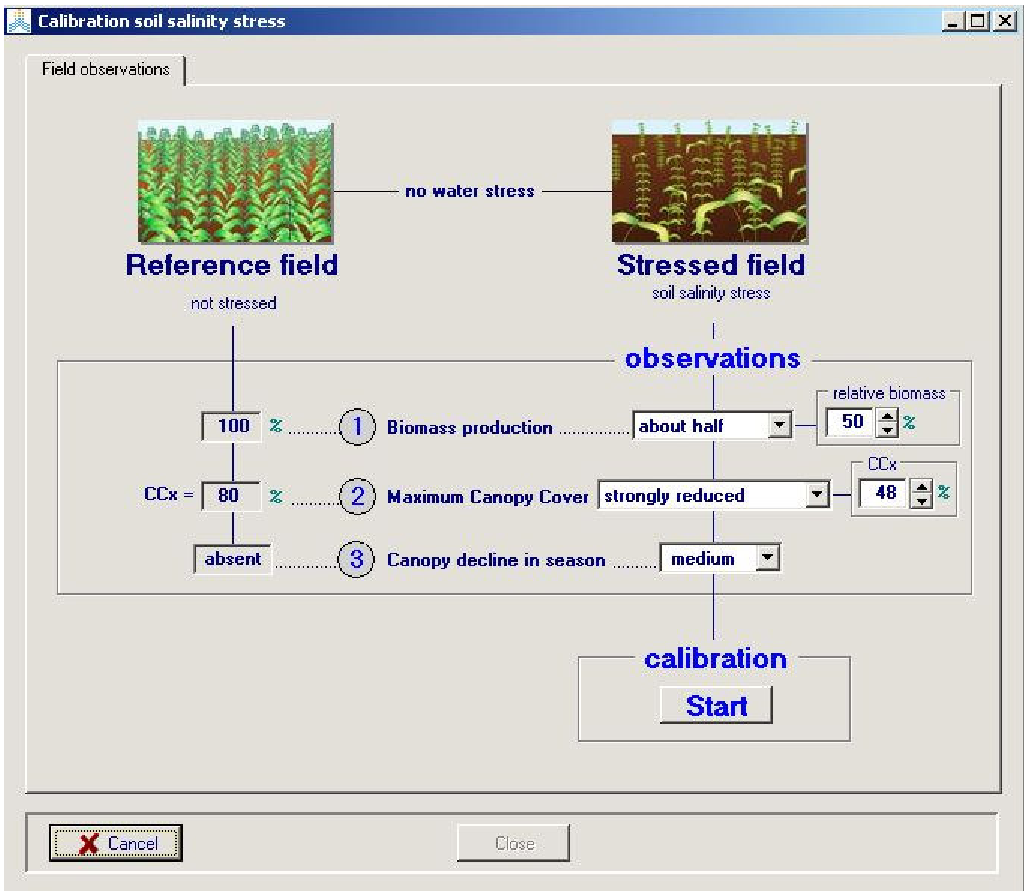


Figure 2.9j3 – Specification of field observations from the 'Stressed field' in the ***Calibration soil salinity stress*** menu

By clicking on the **<Start>** button in the 'Field observations' tab sheet of the ***Calibration soil salinity stress*** menu (Fig. 2.9j3), AquaCrop selects values for the stress coefficients ($Ks_{exp,f}$, Ks_{CCx}, $Ks_{sto,salt}$, $f_{CDecline}$) and alters as such the simulated green canopy cover (CC) and crop transpiration (Tr) for the Stressed field.

By trying different values for the various stress coefficients, and by respecting the specified observations (Fig. 2.9j3), AquaCrop calculates for each set of stress coefficients, the corresponding CC_{stress}, crop transpiration (Tr) 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 tab sheet ‘Crop response to soil salinity stress’ (Fig. 2.9j4). The effect of soil fertility and soil salinity stress on canopy development (CCx, CGC, and canopy decline) is assumed to be identical. But soil fertility stress differs from soil salinity stress because soil fertility stress results in a reduced biomass water production (Fig. 2.9h4) while soil salinity stress induces stomatal closure (Fig. 2.9j4).

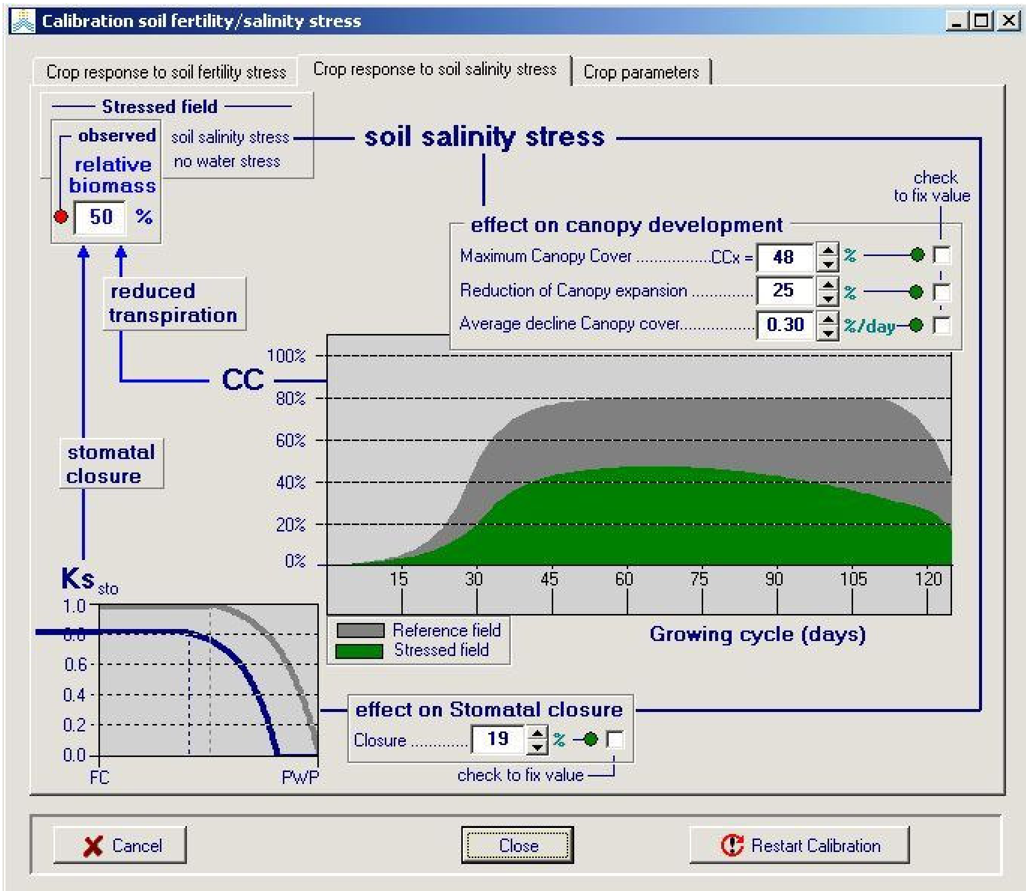


Figure 2.9j4 – The simulated relative biomass (similar as observed in the stressed field) obtained by considering the effect of soil salinity stress on (i) canopy development (CCx, CGC and canopy decline) and (ii) stomatal closure (Ks_{sto}), as displayed in the tab sheet ‘Crop response to soil salinity stress’ of the ***Calibration soil salinity stress*** menu.

In the ‘Crop parameters’ tab sheet of the ***Calibration soil salinity stress*** menu, the reduction in Canopy development and in crop Transpiration 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.

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

$$stress = 100\,(1 - B_{rel}) \qquad \text{(Eq. 2.9)}$$

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, Tr, and canopy decline), the corresponding values for Ks and f are obtained for the defined stress level.

Once a curve is calibrated, the Ks corresponding to other soil salinity stresses can be obtained from the curves.

Fine tuning

The user can fine tune the calibration by altering in the ***Calibration soil salinity stress*** menu (Fig. 2.9j4): (i) the maximum canopy cover (CCx), (ii) the reduction of canopy expansion, (iii) the average decline of the Canopy cover, or (iv) the effect on stomatal closure. 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. 2.9j4).

By clicking on the **<Restart calibration>** button key, the user returns to the 'Field observation' tab sheet (Fig. 2.9j3).

- **The effect of stress on biomass is considered**

Relationship between Biomass and soil salinity stress

For crop files where the effect of soil salinity stress on biomass is considered, AquaCrop displays in the ***Crop characteristics*** menu the effect on canopy development, crop transpiration, and biomass production for several stress levels (mild up to severe stress). In the menu the relationship between Biomass and soil salinity stress is displayed as well (Fig. 2.9j5). The relationships are obtained by (i) considering for various stress levels the individual effect on CCx, CGC, canopy decline, and crop transpiration (Tr), and (ii) calculating the corresponding canopy development, crop transpiration and reduction in relative biomass production by assuming no water stress. The effect of the various considered stress levels on CCx, on CGC, on canopy decline, and on Tr are described in the individual calibrated Ks and reduction curves. Since the shapes of the Ks curve are not identical, the B-stress relationship is not linear and differ also between soil fertility and soil salinity stress (Fig. 2.9j5).

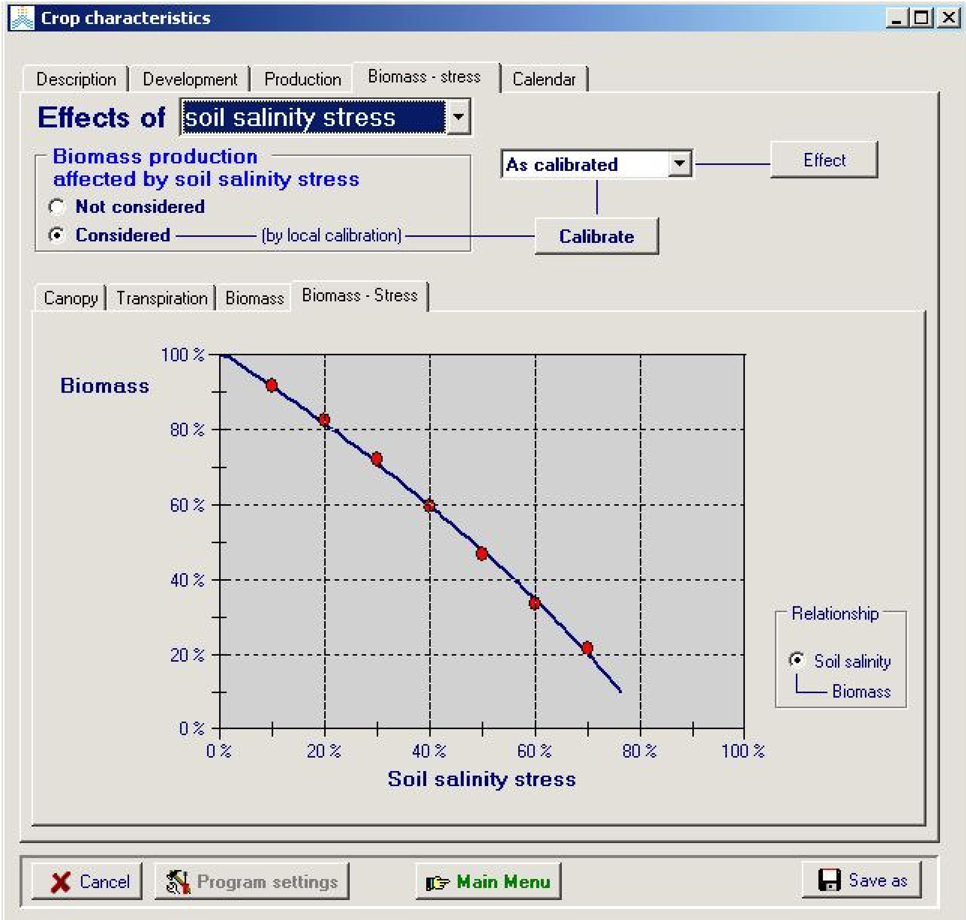


Figure 2.9j5 – Display of the relationship between Biomass and soil salinity stress in the Biomass-Stress tab-sheet of the ***Crop characteristics*** menu.

Fine tuning

For crop files where the effect of soil salinity 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 salinity stress*** menu (Fig. 2.9j4).

By clicking on the **<Restart calibration>** button key in the control panel of the ***Calibration soil salinity stress*** menu, the user returns to the 'Field observation' tab sheet (Fig. 2.9j3).

2.9.11 Calendar

An overview of the calendar of the growing period is displayed in the Calendar folder of the ***Crop characteristics*** menu (Fig. 2.9k).

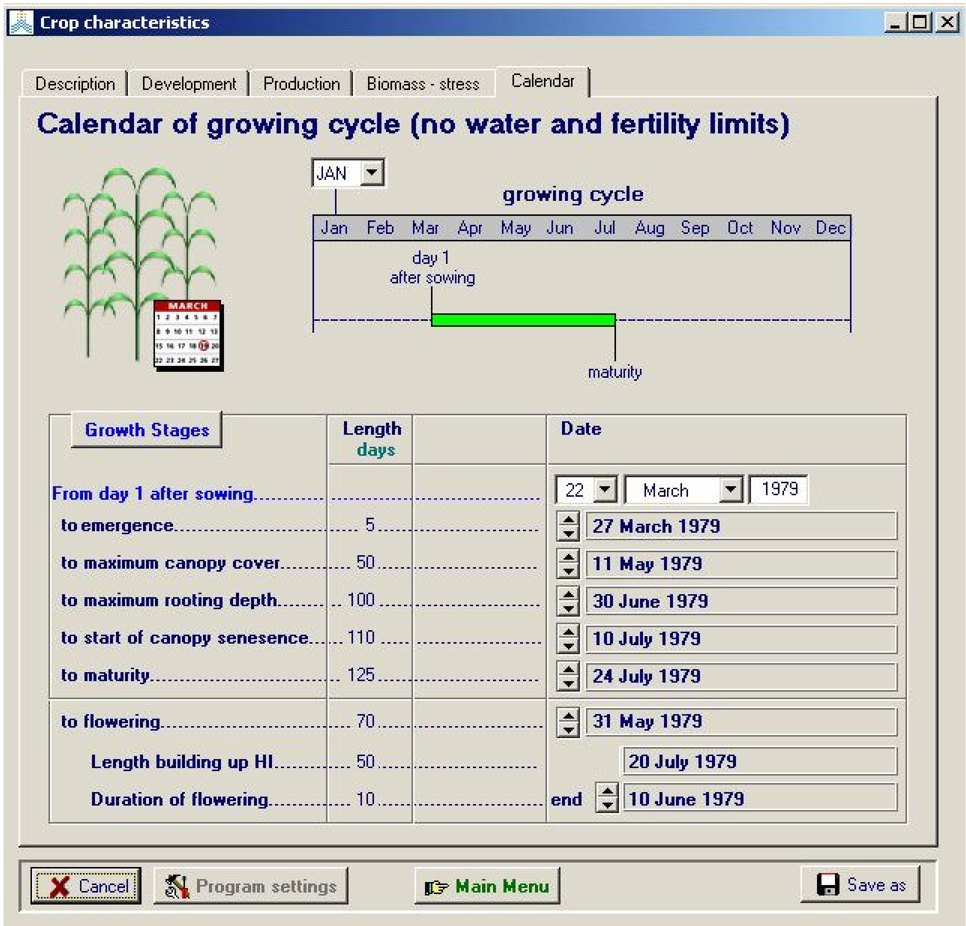


Figure 2.9k

Crop calendar 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.

2.9.12 Program settings

From the ***Crop characteristics*** menu the user has access to the program settings listed in Table 2.9l. The effect of the settings on soil evaporation, crop transpiration, canopy expansion and decline, and soil water stress are explained in the relevant sections of Chapter 3 (Calculation procedures).

Table 2.9l
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
-	▪ Soil salinity stress: Thresholds for water stress for stomatal closure	affected by soil salinity

2.10 Start of the growing cycle

The start of the growing cycle is specified in the ***Main menu*** (Fig. 2.10a) by
- specifying the date, or
- generating an onset based on rainfall or air temperature.

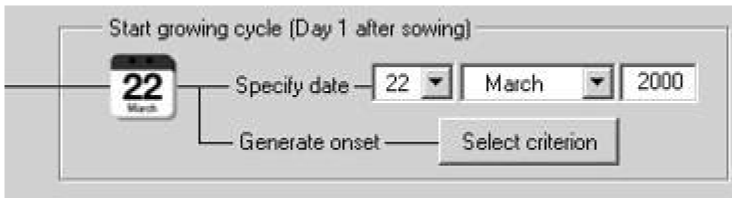


Figure 2.10a
Panel in *Main menu* where the start of the growing cycle is specified

2.10.1 Specified date

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

2.10.2 Generated onset

- **Onset generated based on rainfall**

In rainfed cropping, sowing or planting is typically determined by rainfall events. By clicking on the **<Select criterion>** commanding the ***Main menu***, the ***Onset based on rainfall*** menu is displayed (Fig. 2.10b). By selecting one or another criterion, the start of the growing cycle is determined by appraising the rainfall data specified in the selected Rain data file. By specifying the first and last day in a 'Search window', only rainfall within the specified window is evaluated. The following criteria can be selected to determine the onset of the growing cycle:
- ***cumulative rainfall*** since the start of the search period is equal to or exceeds the preset value;
- observed ***rainfall during a number of successive days*** is equal to or exceeds the preset value;
- ***10-day rainfall*** is equal to or exceeds the preset value;
- ***10-day rainfall exceeds*** the preset ***fraction of the 10-day ETo***.

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

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

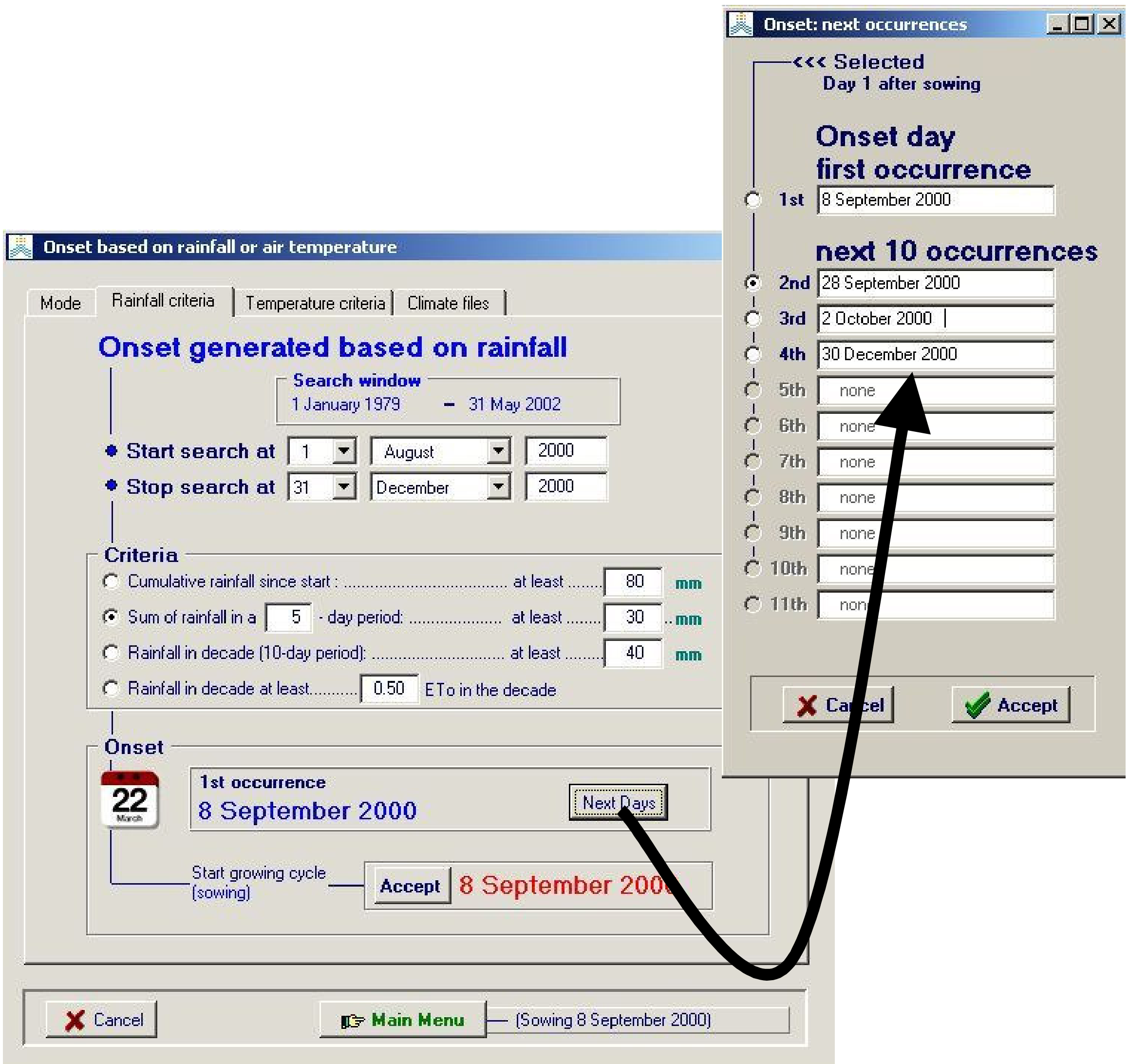


Figure 2.10b
Onset based on rainfall **menu where the onset of the growing period is determined by the exceedance of 25 mm of rainfall in a period of 5 successive days, counting from 1 August 2000 (start of the search window)**

▪ **Onset generated based on air temperature**

Climate change is likely to increase the air temperature in many regions. To estimate the planting dates for future years for spring crops in cool climates, AquaCrop offers the possibility to generate the sowing/planting date based on air temperature. By selecting one or another criterion, the likely planting/sowing date is generated by appraising the air temperature data specified in the selected 'Air temperature' data file. By specifying the first and last day in a 'Search window', only temperature data within the specified window is evaluated (Fig. 2.10c).

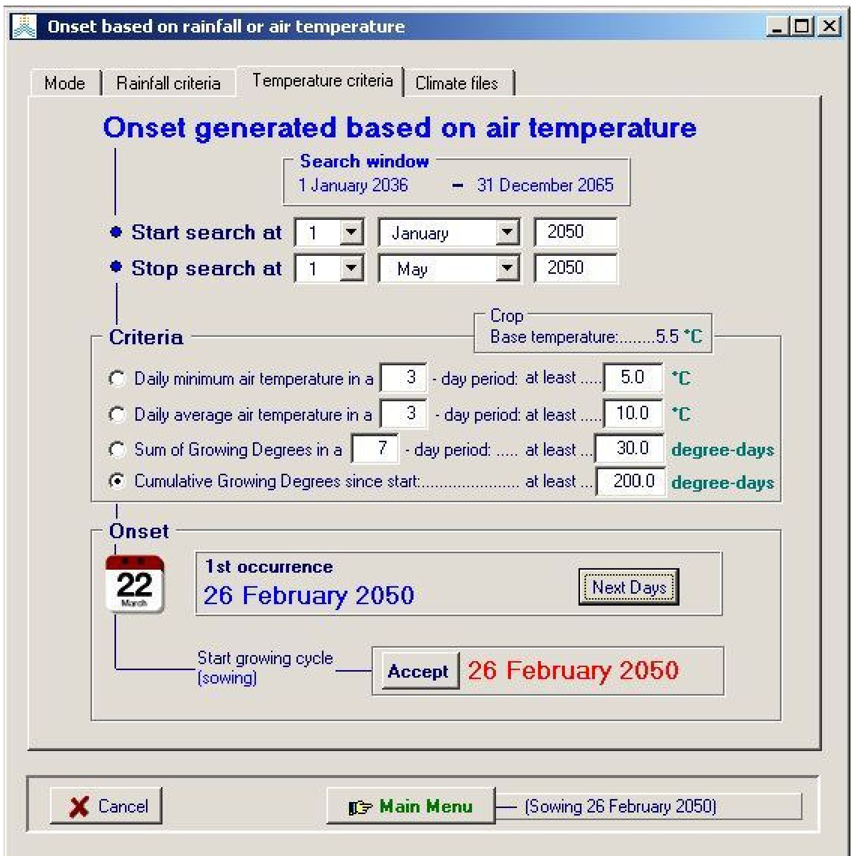


Figure 2.10c – Selection of a temperature criterium in the ***Onset based on rainfall or air temperature*** menu

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

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

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

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

2.11 Irrigation management

The selected irrigation management can be displayed in the ***Display of irrigation management*** menu and updated in the ***Irrigation management*** menu (Fig. 2.11a). Various irrigation modes can be considered in AquaCrop. One opts for (i) rainfed cropping (no irrigation in season), (ii) the determination of Net irrigation water requirement, (iii) an irrigation schedule by specifying the events or (iv) the generation of an irrigation schedule by specifying a time and depth criterion.

Figure 2.11a
The selection of the mode in the *Irrigation management* menu

2.11.1 No irrigation (rainfed cropping)

When selecting this option, no irrigations will be generated when running a simulation.

2.11.2 Determination of net irrigation water requirement

When selecting this option, AquaCrop will calculate during the simulation run the amount of water required to avoid crop water stress. When the root zone depletion exceeds a given 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. The threshold for the allowable root zone depletion can be adjusted.

The total amount of irrigation water required to keep the water content in the soil profile above the 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.

2.11.3 Irrigation schedule (specified events)

The user specifies the date, application depth and water quality for each irrigation event (Fig. 2.11b). 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 be added.

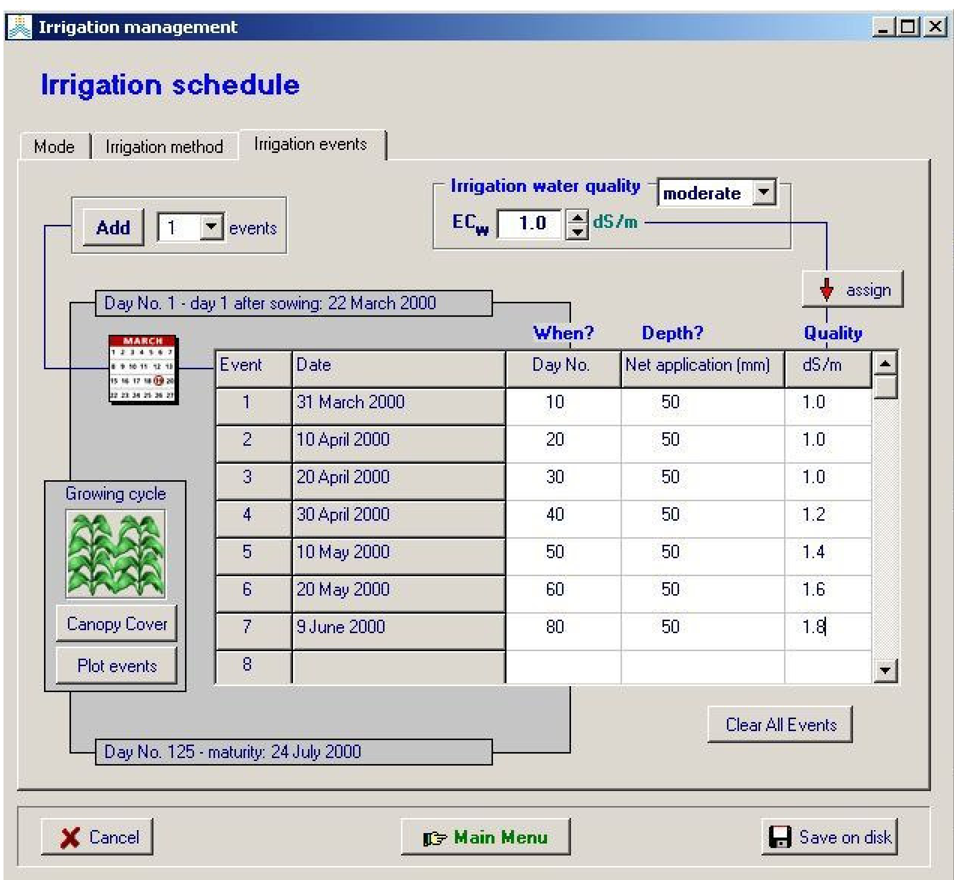


Figure 2.11b
Specification of the time, application depth and water quality for irrigation events

2.11.4 Generation of irrigation schedules

At run time irrigations can be generated by specifying a 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. After the selection of the criteria the values linked with the time, depth criteria and water quality have to be specified (Fig. 2.11c). 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 2.11d the generated irrigation schedules as defined in Figure 2.11c is presented.

The time and depth criteria with their corresponding parameters that need to be specified are listed in Tables 2.11a and 2.11b.

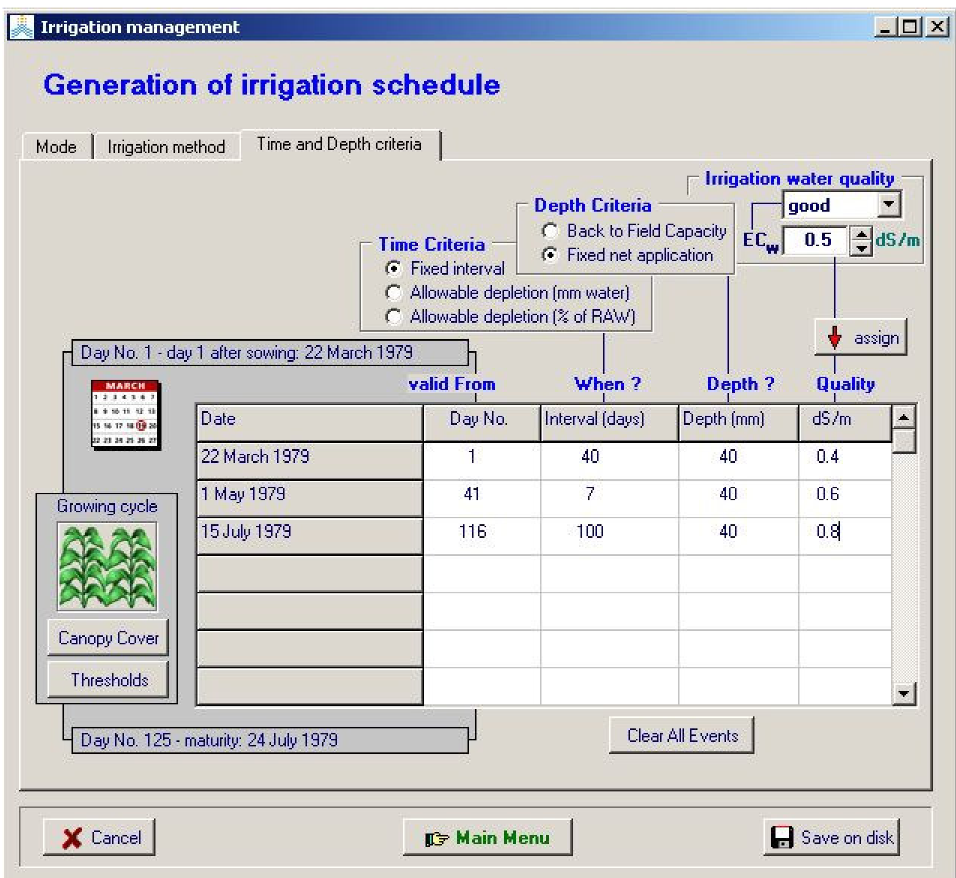


Figure 2.11c
Specifying an irrigation schedule
where the fixed irrigation interval (time criterion) varies over the season,
while the fixed irrigation application depth (depth criterion) remains constant,
and the irrigation water quality deteriorates

Figure 2.11d
Generated irrigation schedules as defined in Figure 2.11c.

Table 2.11a
Time criteria with corresponding parameter

Criterion	Parameter
Fixed interval (days)	Interval between irrigations (for example 10 days)
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 %)

Table 2.11b
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

2.11.5 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. 2.11c). The user can alter the value if more specific information is available from field observations.

Table 2.11c
Indicative values for the fraction 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

2.11.6 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 2.11b and 2.11c). 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 2.11d.

Table 2.11d
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 Field management

The selected field management can be displayed in the ***Display of field management*** menu and updated in the ***Field management*** menu (Fig. 2.12a). Options of soil fertility levels and practices that affect the soil water balance are specified in this menu.

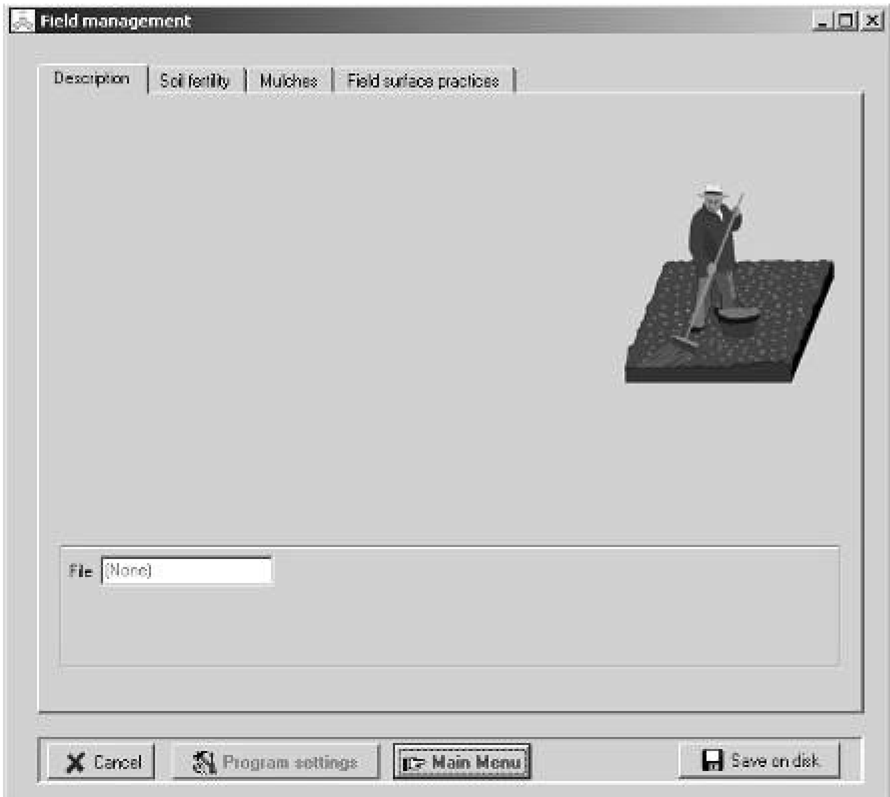


Figure 2.12a.
***Field management* menu**

2.12.1 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 biomass production that can be expected as a result of soil fertility stress is specified by:

- selecting one of the classes ranging from non limiting to very poor (Tab. 2.12a), or
- specifying directly the biomass production in the ***Field management*** menu.

The selected biomass production is the production that can be expected for the given climatic conditions in absence of any other stresses. The crop response on soil fertility will be different if additionally stresses occur during the season.

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. 2.12b).

Table 2.12a
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 %

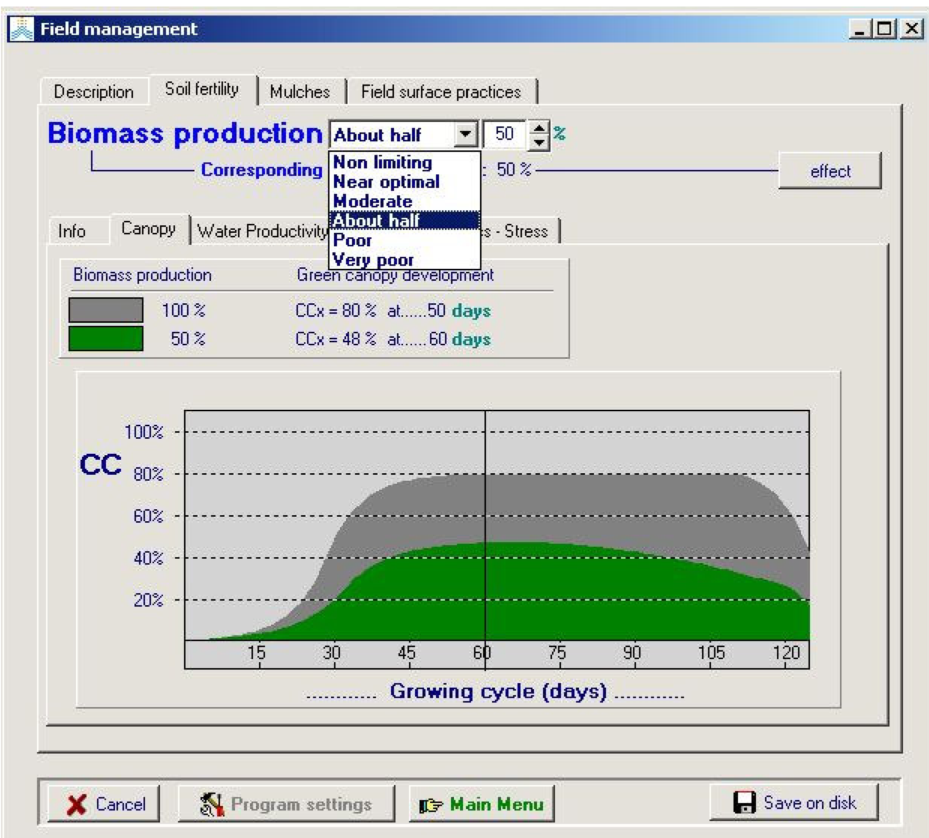


Figure 2.12b
Display of the crop response
for the selected biomass production in the *Field management* menu

The biomass – stress relationship (Fig. 2.12c), 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}, $f_{CDecline}$).

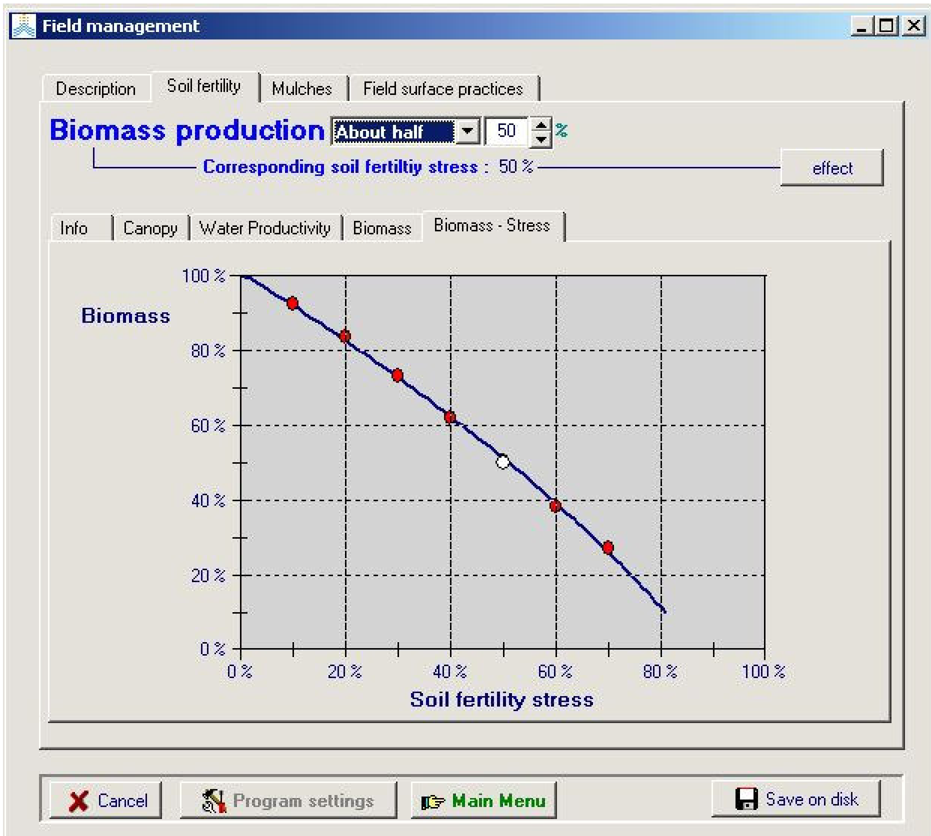


Figure 2.12c
Display of the calibrated Biomass - stress relationship
in the *Field management* menu

2.12.2 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. 2.12d).

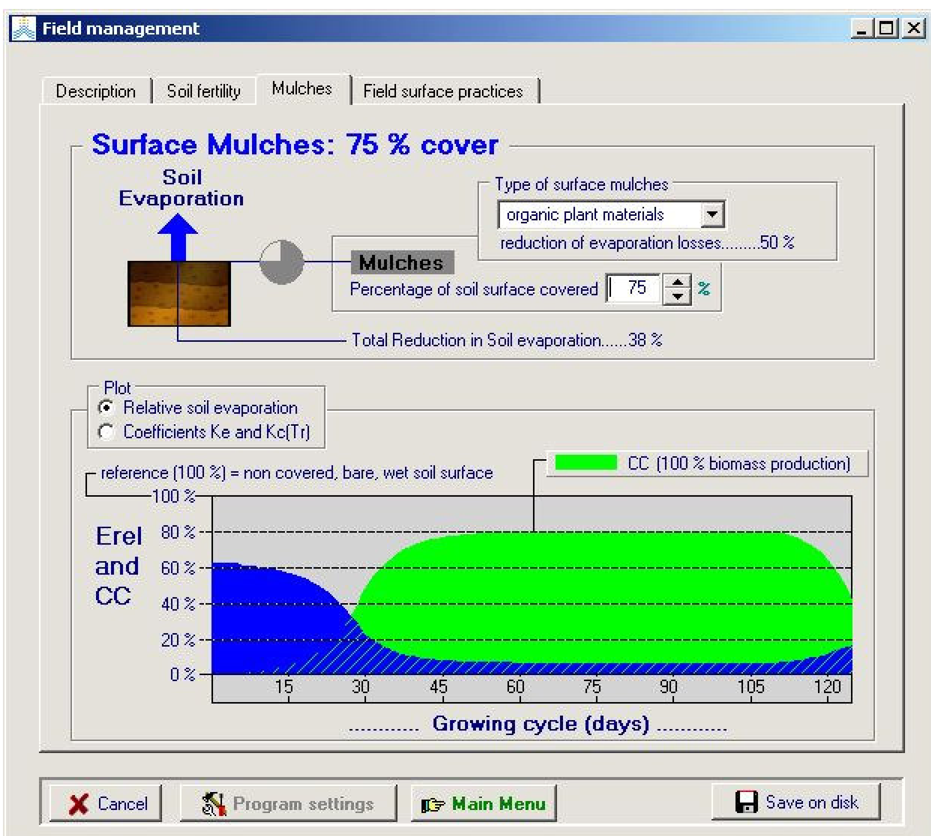


Figure 2.12d
Display of the effect of mulches on soil evaporation

2.12.3 Field surface practices

Field surface practices and soil bunds might prevent that part of intense rainfall or excessive irrigation will be lost as surface runoff:

- If ploughing or tillage practices, such as soil ridging or contours, eliminate run-off of rain water, the user can switch off the run-off procedure. However runoff will still occur if rain or irrigation events exceed the infiltration rate of the top soil layer. Only if the excess of rain or irrigation water can be stored on the field between soil bunds the surface runoff will be completely inhibited.
- Soil bunds are built to store water on the field (as is the case in rice paddy fields). When bunds are present, the user specifies the height of the bunds (Fig. 2.12e).

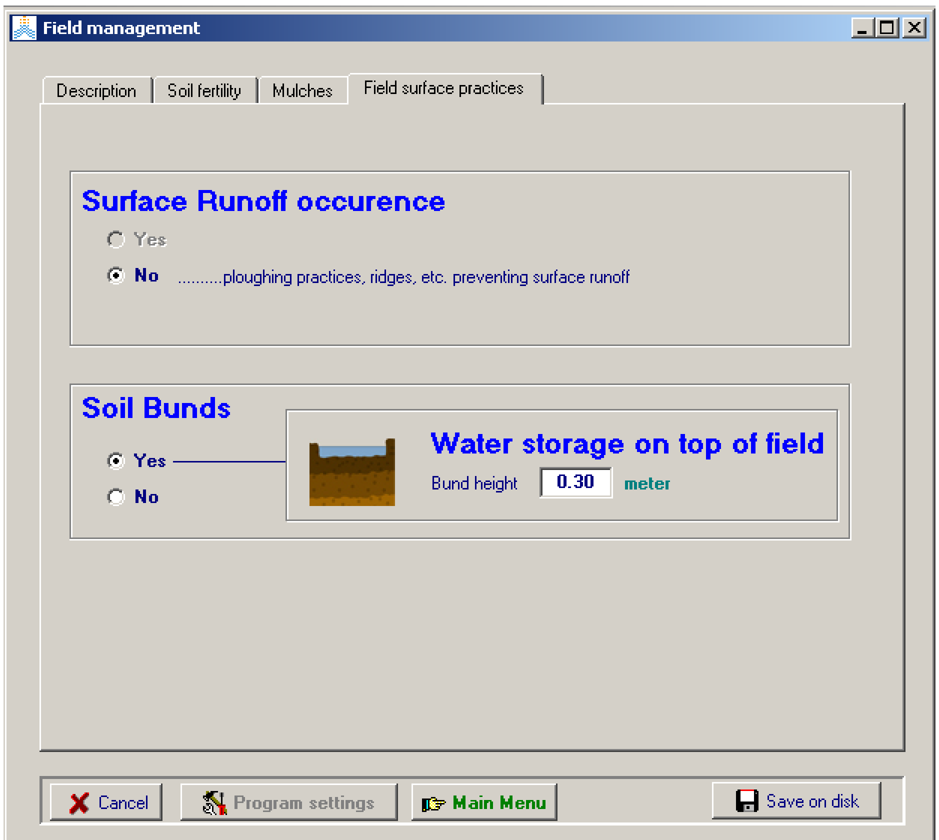


Figure 2.12e
Selection of soil bunds as field management

2.12.4 Program settings

From the ***Field management*** menu the user has access to the program setting of field parameters listed in Table 2.12b.

Table 2.12b
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 Soil profile characteristics

The selected characteristics of the various soil horizons and of the soil surface layer, the presence of a restrictive soil layer that might block the root zone expansion, and the maximum possible capillary rise are displayed in the ***Display of soil profile characteristics*** menu and updated in the ***Soil profile characteristics*** menu (Fig. 2.13a).

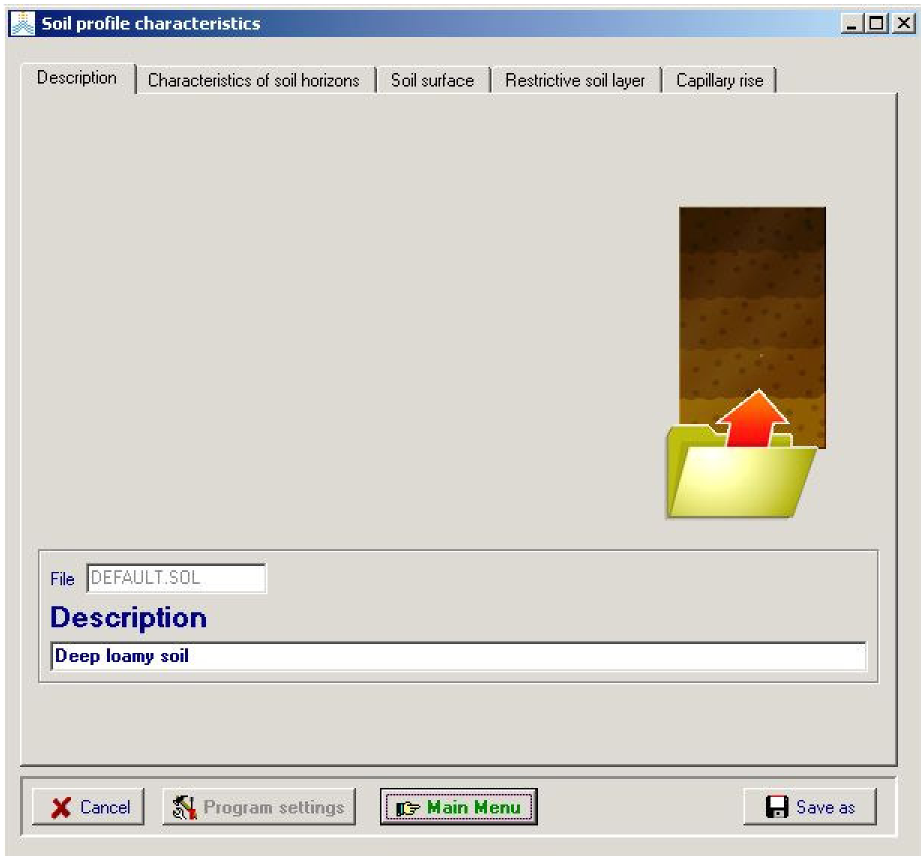


Figure 2.13a
***Soil profile characteristics* menu**

2.13.1 Soil horizons and their physical characteristics

The soil profile can be composed of up to five different horizons, each with their own physical characteristics. The soil data consist of the various soil horizons, their volumetric water content at saturation, field capacity, and permanent wilting point, and their hydraulic conductivity at soil saturation.

- **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 (K_{sat}).** 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.

▪ **Total Available soil Water (TAW) and drainage coefficient (tau).** From the specified hydraulic characteristics, AquaCrop determines for each soil horizon the total amount of soil water (TAW) that is available for crop transpiration and the drainage coefficient (tau). TAW is the amount of water held in the soil between field capacity and permanent wilting point. The dimensionless drainage coefficient is used for the simulation of the downward water movement in the soil profile (Chapter 3).

2.13.2 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.

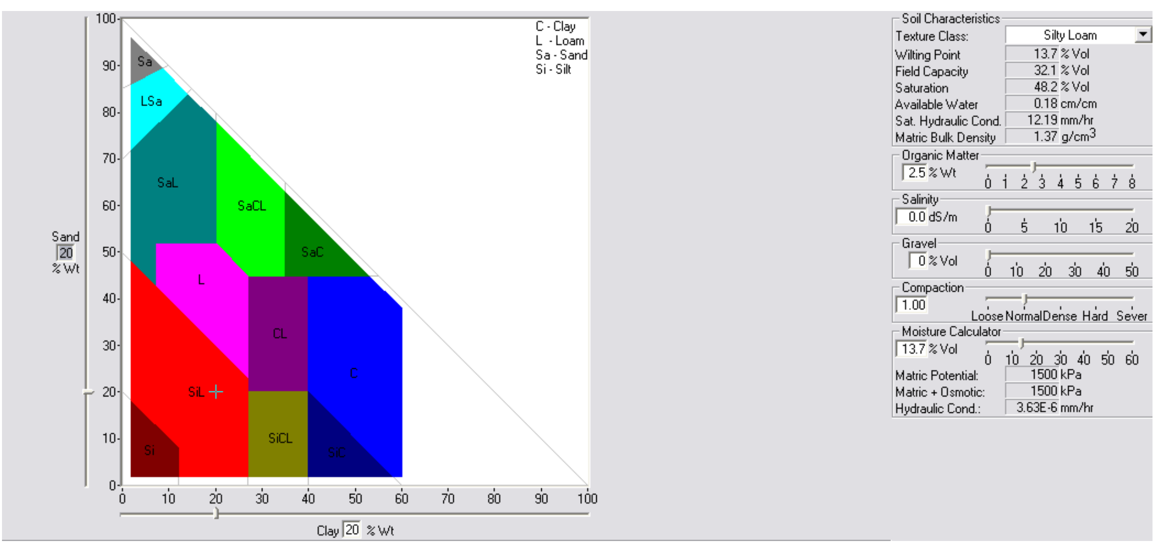
The user can make use of indicative values provided by AquaCrop for various soil textural classes (Tab. 2.13a), or import locally determined or derived data from soil texture with the help of pedo-transfer functions (Box 2.13). The values presented in Table 2.13a or derived with the help of pedo-transfer functions are only indicative values. They are not intended to replace measurements.

By selecting the **<Update list of soil type characteristics>** command in the ***Soil Profile characteristics*** menu, 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 AquaCrop directory.

Table 2.13a
Default soil physical characteristics for various soil types (listed in Soils.DIR)

Soil type	soil water content			Saturated hydraulic conductivity
	Saturation	Field Capacity	Permanent Wilting Point	
	vol %	vol %	vol %	mm/day
Sand	36	13	6	1500
Loamy sand	38	16	8	800
Sandy loam	41	22	10	500
Loam	46	31	15	250
Silt loam	46	33	13	150
Silt	43	33	9	50
Sandy clay loam	47	32	20	125
Clay loam	50	39	23	100
Silty clay loam	52	44	23	120
Sandy clay	50	39	27	75
Silty clay	54	50	32	15
Clay	55	54	39	2

Box 2.13
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

2.13.3 Characteristics of the soil surface layer

When specifying soil data for the top horizon, default values for the Curve Number (Tab. 2.13b) and the Readily Evaporable Water are derived and displayed (Fig. 2.13b).

- 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.

Table 2.13b
Default CN values for various saturated hydraulic conductivities of the top horizon

Saturated hydraulic conductivity (K_{sat}) mm/day	CN default value for AMC II
> 250	65
250 – 50	75
50 – 10	80
< 10	85

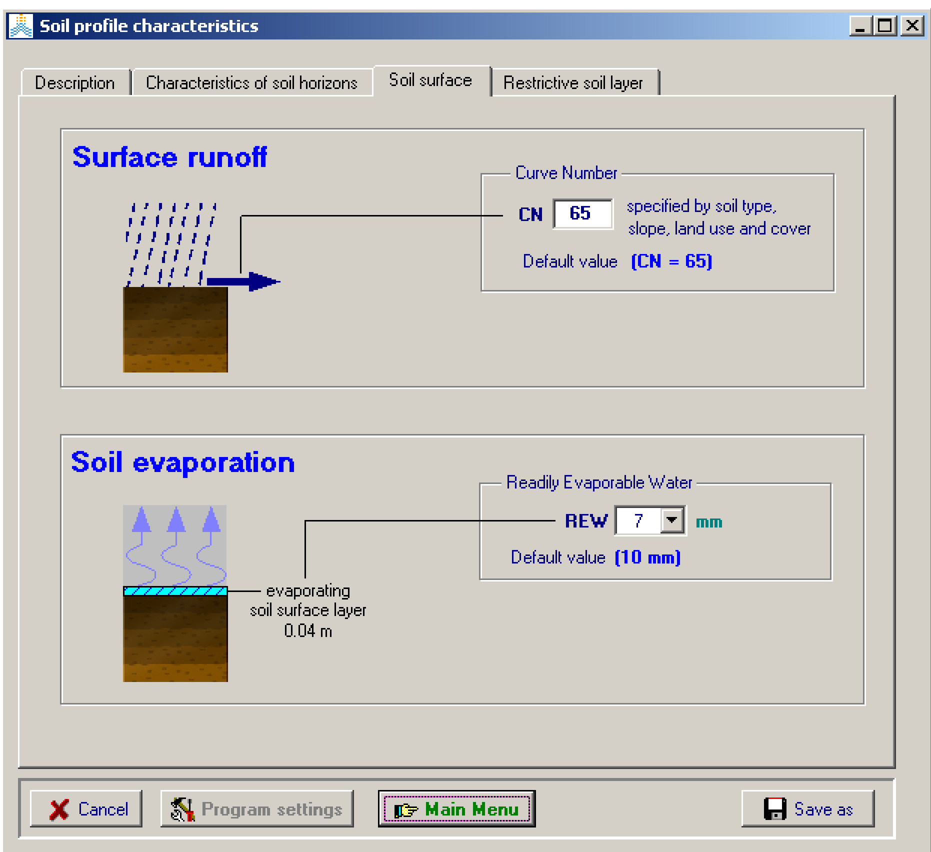


Figure 2.13b
Characteristics of the soil surface layer

2.13.4 Restrictive soil layer

If an impermeable soil layer blocks root development, the user specifies its depth (Fig. 2.13c). The root zone expansion is halted once the restrictive soil layer is reached (see 2.9.2 Development and 2.9.3 Evapotranspiration). If also water movement is hampered depends on the specified characteristics of the soil horizons below the restrictive layer (section 2.13.1)

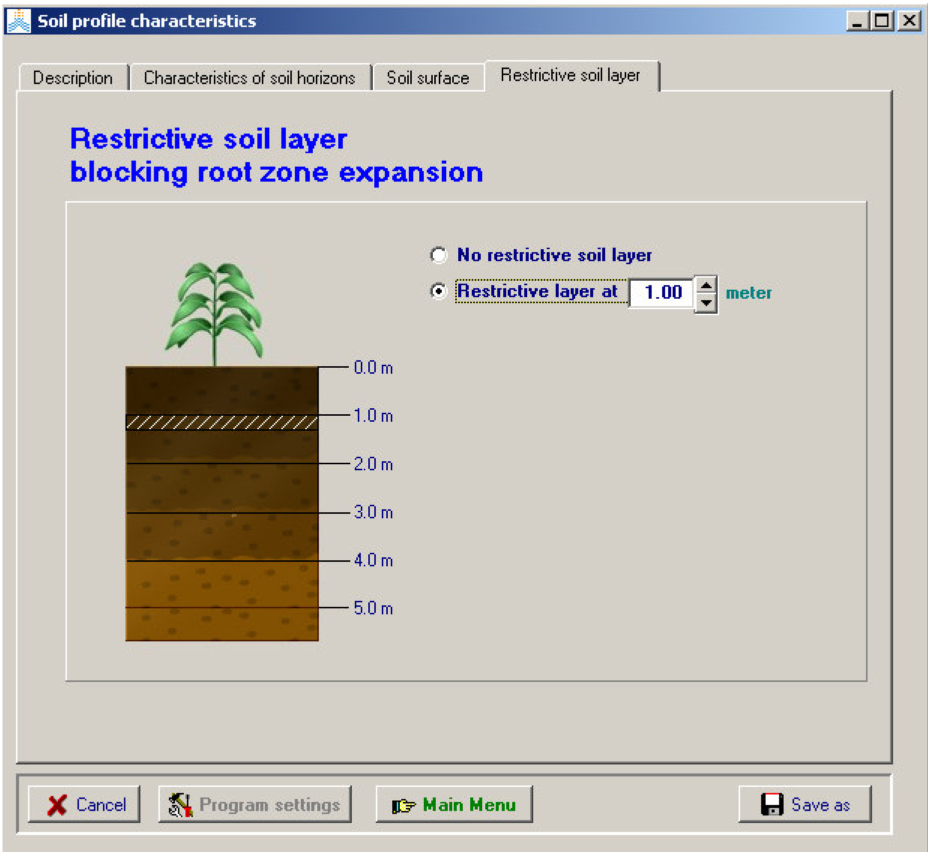


Figure 2.13c
Restriction soil layer blocking root zone expansion

2.13.5 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. 2.13d). If the water potential gradient in the soil profile is not strong enough, the capillary rise will be smaller than indicated (see Chapter 3).

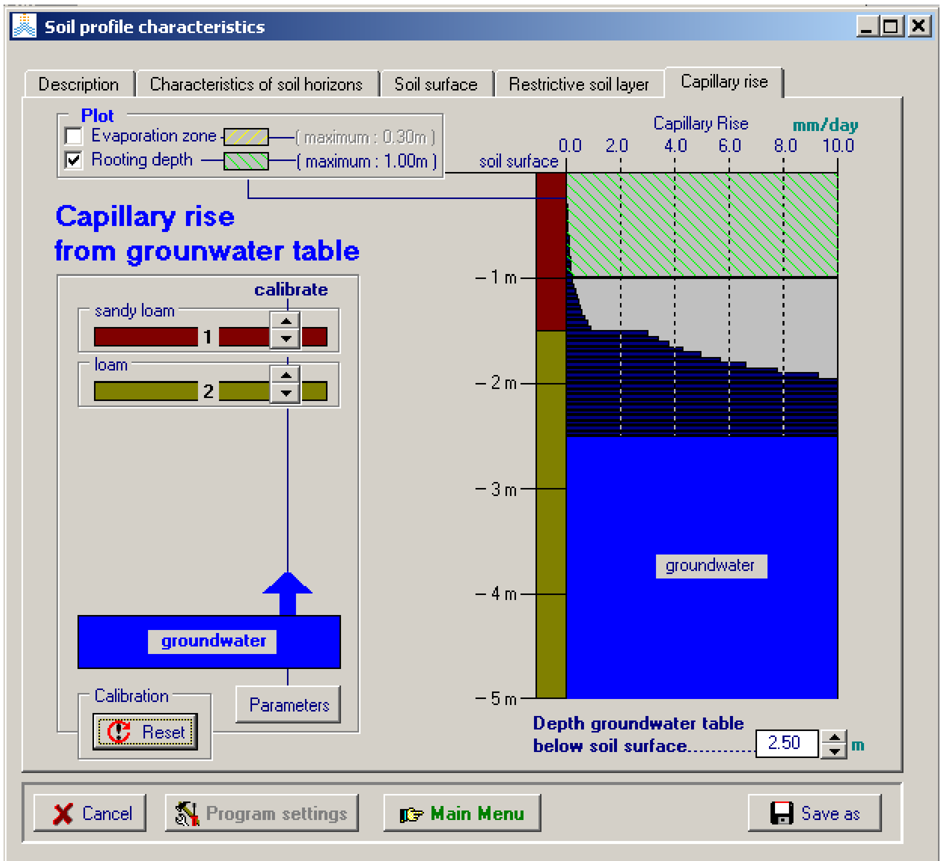


Figure 2.13d - The Capillary rise tab sheet in the ***Soil profile characteristics*** menu

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 spin buttons the user can calibrate the a and b parameters for each soil horizon and match the observed maximum possible upward flow with the simulated and plotted capillary rise. 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.

2.13.6 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. 2.13c).

Table 2.13c
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 % 20 g/liter
	Capillary rise	
	▪ Shape factor for effect of soil water content gradient on capillary rise	16

2.14 Groundwater characteristics

The selected characteristics of the groundwater 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.

2.14.1 Constant depth and salinity

If the characteristics remain constant during the season the user specifies the deptjh and salinity of the groundwater table (Fig. 2.14a). The characteristics are graphically displayed in the Plot tab sheet.

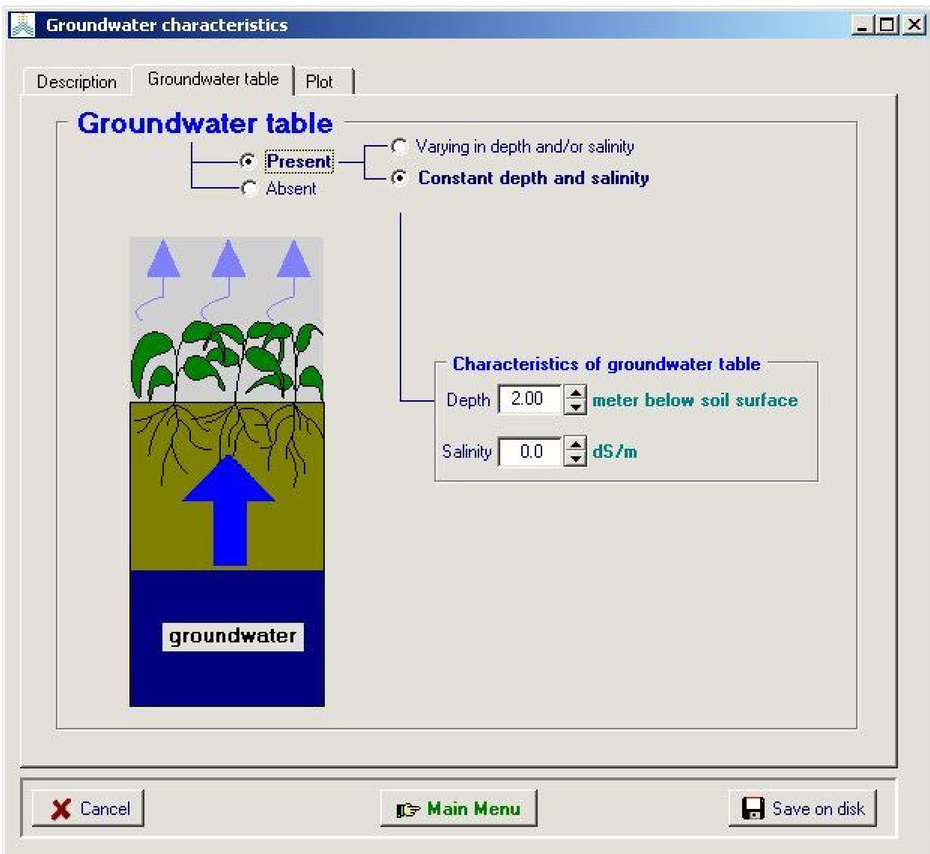


Figure 2.14a – Specifying the constant characteristics of a groundwater table in the Groundwater table tab sheet of the ***Groundwater characteristics*** menu.

2.14.2 Characteristics vary throughout the year(s)

The characteristics can vary throughout the year. The characteristics are specified in the Groundwater table tab sheet (Fig. 2.14b and 2.14d) and graphically displayed in the Plot tab sheet (Fig. 2.14c and 2.14e). The characteristics of the groundwater table for days between specified day numbers will be obtained at run time by means of linear interpolation.

- **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. 2.14b and 2.14c).

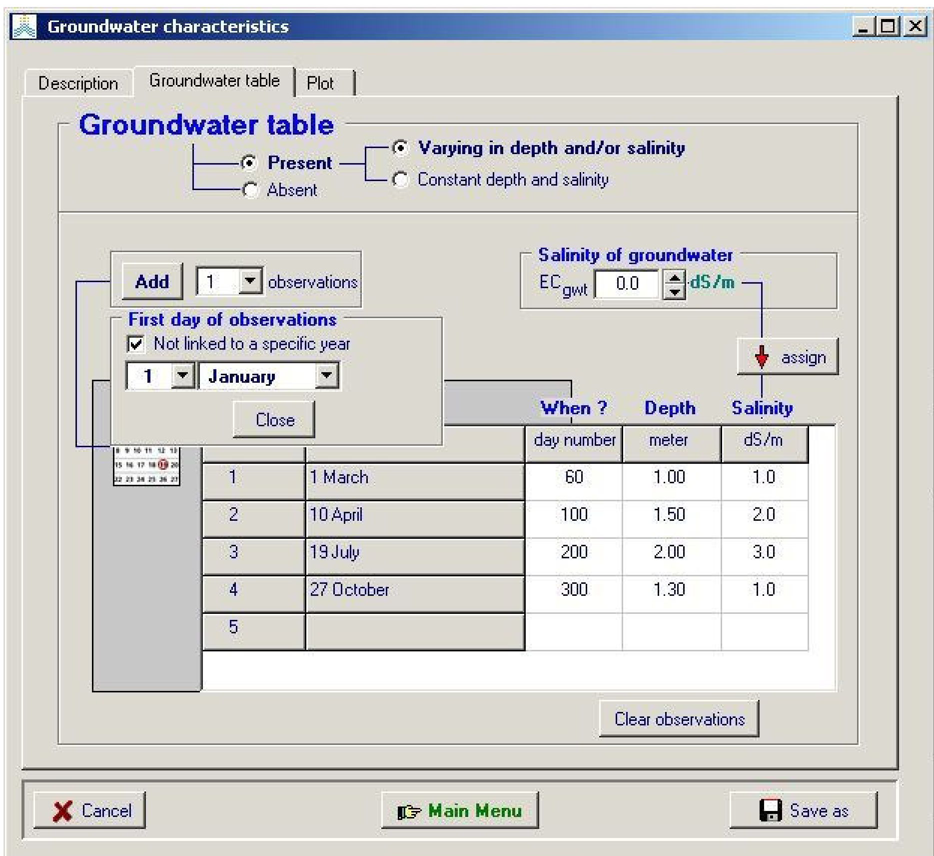


Figure 2.14b – Specifying the variable characteristics of a groundwater table not linked to a specific year in the ***Groundwater characteristics*** menu.

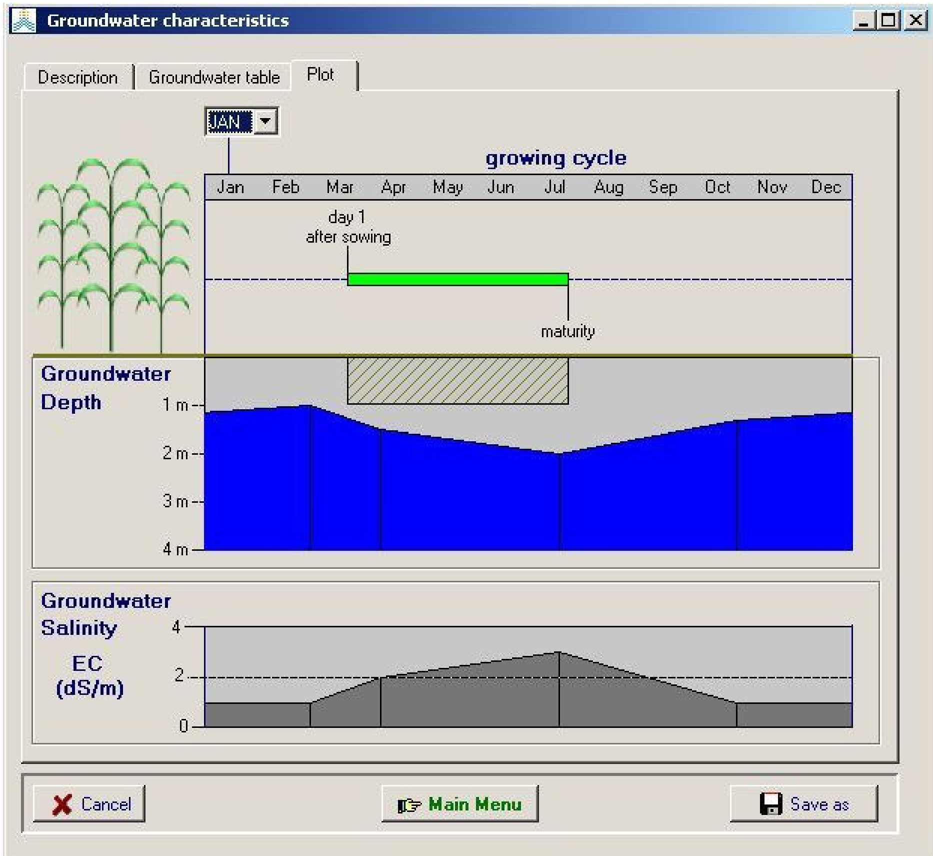


Figure 2.14c – Graphical display of the variable characteristics of a groundwater table not linked to a specific year in the ***Groundwater characteristics*** menu.

▪ **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. 2.14d and 2.14e). 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.

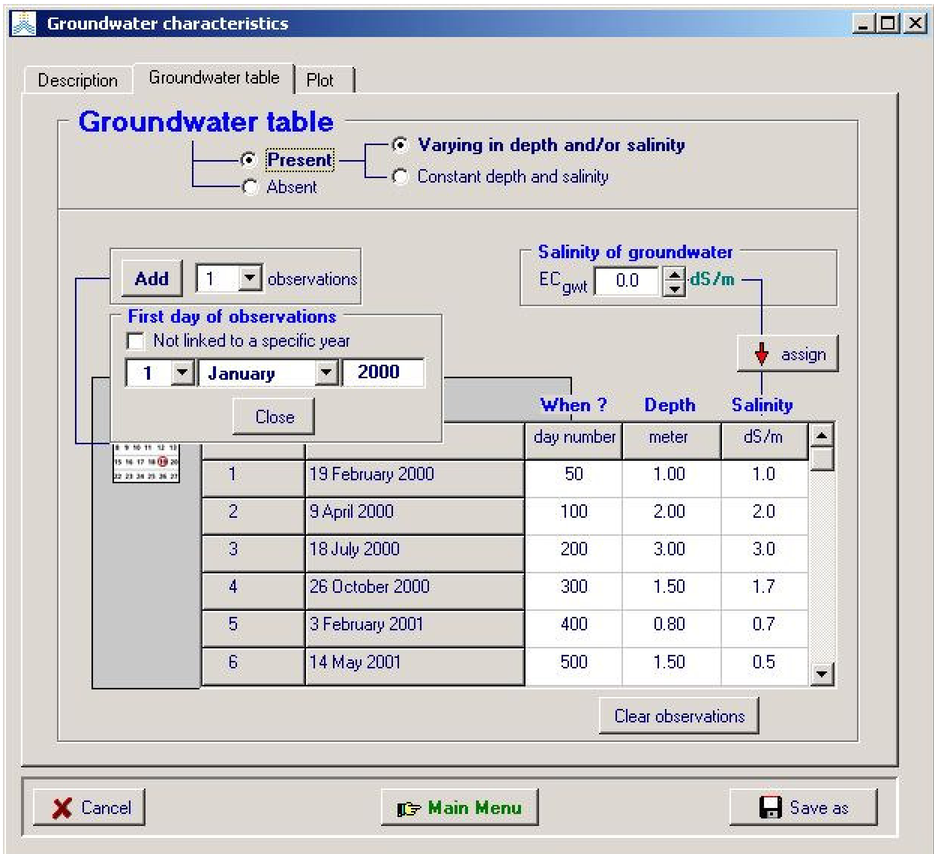


Figure 2.14d – Specifying the variable characteristics of a groundwater table linked to a specific year in the ***Groundwater characteristics*** menu.

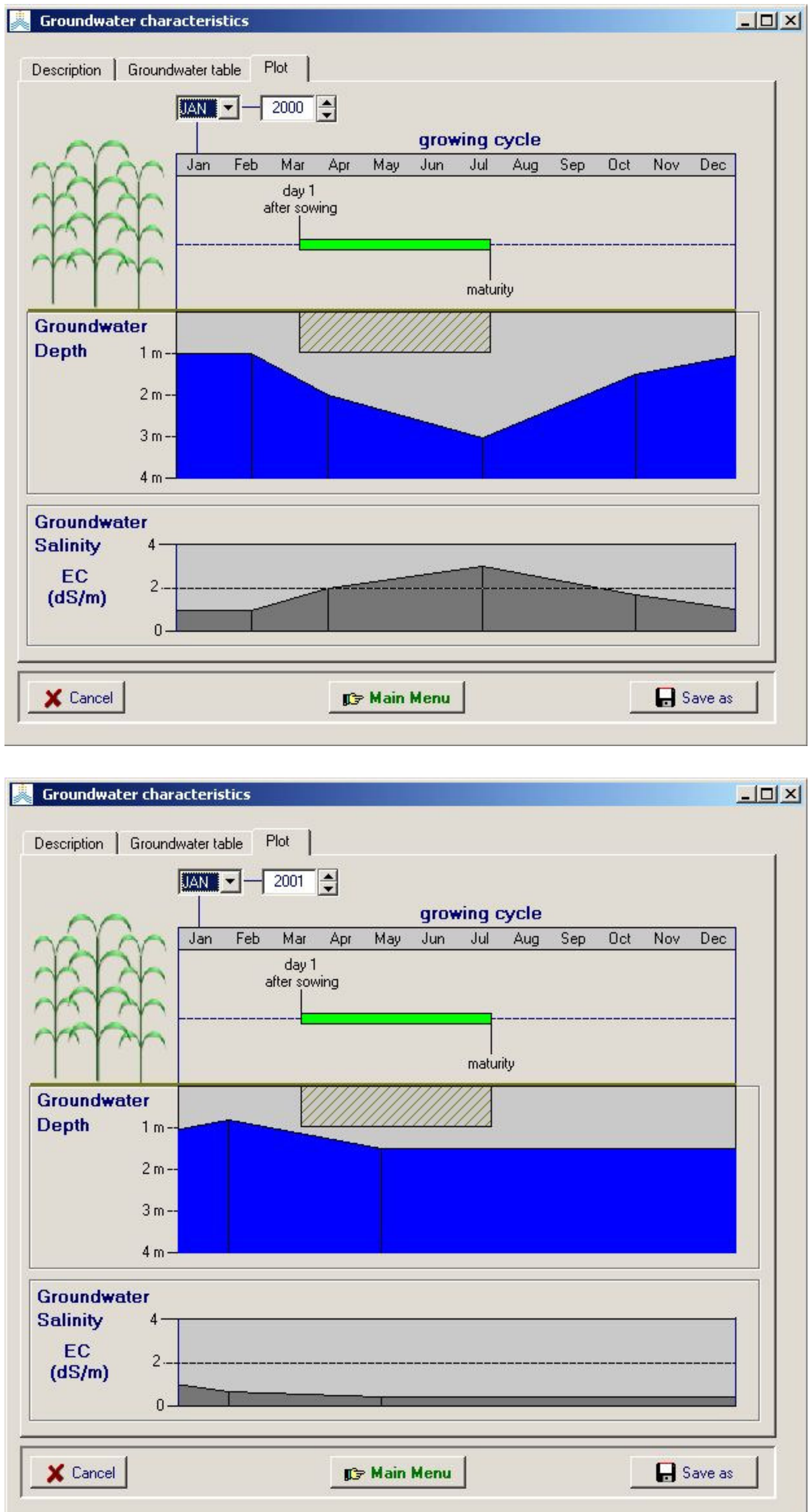


Figure 2.14e – Graphical display of the variable characteristics of a groundwater table linked to specific years (2000 and 2001) in the ***Groundwater characteristics*** menu.

2.15 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 (Fig. 2.15). The length of the growing cycle and range of available climatic data is given as a reference in the menu.

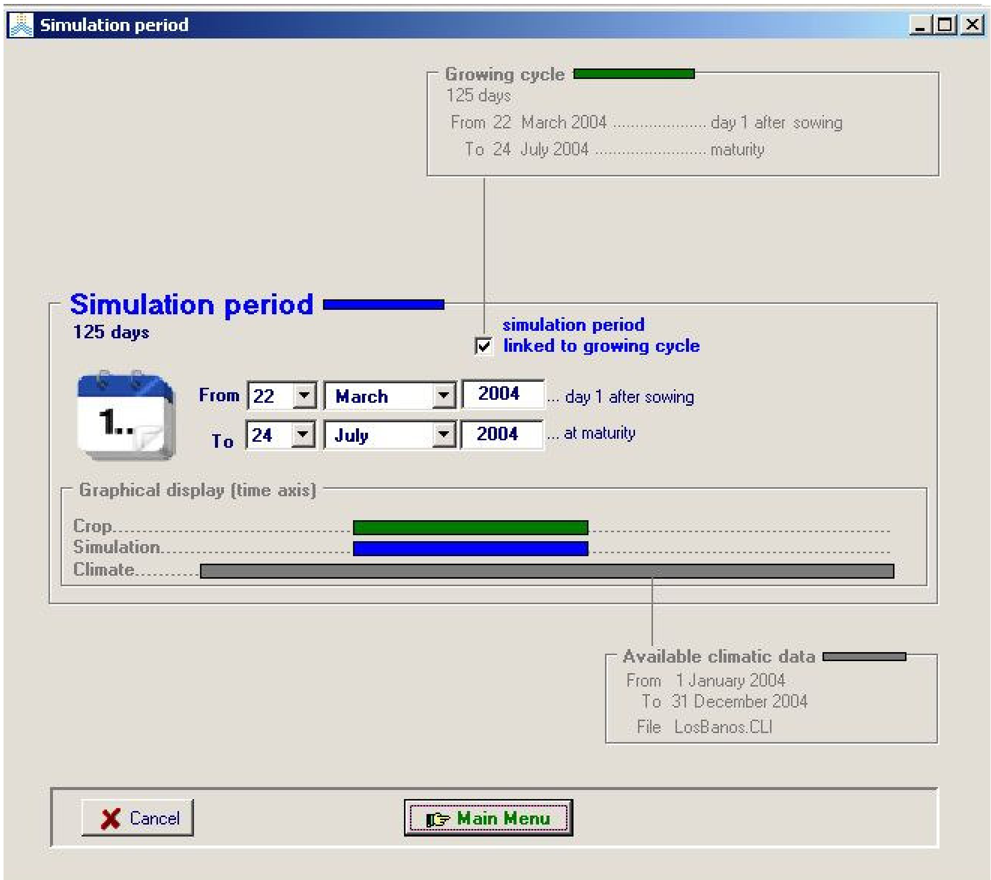


Figure 2.15
Specification of the simulation period in the *Simulation period* menu

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 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.

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

2.16 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. 2.16a).

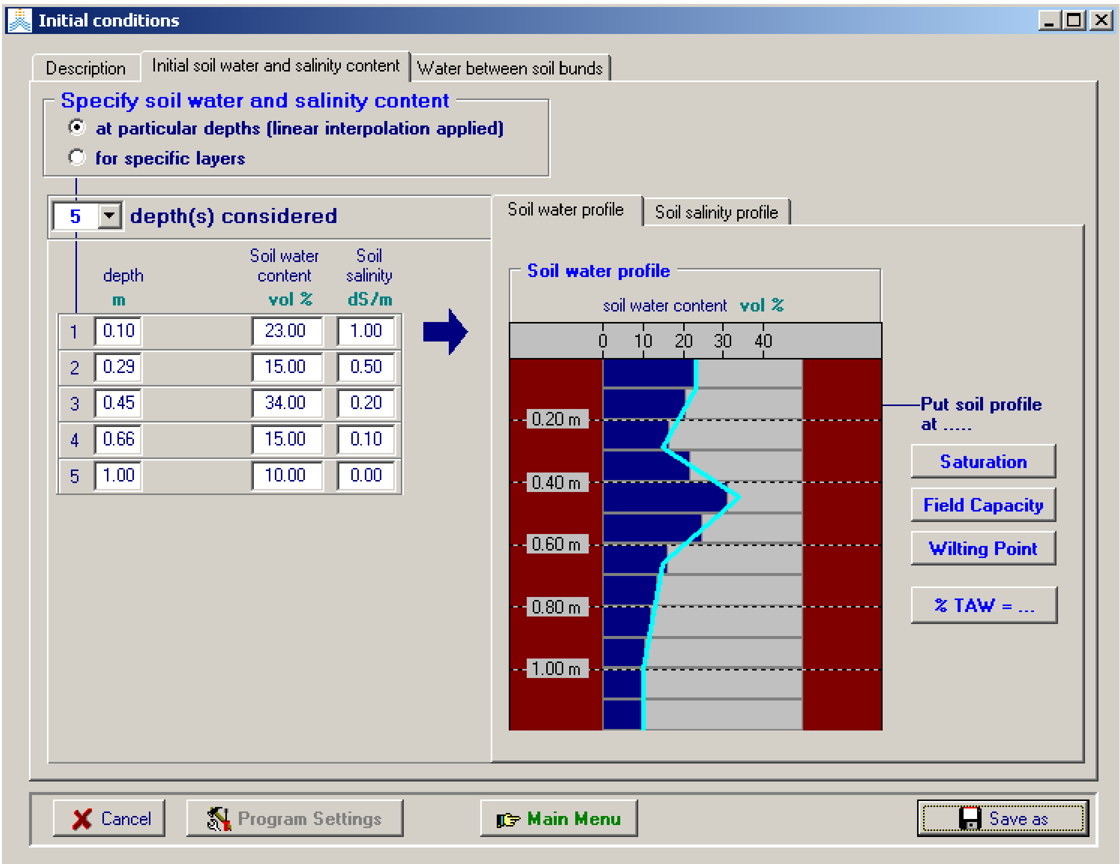


Figure 2.16a
Specification of the initial soil water content in the *Initial conditions* menu

2.16.1 Initial soil water content

The soil water content at the start of the simulation run can be adjusted by (i) specifying the soil water content at particular depths of the soil profile, (ii) specifying it for specific layers, or by (iii) setting the whole soil profile at Saturation, Field Capacity, Wilting Point, or at specific percentage of TAW (Total Available soil Water).

The initial soil water conditions are strongly determined by the climatic conditions (ETo and Rain) and irrigation applications in the period before the simulation period. If the simulation 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 simulation starts 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.

2.16.2 Initial soil salinity

The soil salinity at the start of the simulation run can be adjusted by by (i) specifying the Electrical Conductivity of the saturated soil-paste extract (ECe) at particular depths of the soil profile, (ii) specifying it for specific layers, or by (iii) setting the whole soil profile at a specific ECe (Fig.2.16b).

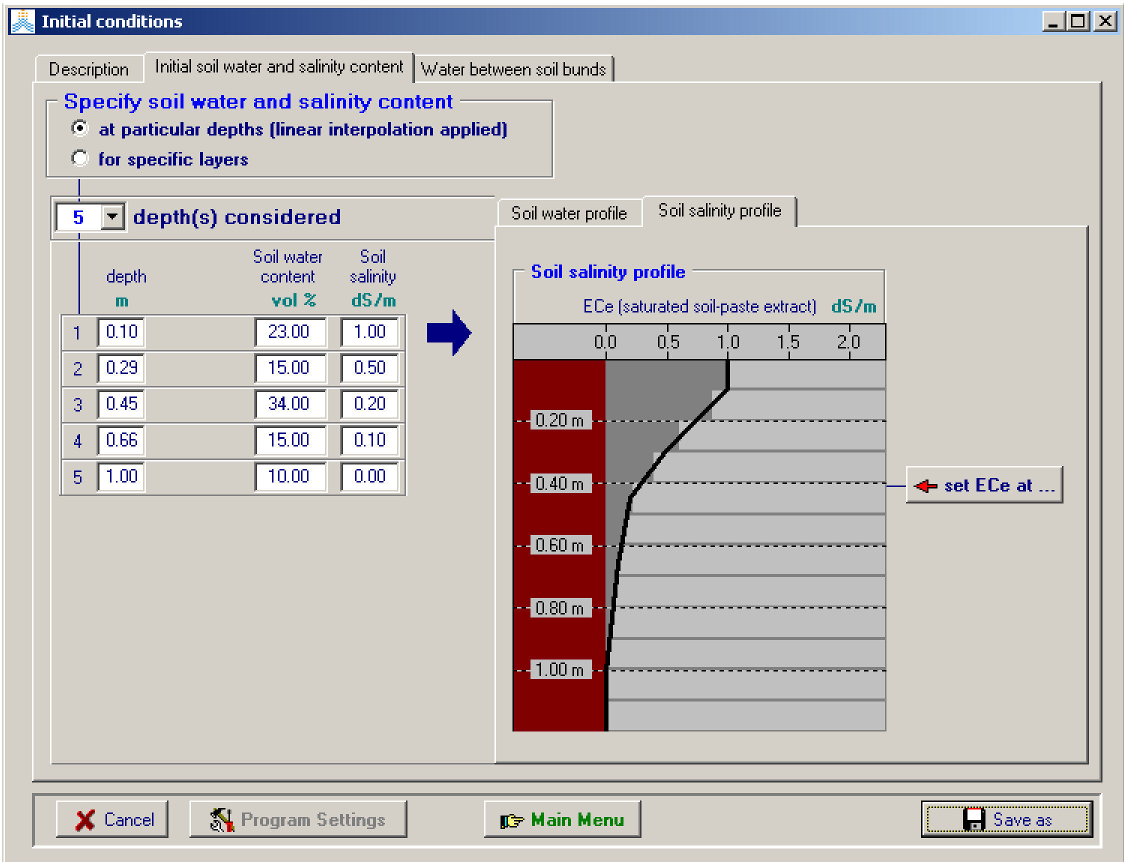


Figure 2.16b

Specification of the initial salinity in the soil profile in the *Initial conditions* menu

2.16.3 Water between soil bunds

If the field is surrounded by soil bunds (see 2.12 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. 2.16c).

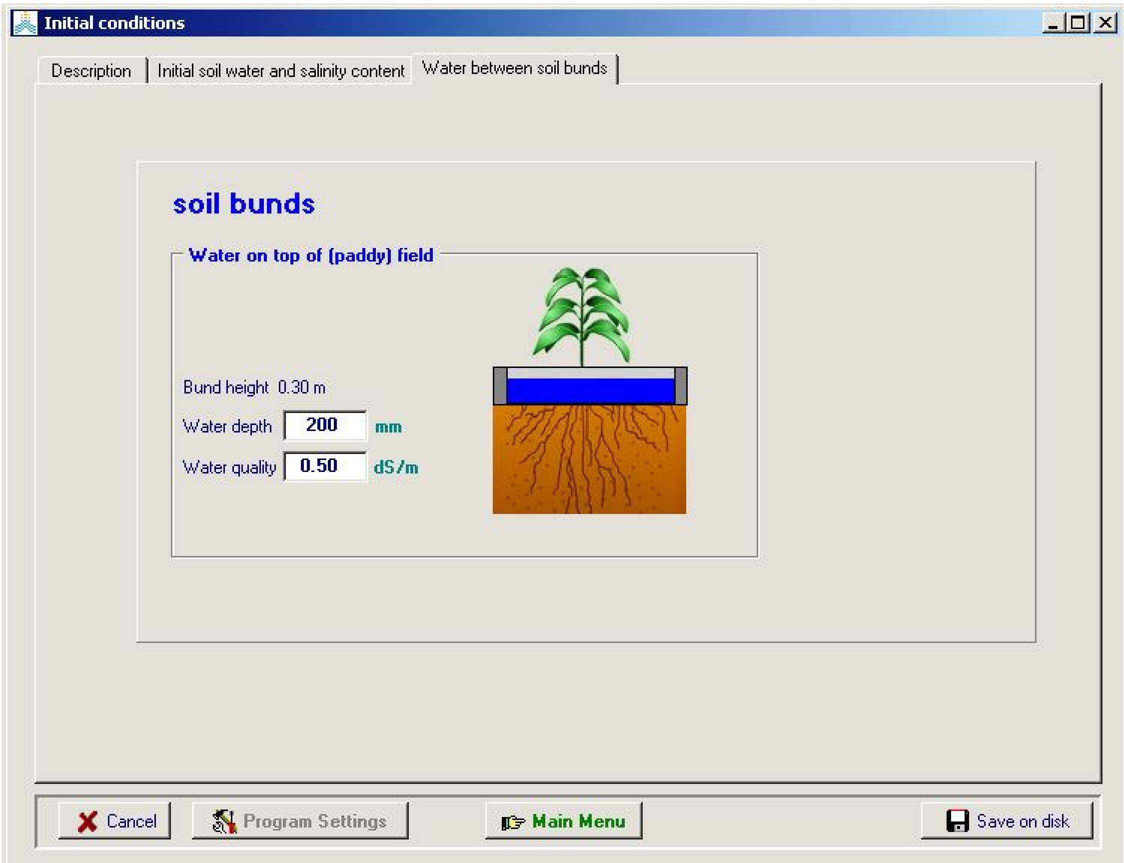


Figure 2.16c
Specification of the depth and quality between soil bunds at the start of the simulation period in the *Initial conditions* menu

2.16.4 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.

- **Setting at the start of the simulation run**

When starting a new simulation run, the soil water content and soil salinity conditions in the soil profile are by default reset to the specified initial conditions (see 2.16.1 and 2.16.2). 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. 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.

2.17 Off season conditions

If the simulation period (see 2.15 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. 2.17a and 2.17b).

2.17.1 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. 2.17a). The soil cover will reduce the evaporation losses from the non-cropped land.

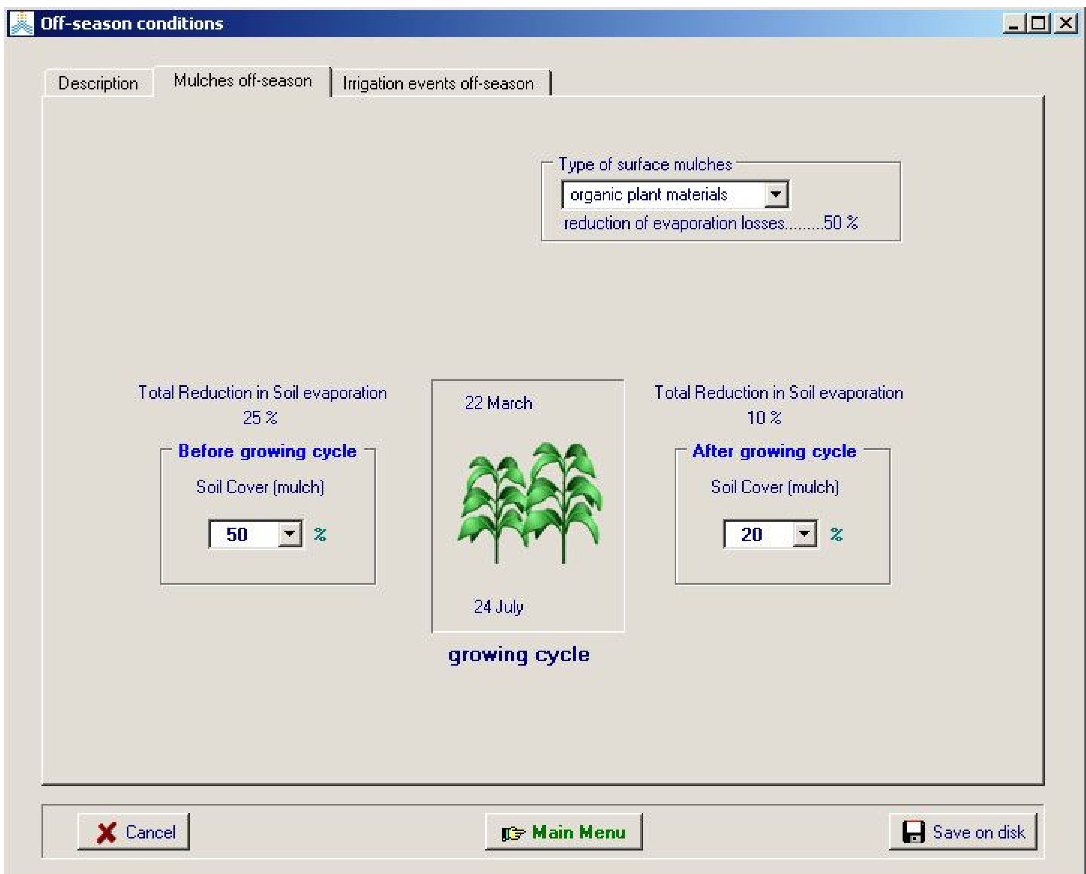


Figure 2.17a
Specification of mulches in the *Off-season conditions* menu

2.17.2 Irrigation events in the off-season

Irrigation events can be scheduled before and after the growing cycle (Fig. 2.17b). 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. 2.17) or by specifying a value for the electrical conductivity of the irrigation water.

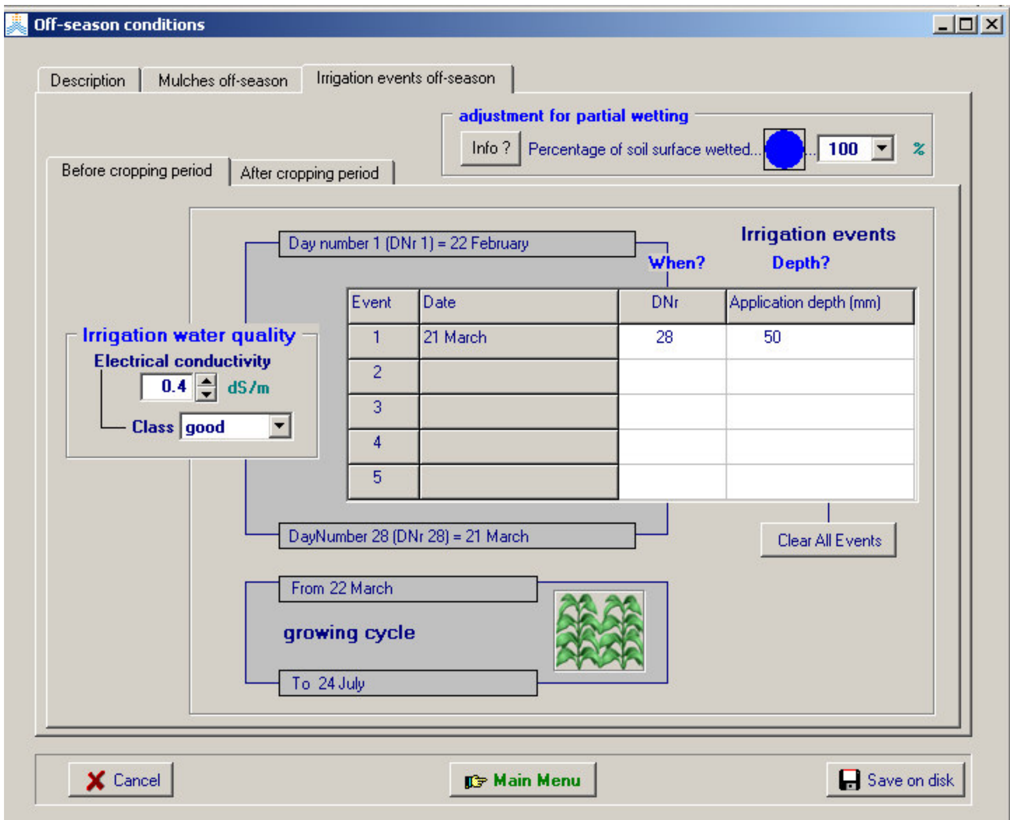


Figure 2.17b
Specification of a pre-irrigation in the *Off-season conditions* menu

Table 2.17
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

2.18 Project characteristics

When running a simulation, initial conditions applicable at the start of the simulation period and environmental conditions relevant during the simulation period are considered. If the simulation period does not fully coincide with the growing cycle of the crop, off-season conditions valid outside the growing period will be considered as well. Before running a simulation, the user can specify in the Main menu the sowing date, the simulation period and the appropriate environmental, initial and off-season conditions (Project file is 'None'). The user can also load a project file containing all the required information for that run.

Once a project file is selected, its characteristics can be displayed in the ***Display of project characteristics*** menu and adjusted in the ***Project characteristic*** menu. Once the project file is selected, the **<Select/Create>** and the **<Display/Update>** commands for climate, crop, irrigation, field, soil profile, groundwater, initial and off-season conditions are no longer available in the ***Main Menu*** (Fig. 2.18a). By clicking on the **<UNDO selection>** command, one return to the default settings considered at the start of AquaCrop (see 2.3 Default settings at start).

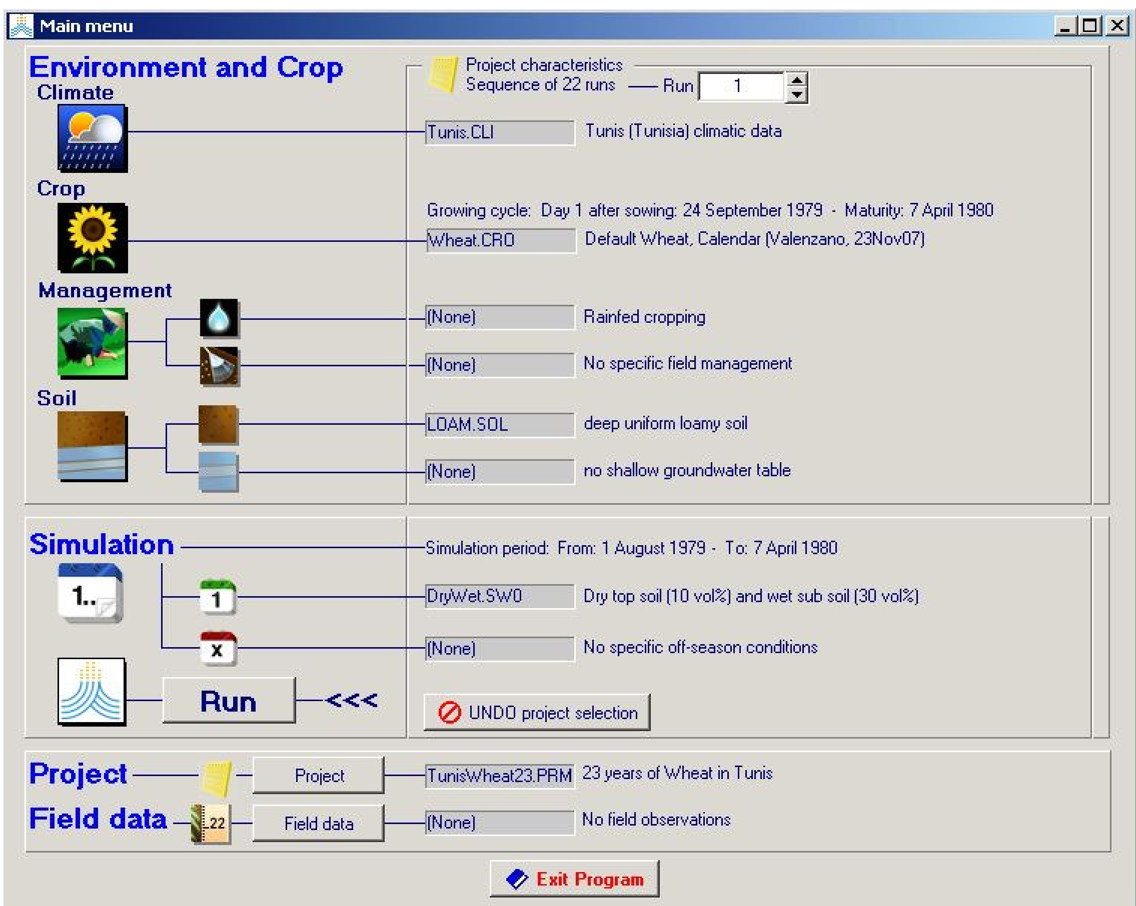


Figure 2.18a
***Main menu* once a project file is selected.**

2.18.1 Single run and multiple run projects

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

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

A project file contains:

- the period(s) of the growing cycle (from day 1 after sowing/transplanting to crop maturity);
- the simulation period(s): the first and last day of the simulation period need not to coincide with the growing cycle;
- the file names (with their directory) containing the characteristics of the selected environment (climate, crop, irrigation management, field management, soil profile, and groundwater file);
- the file names (with their directory) containing the initial and off-season conditions; and
- the specific program settings for the run(s).

If no file names are specified the default conditions are considered (see 2.3 Default settings at start).

2.18.2 Selecting and creating a project

- **Selecting a project**

Since the single and multiple run projects have different file extensions, the list of project files displayed in the ***Select project file*** menu depends on the selected type of projects (Fig. 2.18b).

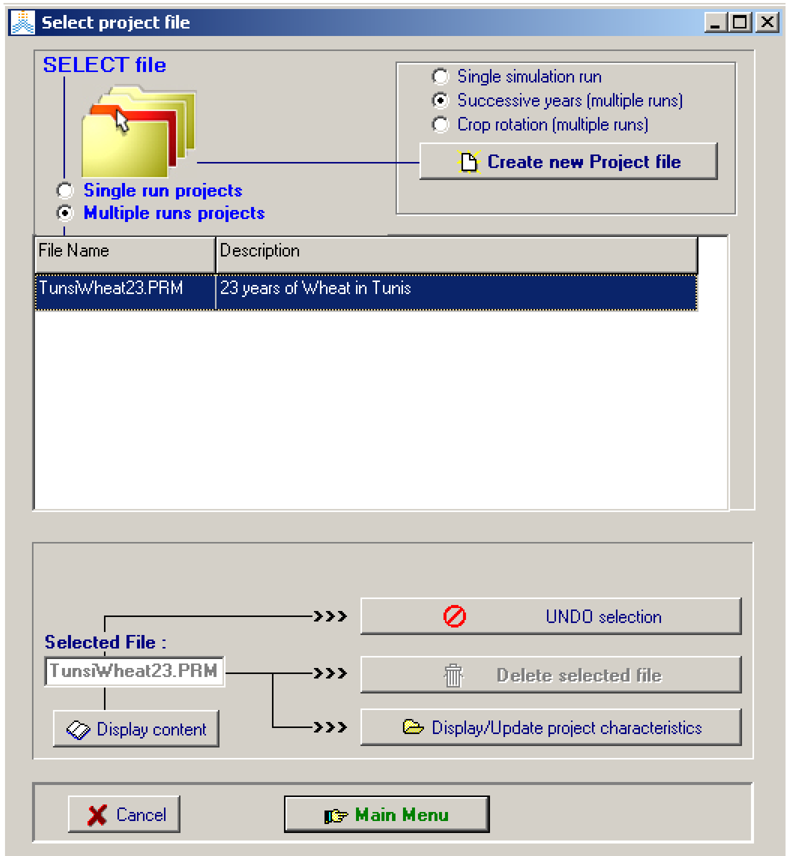


Figure 2.18b
The *Select project file* menu where the user can select a project file from one of the displayed lists of projects (single run or multiple runs projects) and can indicate which type of project needs to be created (Single simulation run; Successive years (multiple runs); Crop rotation (Multiple runs)

- **Creating a project**

When creating a new project file, the user specifies the type of file:

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

Create project (single run)

The user selects:

- the climate file;
- the crop file, and specifies
    - day 1 after sowing/planting, or
    - select a criterion (see 2.10.2 Generate onset) to generate an onset day (only available if a climate file is selected);
- the irrigation file;
- the field management file;
- the soil profile file;
- the groundwater file;
- the simulation period;
- the file with initial conditions; and
- the file with off-season conditions (only available if the simulation period is not linked with the growing cycle).

The selected crop growing cycle and simulation period are displayed by selecting the **<Calendar>** command.

If no file is selected default conditions are considered (see 2.3 Default settings at start).

Create project (multiple runs) - successive years

The user selects:

- the climate file;
- the crop file, and specifies
    - day 1 after sowing/planting, or
    - select a criterion (see 2.10.2 Generate onset) to generate an onset day (only available if a climate file is selected); and
    - the year at which the series of successive years start;
- the common irrigation file;
- the common field management file;
- the soil profile file;
- the common groundwater file;
- the simulation period by specifying:
    - day 1 of the initial run;
    - the simulation period for the next runs (only available if a climate file is selected);
- the file with initial conditions;
- the initial conditions for next runs (only available if a climate file is selected);
- the common file with off-season conditions (only available if the simulation period is not linked with the growing cycle); and
- the number of years.

The determined crop growing cycles and simulation periods for the successive years are displayed by selecting the **<Calendar>** command (Fig. 2.18c).

If no file is selected default conditions are considered (see 2.3 Default settings at start).

If the selected irrigation management, field management, and/or file with off-season conditions are not common between the successive years, the selection can be adjusted in the **Project characteristics** menu (see 2.18.3).

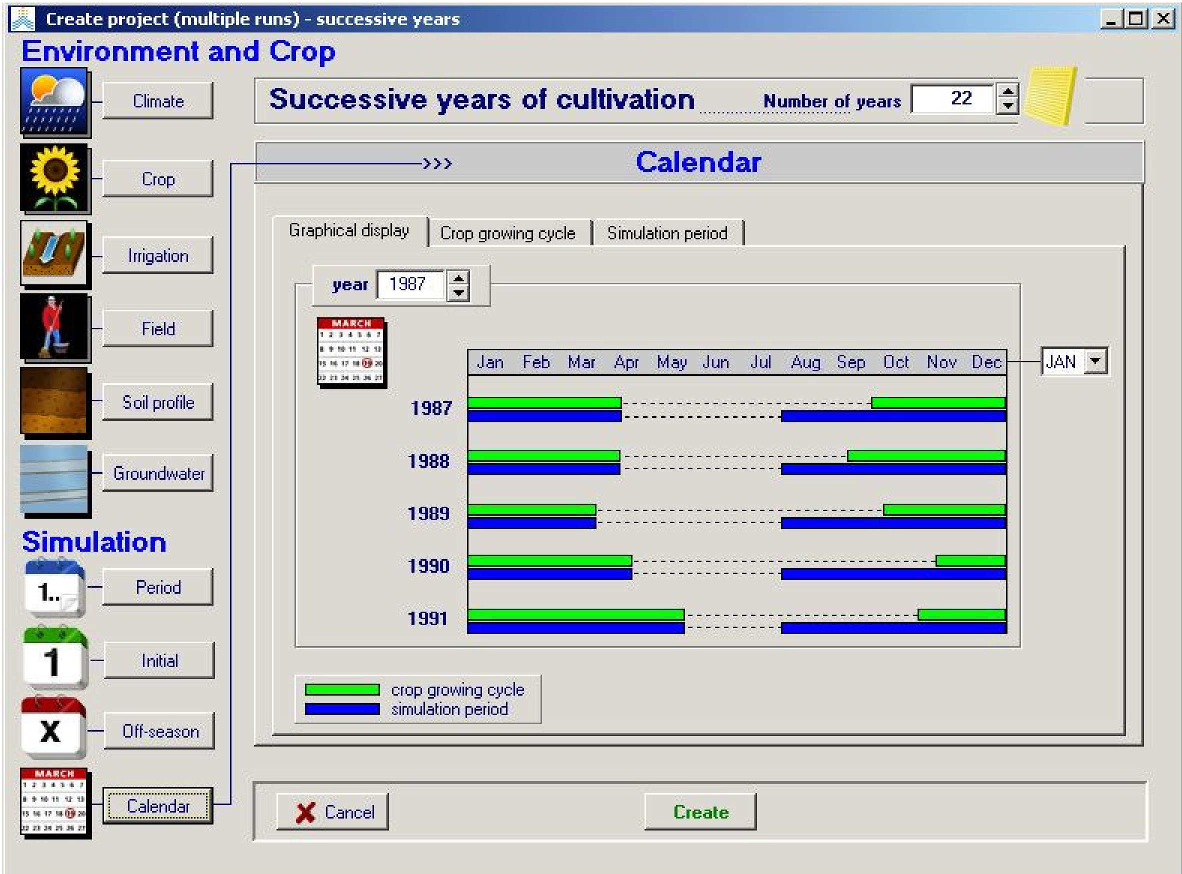


Figure 2.18c
The calendar in the *Create project (multiple runs) – successive years* menu, indicating the determined crop growing cycles and simulation periods for the successive years

Create project (multiple runs) – crop rotation

The user selects:

- the climate file;
- the number of crops, and specifies for each of the crops:
    - the crop file; and
    - day 1 after sowing/planting (Fig. 2.18d);
- the common irrigation file;
- the common field management file;
- the soil profile file;
- the common groundwater file;
- the simulation period by specifying:
    - day 1 of the initial run; and
    - the simulation period for the next runs (only available if a climate file is selected);
- the file with initial conditions;
- the initial conditions for next runs (only available if a climate file is selected); and

- the common file with off-season conditions (only available if the simulation period is not linked with the growing cycle).

The determined crop growing cycles and simulation periods for each of the crops of the rotation are displayed by selecting the **<Calendar>** command.

If no file is selected default conditions are considered (see 2.3 Default settings at start).

If the selected irrigation management, field management, groundwater and/or file with off-season conditions are not common in the crop rotation, the selection can be adjusted in the **Project characteristics** menu (see 2.18.3).

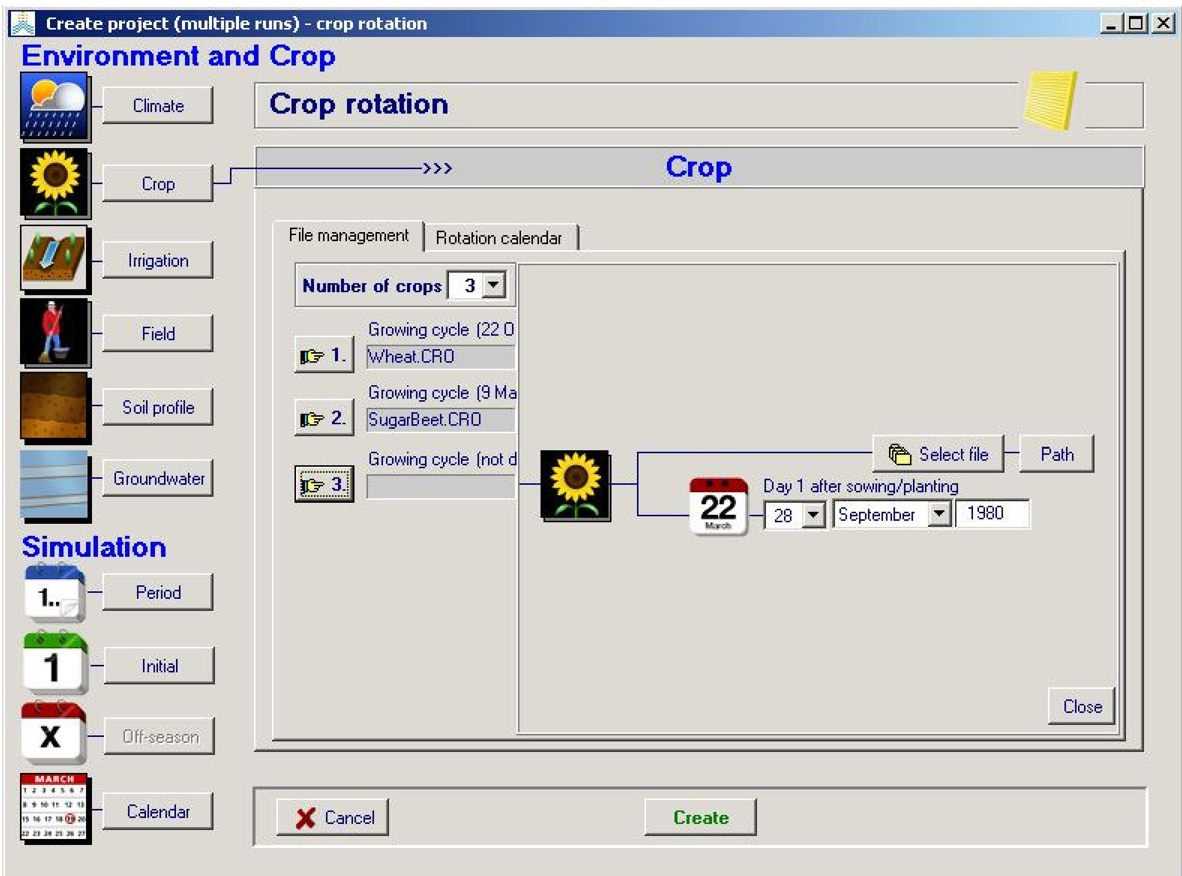


Figure 2.18d
Crop file management in the *Create project (multiple runs) – crop rotation* menu

2.18.3 Updating project characteristics

In the ***Project characteristics*** menu (Fig. 2.18e), the user can:

- select other crop file(s), irrigation file(s), field management file(s), another soil profile file, groundwater file(s), file(s) with initial conditions, and file(s) with off-season conditions.
  With the exception of the climate file, the soil profile file and the crop file (if successive years are considered), the files need not to be common between the simulation runs of a multiple runs project;
- alter the start of the growing cycle;
- alter the start and the end of the simulation period; and
- update the program settings.

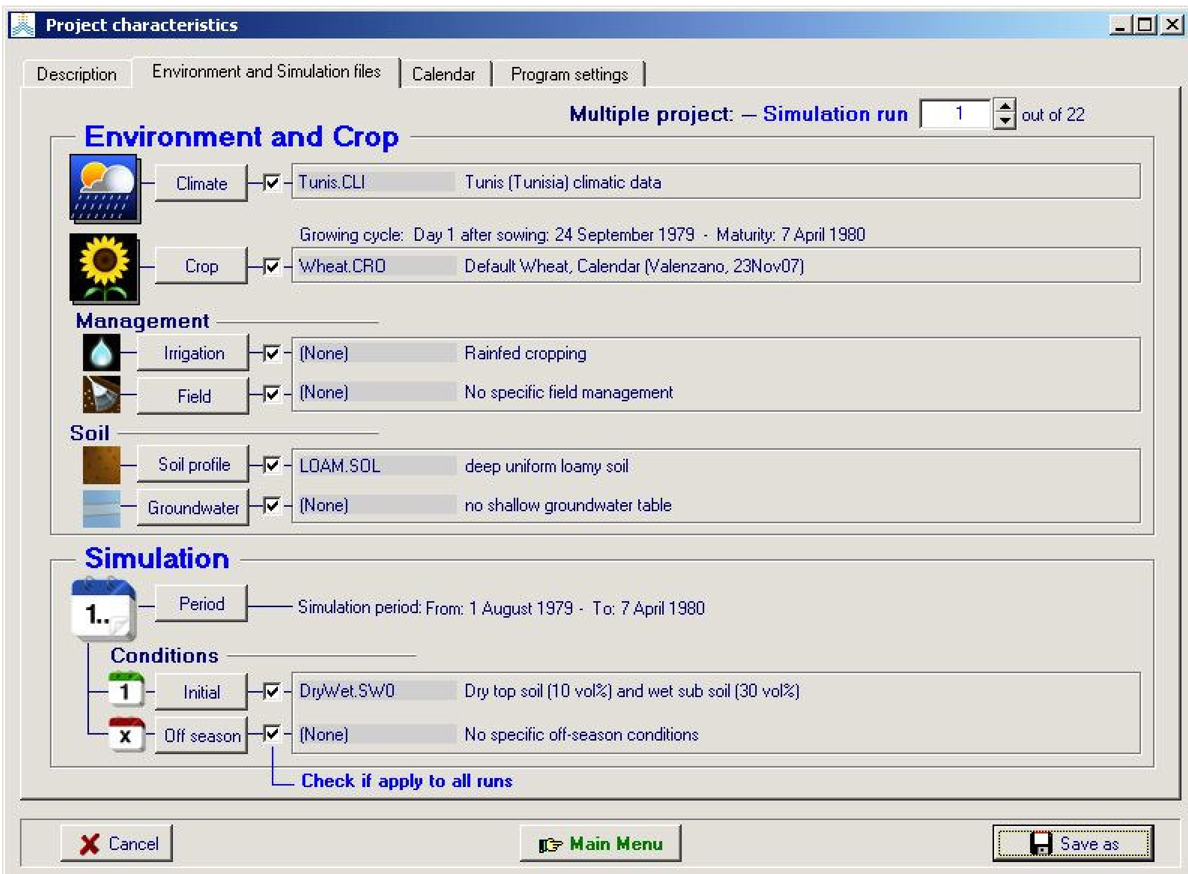


Figure 2.18e
The *Project characteristics* menu

2.19 Field data

2.19.1 Access to field data menus and data base

Next to (i) the crop selection and the description of the environment (Environment and Crop panel), (ii) the selection of the simulation period, and the initial and off-season conditions (Simulation Panel), and (iii) the selection or description of projects, the user can enter field data in the ***Main menu*** of AquaCrop.

By means of the **<Select/Create Observation file>** command in the ***Main menu*** the user has access to the data base where the data files are stored or can create new data files. The default data base is the OBS subdirectory of the AquaCrop folder. With the **<Path>** command the user can specify other directories.

From the ***Main menu*** the user can display the observed field data in the ***Display of field data*** menu. This is done by clicking on the file name or the corresponding icon in the ***Main menu***. By selecting the **<Display/Update Field data>** command, the field data can be displayed, specified or updated in the ***Field data*** menu.

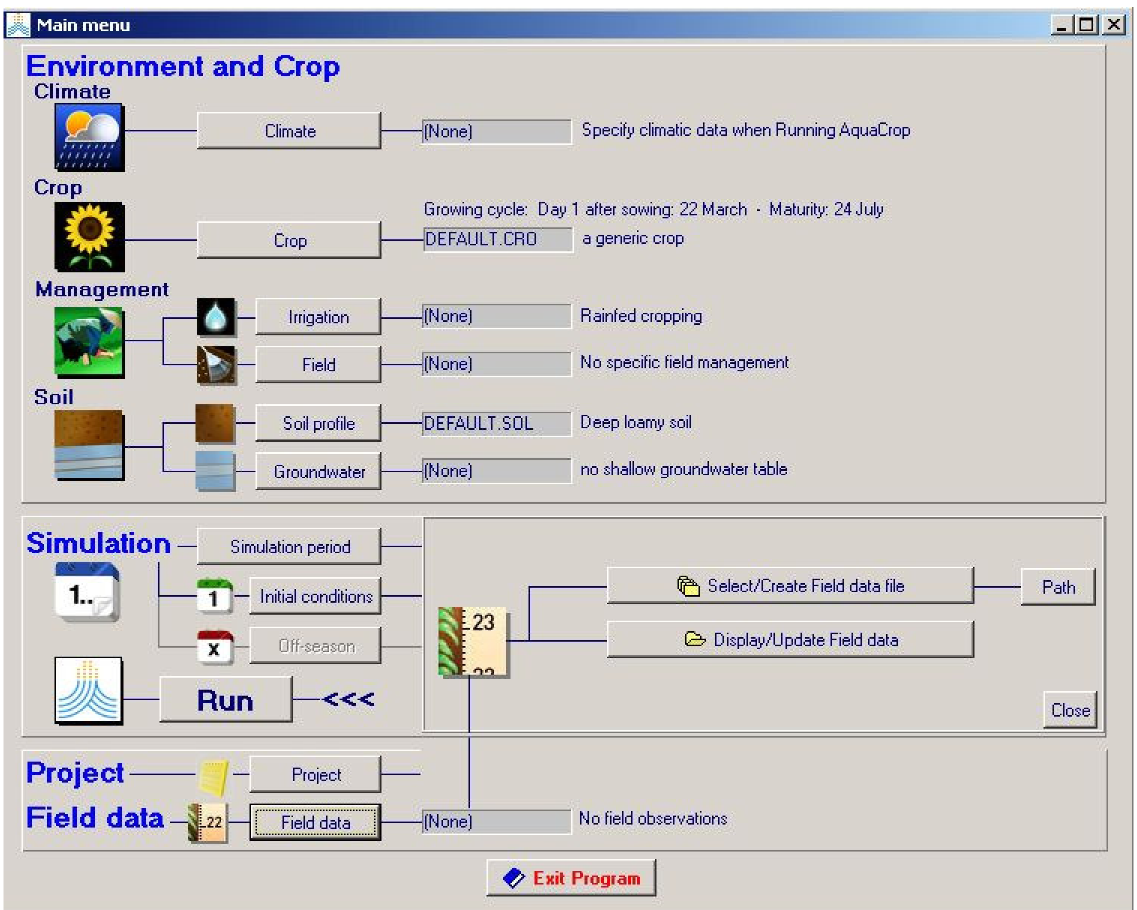


Figure 2.19a - The **<Select/Create Field data file>** and the **<Display/Update Field data>** command in the ***Main menu***.

2.19.2 Specifying field data

In the ***Field data*** menu, the user specifies the 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 (Fig. 2.19b). 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.

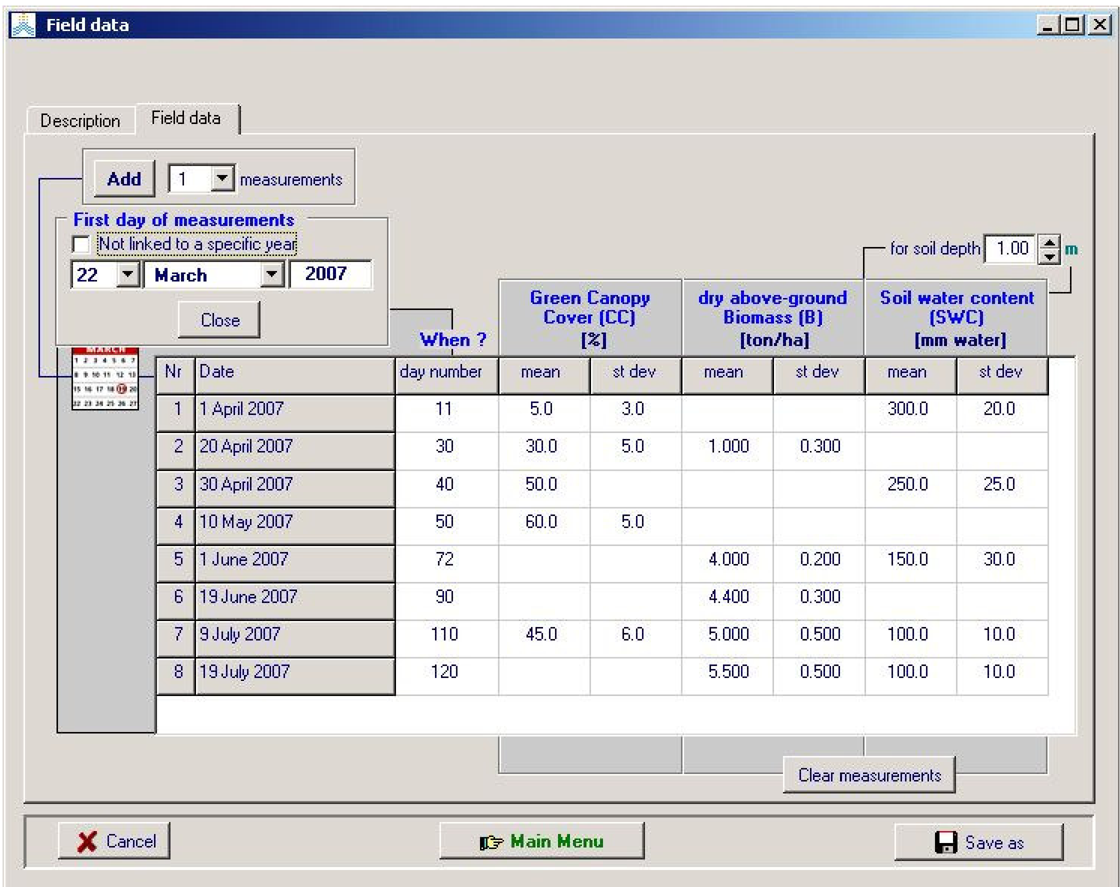


Figure 2.19b – Specifying observations at particular days in the ***Field data*** menu.

2.20 Simulation run

2.20.1 Display of simulation results

Simulation results are plotted in the ***Simulation run*** menu in a number of graphs which are updated at the end of each daily time step (Fig. 2.20a, b, c, d and e). From such plots the user can follow throughout the simulation run the effects of water, temperature, fertility and salinity stress on crop development and production, and switch between several displays, each of a different set of outputs, presented in different folders. 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.

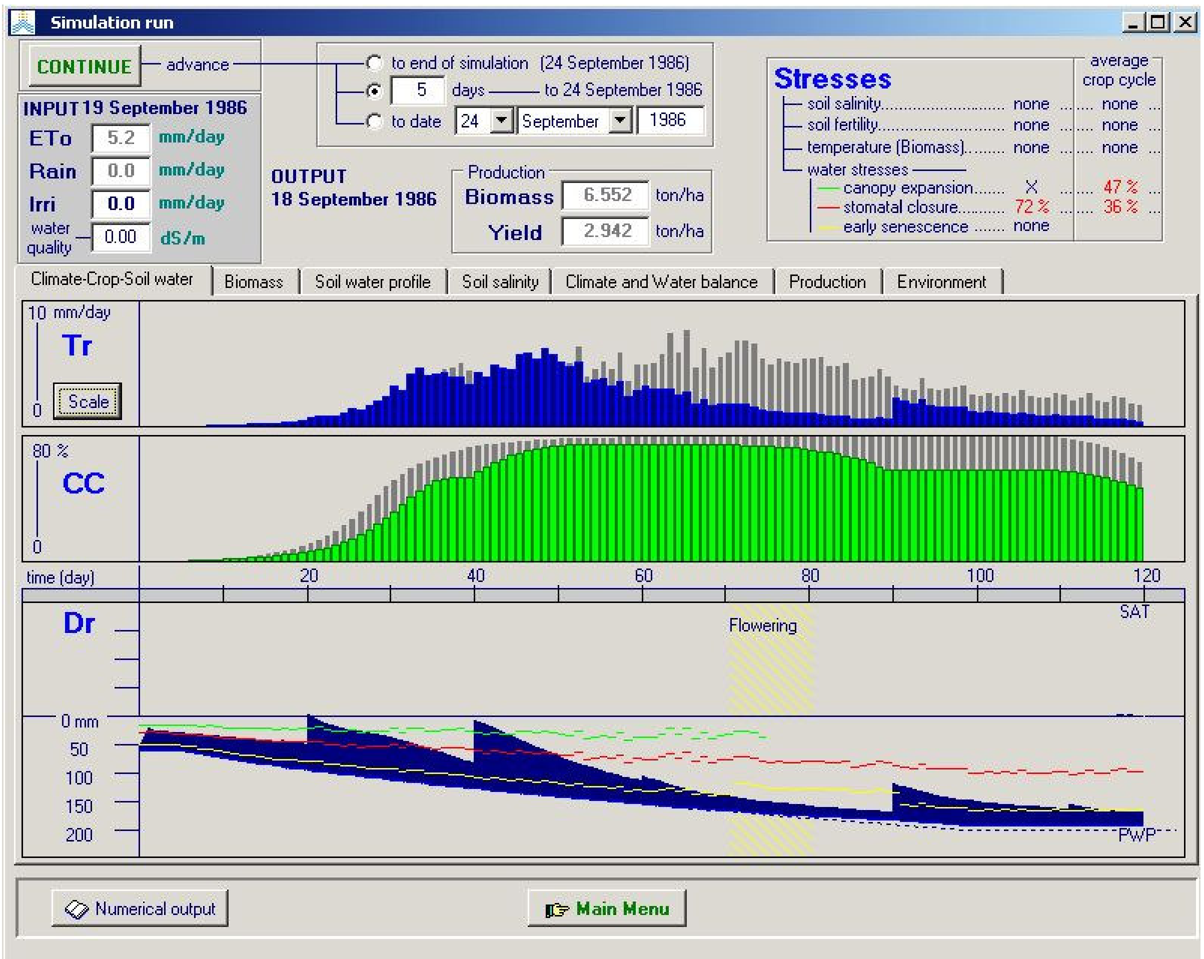


Figure 2.20a
Graphical displays of Climate-Crop-Soil water output in the *Simulation run* menu

- **Climate-Crop-Soil water sheet**

The Climate-Crop-Soil water sheet (Fig. 2.20a) contains graphs with plots of (i) the soil water depletion of the root zone (Dr), (ii) the corresponding development of the green canopy cover (CC), and (iii) the transpiration (Tr), plotted as functions of time.

The absence of rain and irrigation during long periods might led to a drop in root zone water content below the threshold (green line) affecting canopy expansion. 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).

- **Sheet with selected parameter**

In the second sheet of the ***Simulation run*** menu, the user can select particular parameters for further analysis (Tab. 2.20a). Several crop parameters and parameters of the soil water and soil salinity balance can be selected and the scale for the plot can be adjusted (Fig. 2.20b).

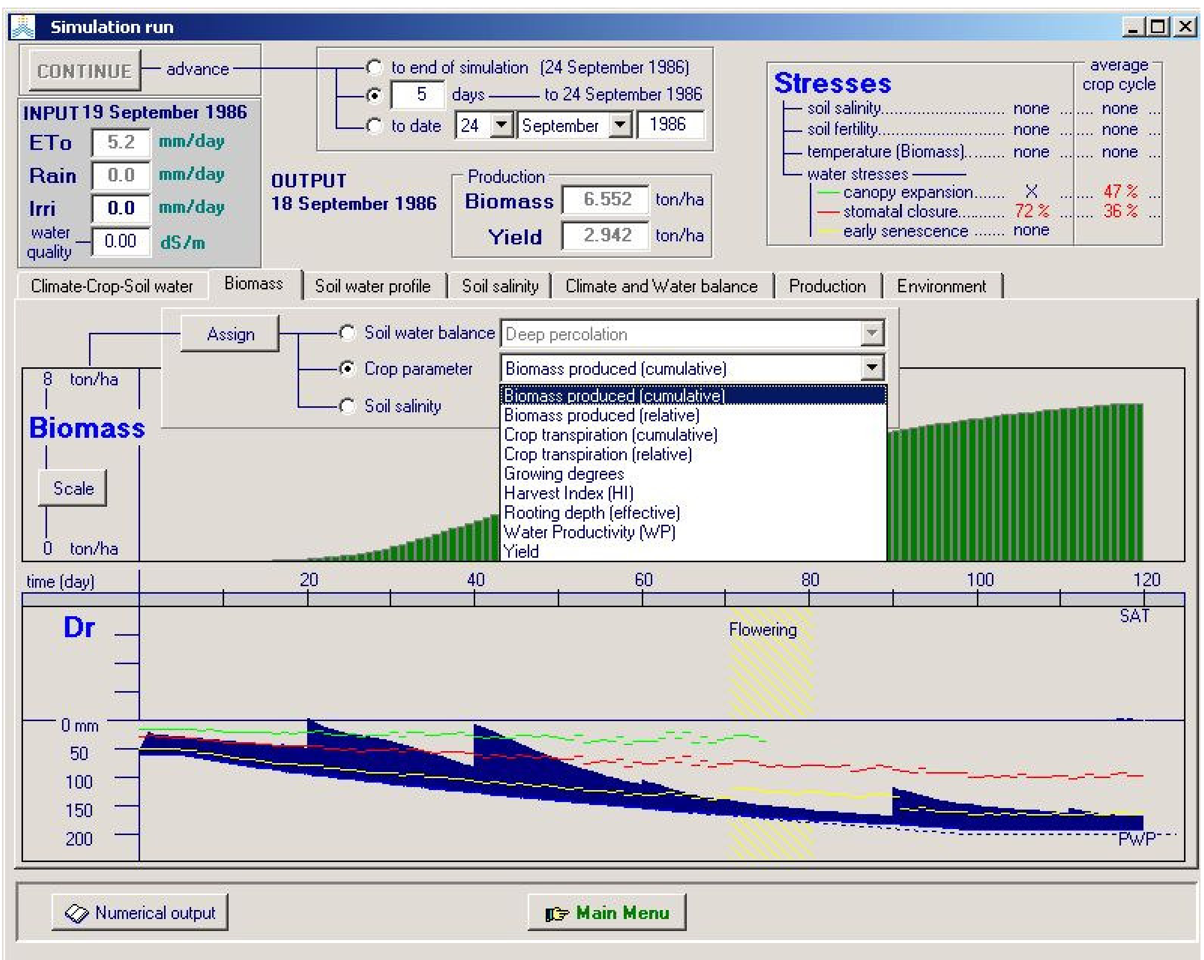


Figure 2.20b
Selection of a parameter for display in the *Simulation run* menu

Table 2.20a
Parameters of the soil water balance, crop parameters, and parameters concerning soil salinity that can be selected for display in the Simulation run menu

Symbol	Description	Units
Parameters of the soil water balance		
Drain	Deep percolation	mm
Sum(Drain)	Deep percolation (cumulative)	mm
ET	Evapotranspiration	mm
Sum(ET)	Evapotranspiration (cumulative)	mm
ETx	Evapotranspiration (maximum)	mm
ET/ETx	Evapotranspriation (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 parameters		
Biomass	Biomass produced (cumulative)	ton/ha
B(rel)	Biomass produced (relative)	%
Sum(Tr)	Crop transpiration (cumulative)	mm
Tr/Trx	Crop transpiration (relative)	%
GDD	Growing degrees	°C-day
HI	Harvest Index (HI)	%
Z	Effective rooting depth	m
WP	Water Productivity (WP)	g/m^2
Yield	Yield	ton/ha
Parameters concerning 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

- **Soil water profile sheet**

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.

- **Soil salinity sheet**

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. 2.20c).

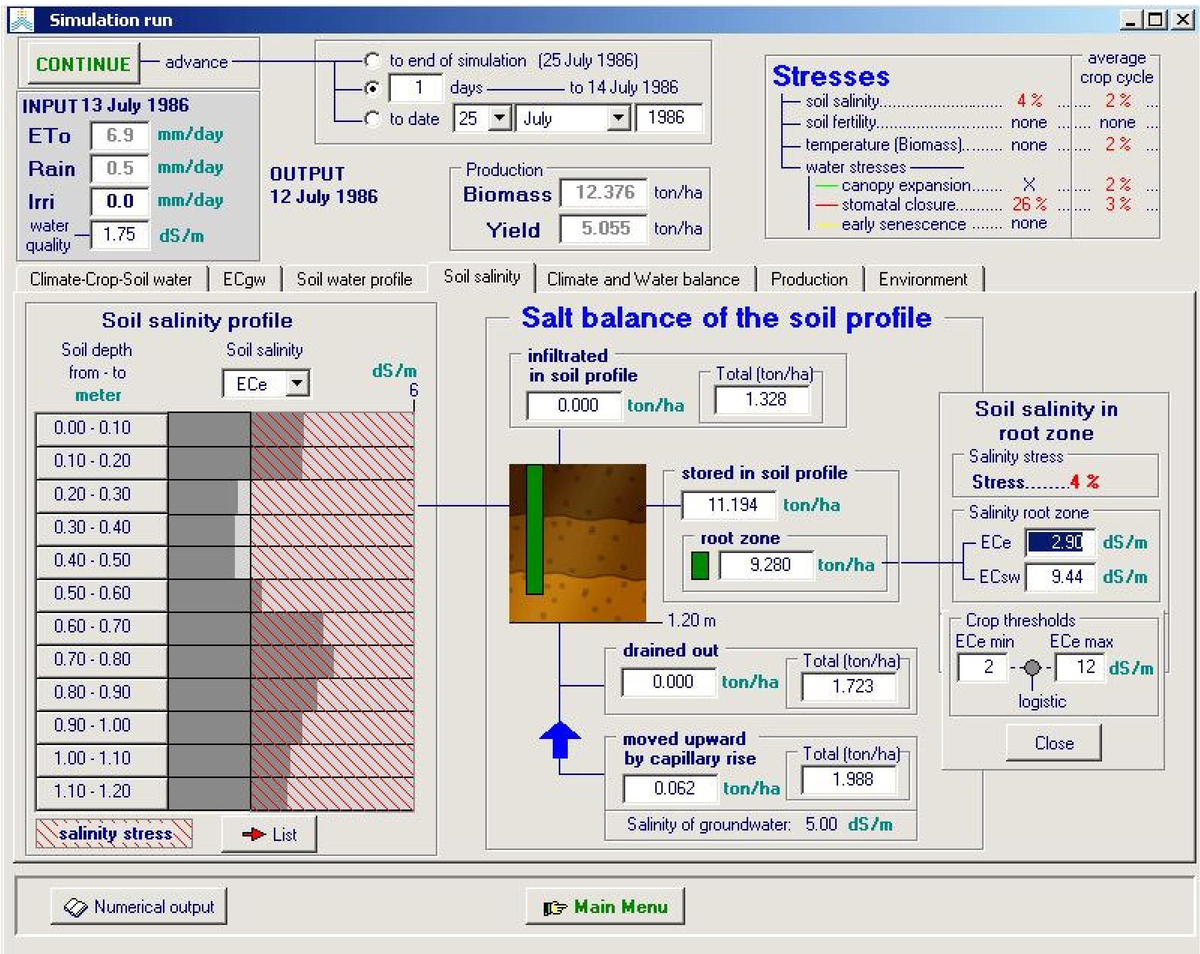


Figure 2.20c
Display of the soil salinity profile and the salt balance in the *Simulation run* menu

- **Climate and Water balance sheet**

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. The irrigation events are displayed in the ***Irrigation Events*** menu (Fig. 2.20d).

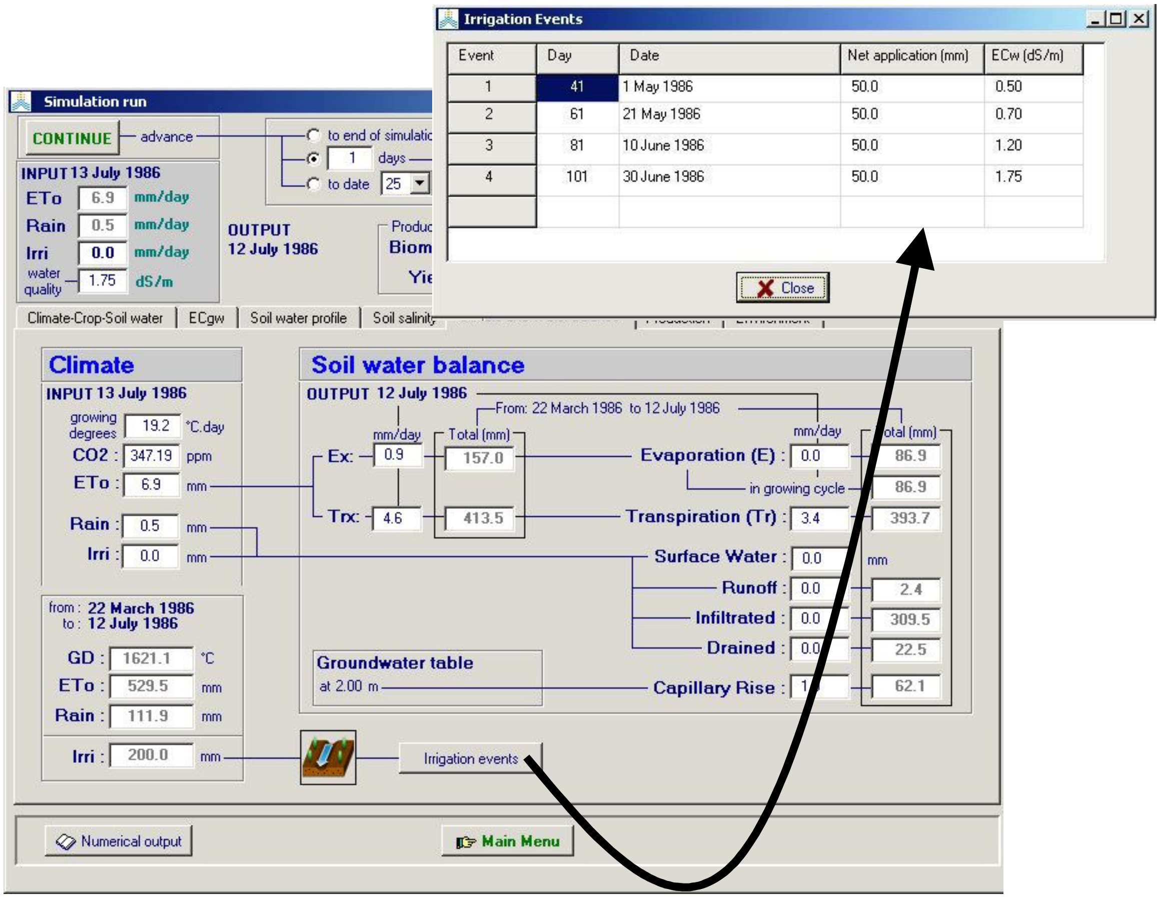


Figure 2.20d
Display of the parameters of the climate and soil water balance in the *Simulation run* menu and the irrigation events in the *Irrigation Events* menu

- **Production sheet**

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 2.20e). 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).

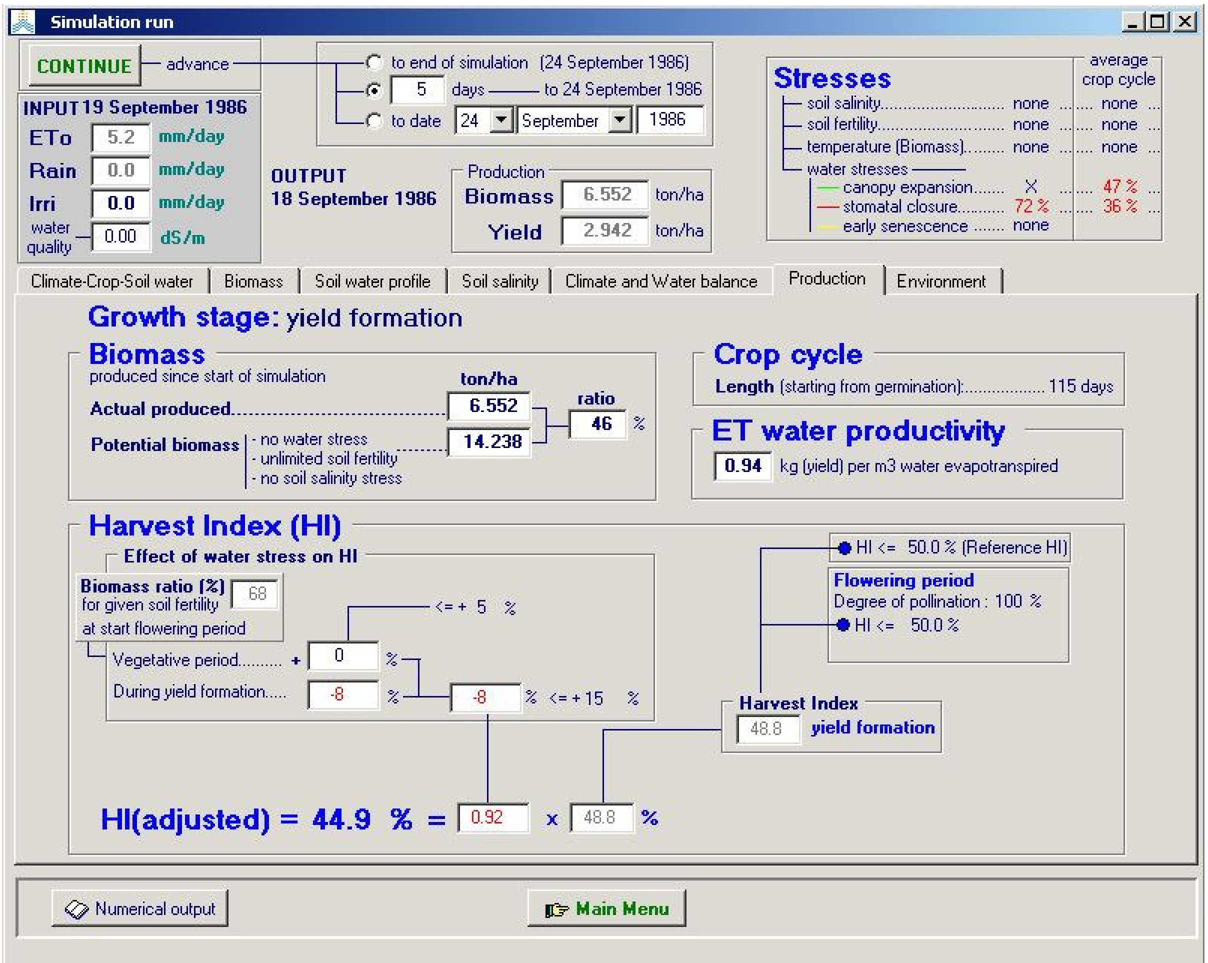


Figure 2.20e

Information on biomass production, ET water productivity, and the ante and post-anthesis impact of water stress on the adjustment of HI in the *Simulation run* menu

- **Totals Run sheet**

In the Totals Run sheet of the ***Simulation run*** menu, information is given on totals of a selected number of parameters (Tab. 2.20b) at the end of each simulation run (Fig. 2.20f).

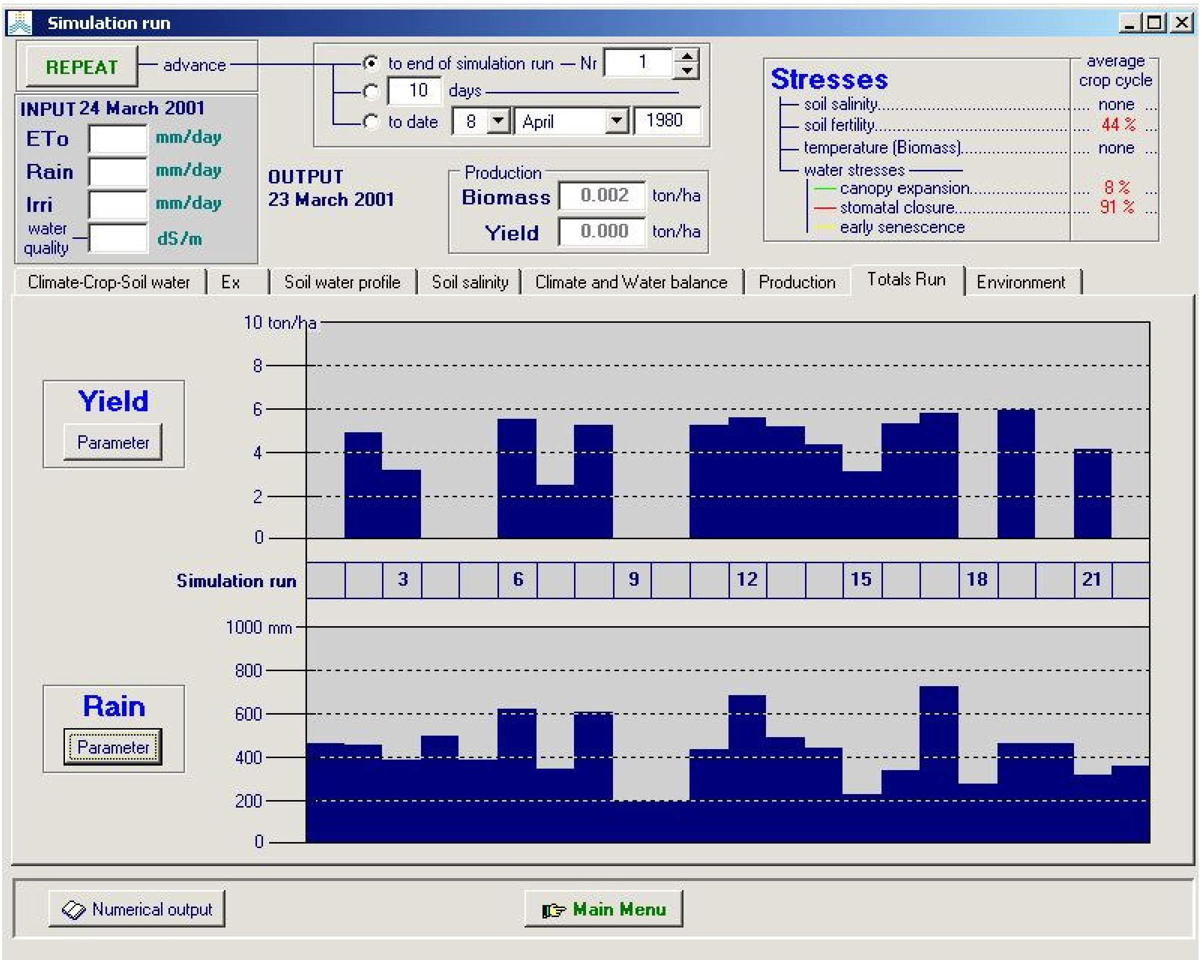


Figure 2.20f
Information on the simulated yield and total rainfall (during the simulation period) for the successive years of a multiple run project in the *Simulation run* menu

Table 2.20b
Parameters that can be selected for display in 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	Crop transpiration	mm
Tr/Trx	Crop 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
Ccyle	Length of crop cycle	day
SaltStr	Average salinity stress	%
FertStr	Average soil fertility stress	%
TempStr	Average temperature stress (biomass)	%
ExpStr	Average leaf expansion stress	%
StStr	Average stomatal stress	%
Biomass	Biomass	ton/ha
Brelative	Relative Biomass (Ref: optimal conditions)	%
HI	Harvest Index	-
Yield	Yield	ton/ha
WPet(Y)	ET water productivity (for yield)	kg/m^3

- **Simulated environment sheet**

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. 2.20g).

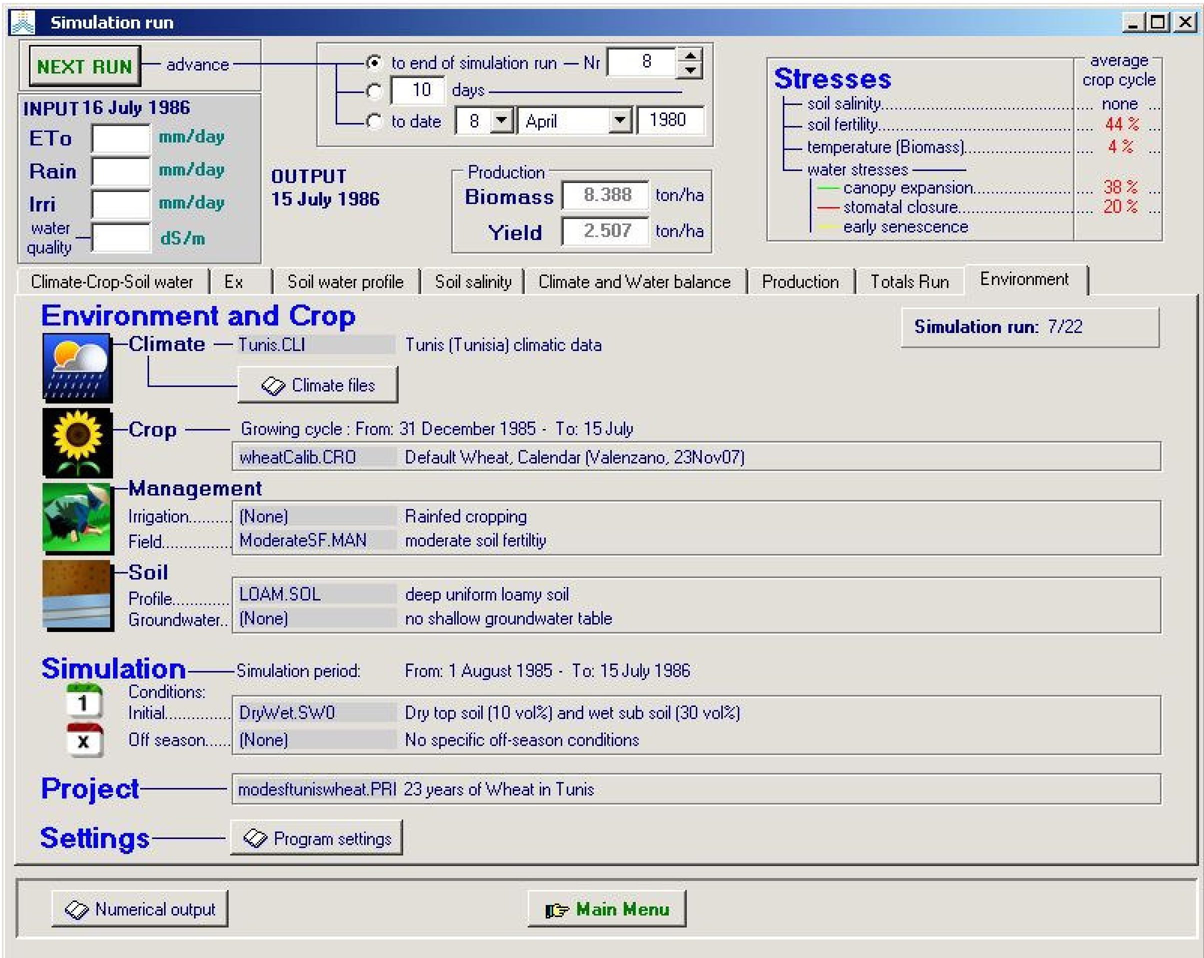


Figure 2.20g
Display of the selected input files in the *Simulation run* menu

2.20.2 Numerical output

Simulation results are recorded in output files and the data can be displayed by clicking on the **<Numerical output>** command in the ***Simulation run*** menu (Fig. 2.20h). The data can be aggregated in 10-day, monthly or yearly data.

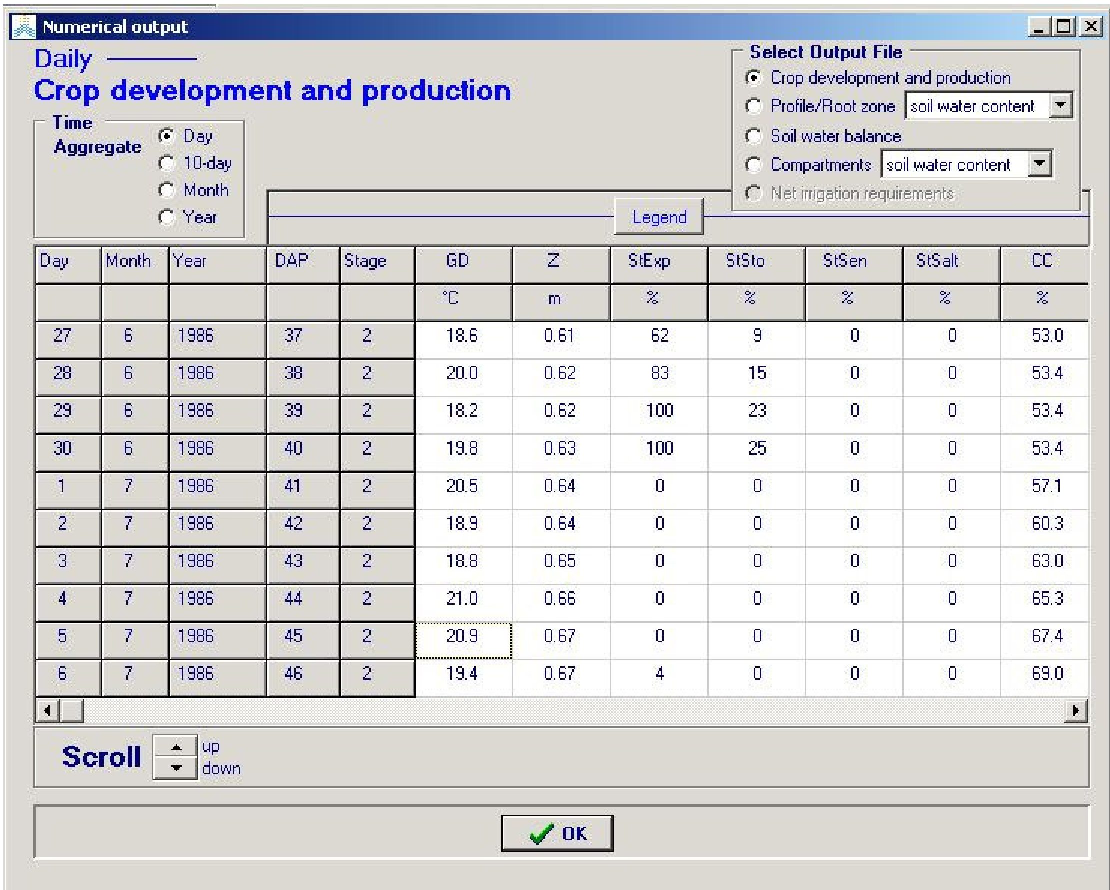


Figure 2.19h
Display of data recorded in output files

2.20.3 Evaluation of simulation results

When running a simulation, users can evaluation the simulation results with the help of the field data stored in an observation file (see 2.19 Field observations). The user gets access to the ***Evaluation of simulation results*** menu by clicking on the **<Observations>** command in the command panel of the ***Simulation run*** menu (Fig. 2.20i).

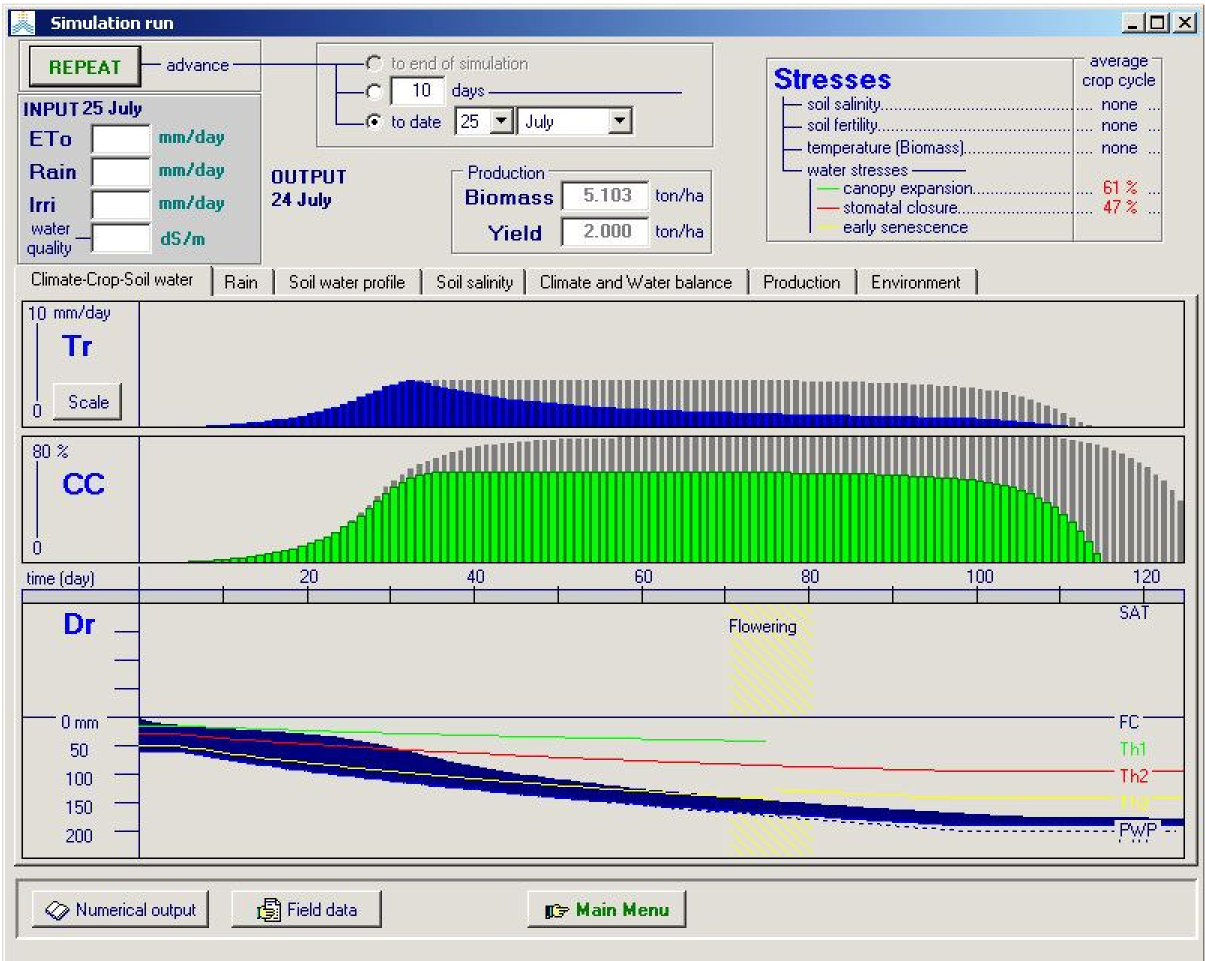


Figure 2.20i – The ***Simulation run*** menu with the **<Observations>** command in the command panel.

- **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. 2.20j);
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. 2.20k).

The assessment can be saved on disk for later use.

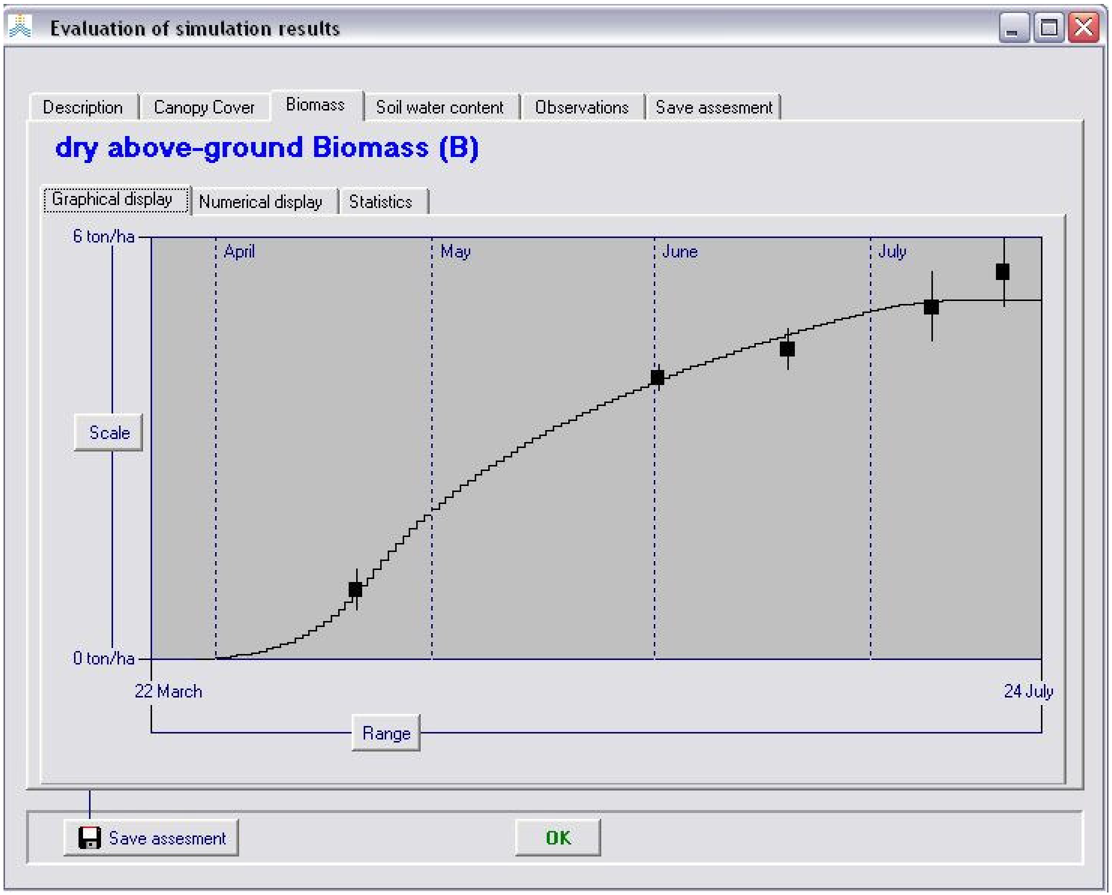


Figure 2.20j – Simulated (line) and observed (dots) dry above-ground Biomass with their standard deviations (vertical lines) in the ***Evaluation of simulation results*** menu.

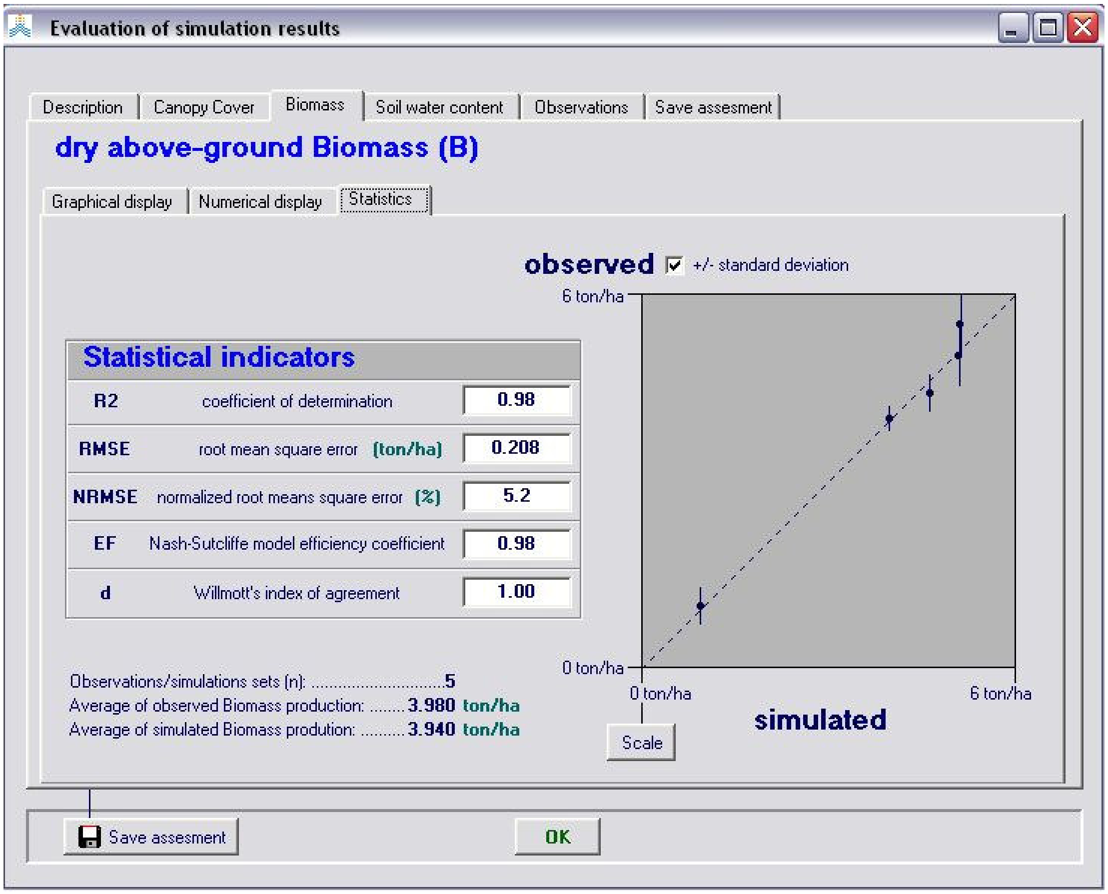


Figure 2.20k – Statistical indicators for the assessment of the simulated dry above-ground Biomass in the ***Evaluation of simulation results*** menu.

- **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 8.4a to 8.4e, O_i and P_i are the observations and predictions respectively, $\bar{O}$ and $\bar{P}$ their averages and n the number of observations.

Coefficient of determination (R^2)

The coefficient of determination r^2 is defined as the squared value of the Pearson correlation coefficient. r^2 signifies the proportion of the variance in measured data explained by the model, or can also be interpreted as the squared ratio between covariance and the multiplied standard deviations of the observations and predictions. It ranges from 0 to 1, with values close to 1 indicating a good agreement, and typically values greater than 0.5 are considered acceptable in watershed simulations (Moriasi et al., 2007).

$$r^2 = \left[\frac{\sum \left(O_i - \overline{O}\right)\left(P_i - \overline{P}\right)}{\sqrt{\sum \left(O_i - \overline{O}\right)^2 \sum \left(P_i - \overline{P}\right)^2}} \right]^2 \tag{8.4a}$$

A major drawback of 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.

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.

$$RMSE = \sqrt{\frac{\sum (P_i - O_i)^2}{n}} \tag{8.4b}$$

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 (NRMSE)

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 variable ($\overline{O}$). The normalized RMSE (NRMSE) is expressed as a percentage and gives an indication of the relative difference between model and observations.

$$NRMSE = \frac{1}{\overline{O}} \sqrt{\frac{\sum (P_i - O_i)^2}{n}}\, 100 \tag{8.4c}$$

A simulation can be considered excellent if NRMSE is smaller than 10%, good if between 10 and 20%, fair if between 20 and 30% and poor if larger than 30%.

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.

$$EF = 1 - \frac{\sum (P_i - O_i)^2}{\sum \left(O_i - \bar{O}\right)^2} \tag{8.4d}$$

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).

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.

$$d = 1 - \frac{\sum (P_i - O_i)^2}{\sum \left(|P_i - \bar{O}| + |O_i - \bar{O}| \right)^2} \tag{8.4e}$$

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).

References

Jacovides, C. P., and Kontoyiannis, H. (1995). Statistical procedures for the evaluation of evapotranspiration computing models. Agricultural Water Management 27, 365–371.

Krause, P., Boyle, D. P., and Bäse, F. (2005). Advances in Geosciences Comparison of different efficiency criteria for hydrological model assessment. Advances In Geosciences, 89–97.

Legates, D. R., and McCabe, G. J. (1999). Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. Water Resources Research 35, 233–241.

Loague, K., and Green, R. E. (1991). Statistical and graphical methods for evaluating solute transport models: Overview and application. Journal of Contaminant Hydrology 7, 51–73.

Moriasi, D. N., Arnold, J. G., Liew, M. W. V., Bingner, R. L., Harmel, R. D., and Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions Of The ASABE 50, 885–900.

Willmott, C. J. (1984). On the evaluation of model performance in physical geography. In Spatial Statistics and Models, Gaile GL, Willmott CJ (eds). D. Reidel: Boston. 443–460.

Willmott, C. J. (1982). Some Comments on the Evaluation of Model Performance. Bulletin American Meteorological Society 63, 1309–1313.

2.20.4 Output files

On exit of the ***Simulation run*** menu, the option is available to save the output on disk. Distinction is made between files containing daily simulation results and seasonal results. The files are stored by default in the OUTP directory of AquaCrop. By using different filenames (and even directories), the user can prevent that the simulation results are overwritten at each run. (Fig. 2.20l).

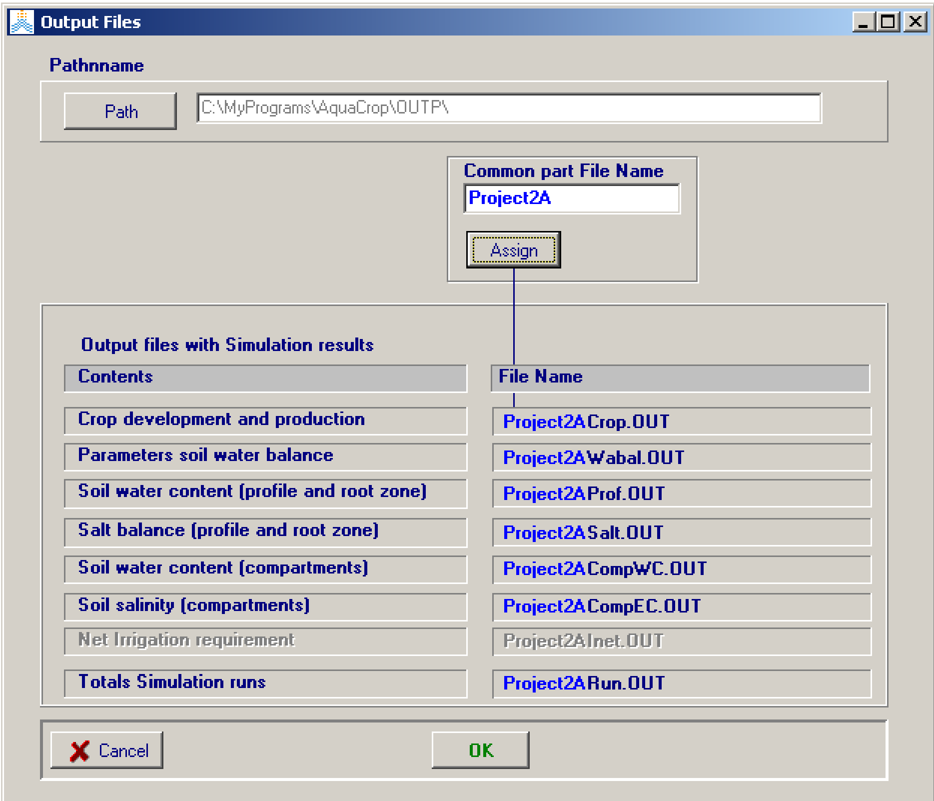


Figure 2.20l
Specification of the path and file name for the Output files

- **Daily results**

The output of the daily results consists of 7 files containing key variables (Tab.2.20c). In section 2.23 (Output files) the list of key variables is presented.

- **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 2.23 (Output files). The data in the files can be retrieved in spread sheet programs for further processing and analysis.

Table 2.20c
Default file name and content of the 7 output files with daily simulation results

Default file name	Content
ProjectCrop.OUT	18 key variables for crop development and production
ProjectWabal.OUT	17 key variables for soil water balance
ProjectProf.OUT	10 key variables for soil water content – Profile/Root zone
ProjectSalt.OUT	10 key variables for soil salinity – Profile/Root zone
ProjectCompWC.OUT	12 key variables for soil water content – Compartments
ProjectCompEC.OUT	12 key variables for soil salinity – Compartments
ProjectInet.OUT	5 key variables for net irrigation requirement

Input/Output and program settings Files

When installing AquaCrop, the installation program (i) creates a FAO folder, (ii) creates the 'AQUACROP' folder (if not yet available) in the FAO folder, and (iii) finally installs the software in C:\ FAO\AquaCrop

```
C:\ ---- |-
         |-
         |-
         |-
         |- FAO -------- |-
         |-              |- AQUACROP ------- |- DATA
                            AquaCrop.EXE     |
                            Default.PAR      |- OUTP
                            General.PAR      |
                            Planting.PAR     |- OBS
                            Onset.PAR        |
                            Soil.PAR         |- SIMUL
                            Rainfall.PAR
                            Crop.PAR
                            Field.PAR
                            Temperature.PAR
                            DEFAULT.CRO
                            DEFAULT.SOL
                            SOILS.DIR
```

If AquaCrop is correctly installed, the AquaCrop folder should contain:
(i) the following files:
- AquaCrop.EXE (the executable file);
- Files with default project settings (*.PAR);
- Files with default Crop and Soil parameters: DEFAULT.CRO, DEFAULT.SOL;
- SOILS.DIR (a file with default values for soil characteristics).

(ii) and four subdirectories:
- DATA (default subdirectory for the input files);
- OUTP (default subdirectory for the output files);
- OBS (default subdirectory for the field observations files);
- SIMUL (subdirectory for simulation purposes, containing between other files the MaunaLoa.CO2 file).

2.21 Input files

The input is stored in text files which are retrieved through the user-interface. By default the input files are stored in the DATA subdirectory of the AquaCrop folder. Distinction is made between:

- Climate files (*.CLI) which contains the names of a set of files containing
  - air temperature data (*.TMP),
  - reference evapotranspiration data (*.ETo),
  - rainfall data (*.PLU), and
  - atmospheric CO_2 data (*.CO2);
- Crop files (*.CRO) containing crop characteristics;
- Irrigation files (*.IRR) containing, apart from the irrigation method, (i) information for the calculation of the net irrigation requirement, (ii) the timing, applied irrigation amounts and the irrigation water quality of an irrigation schedule, or (iii) information for generating irrigation schedules;
- Field management files (*.Man) containing characteristics of the field on which the crop is cultivated;
- Soil profile files (*.SOL) containing characteristics of the soil profile;
- Groundwater files (*.GWT) containing characteristics of the groundwater table;
- Files with the specific conditions in the soil profile at the start of the simulation period (*.SW0);
- Files with off-season field management conditions (*.OFF); and
- Single run project files (*.PRO) containing information on the growing and simulation period, the settings of program parameters, and the names of the set of input files describing the environment, and the initial and off-season conditions;
- Multiple runs project files (*.PRM) containing information on the settings of program parameters and on the growing and simulation period, names of the set of input files describing the environment, and the initial and off-season conditions for each of the runs.

Also field observations can be stored in text files and retrieved through the user-interface for the evaluation of simulations results. By default the field observations files are stored in the OBS subdirectory of the AquaCrop folder.

- Files with field observations (*.OBS).

2.21.1 Climate file (*.CLI)

A climate file (Tab. 2.21a, Fig. 2.21) contains next to its description and the reference of the AquaCrop version, the names of the air temperature file (*.TMP), ETo file (*.ETo), rainfall file (*.PLU), and CO_2 file (*.CO2).

Table 2.21a
Example of a climate file (files with extension CLI)

```
Tunis (Tunisia) climatic data
 4.0     : AquaCrop Version (May 2012)
Tunis.TMP
Tunis.ETo
Tunis7902.PLU
MaunaLoa.CO2
```

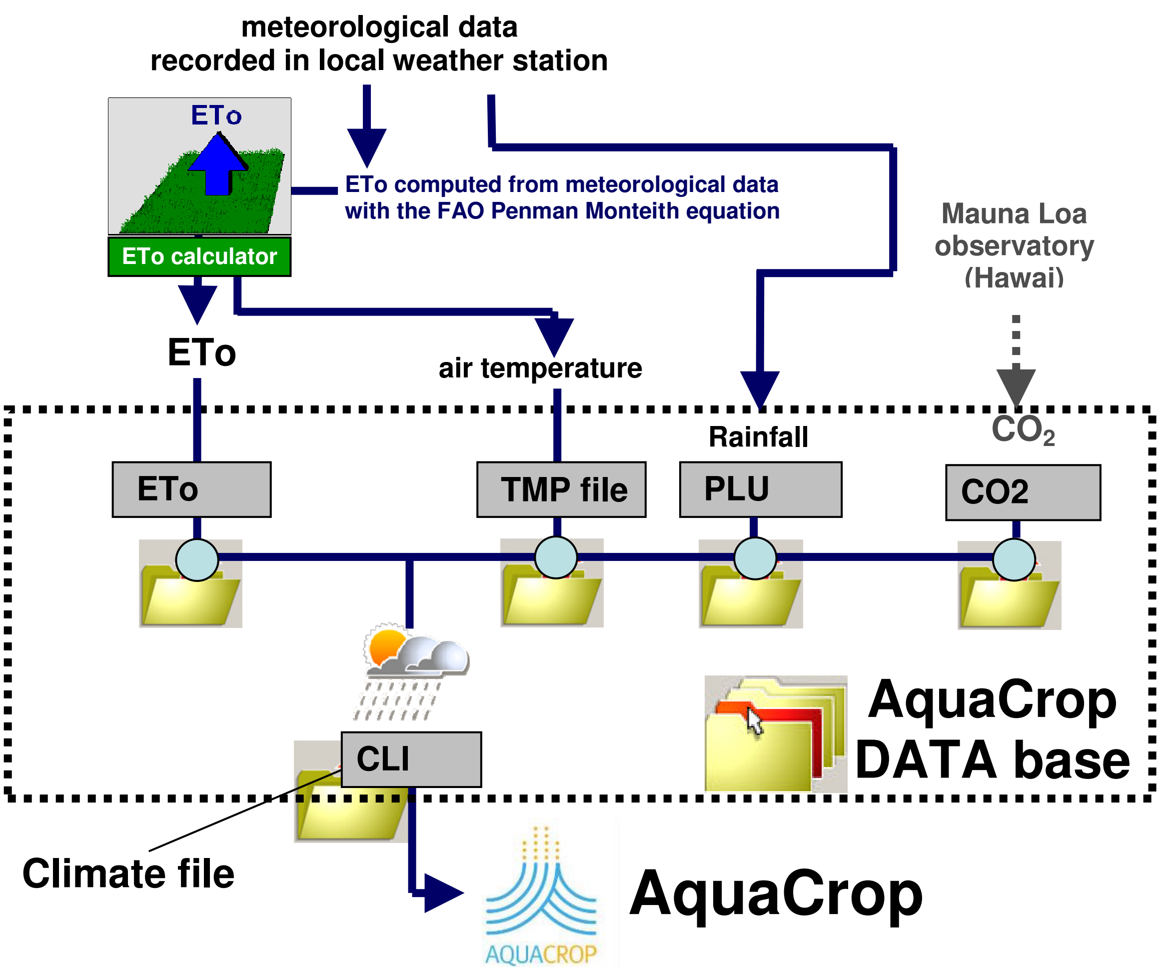


Fig 2.21 – Climatic data and Climate file

2.21.2 Temperature (*.TMP), ETo (*ETo) and rainfall (*.PLU) files

Temperature (Tab. 2.21b), ETo (Tab. 2.21c) and Rainfall files (Tab. 2.21d) 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).

Table 2.21b
Structure of an air temperature file (files with extension TMP)

Line	File content
1	First line is a description which is displayed when selecting the file
2	1 : Daily records (1=daily, 2=10-daily and 3=monthly data)
3	1 : First day of record (1, 11 or 21 for 10-day or 1 for months)
4	1 : First month of record
5	1999 : First year of record (1901 if not linked to a specific year)
6	
7	Tmin (°C) TMax (°C)
8	========================
9	7.0 15.0
10	8.0 16.0
11	9.0 18.0

Table 2.21c
Structure of an ETo file (files with extension ETo)

Line	File content
1	First line is a description which is displayed when selecting the file
2	1 : Daily records (1=daily, 2=10-daily and 3=monthly data)
3	1 : First day of record (1, 11 or 21 for 10-day or 1 for months)
4	1 : First month of record
5	1999 : First year of record (1901 if not linked to a specific year)
6	
7	Average ETo (mm/day)
8	========================
9	1.0
10	1.1
11	1.2

Table 2.21d
Structure of a Rainfall file (files with extension PLU)

Line	File content
1	First line is a description which is displayed when selecting the file
2	1 : Daily records (1=daily, 2=10-daily and 3=monthly data)
3	1 : First day of record (1, 11 or 21 for 10-day or 1 for months)
4	1 : First month of record
5	1999 : First year of record (1901 if not linked to a specific year)
6	
7	Total Rain (mm)
8	========================
9	0.0
10	0.0
11	16.6

2.21.3 CO2 file (*.CO2)

A CO2 file contains mean annual atmospheric CO_2 data (in ppm) for a series of years arranged in chronological order. 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). When creating CO2 file, the structure of the file needs to be respected (Tab. 2.21e).

Table 2.21e
Structure of a CO2 file (files with extension CO2)

Line	File content	Explanation
1	First line is a description	description
2	Year CO2 (ppm by volume)	title
3	============================	title
4	1940 310.5	year(1) and corresponding CO_2
5	1960 316.91	year(2) and corresponding CO_2
6	1961 317.65	year(3) and corresponding CO_2
...	... .	....
n-1	2007 383.72	year(n-1) and corresponding CO_2
n	2020 409.72	year(n) and corresponding CO_2

2.21.4 Crop file (*.CRO)

2.21.5 Irrigation file (*.IRR)

2.21.6 Field management file (*.MAN)

2.21.7 Soil profile file (*.SOL)

2.21.8 Groundwater file (*.GWT)

2.21.9 File with initial conditions (*.SW0)

2.21.10 File with off-season conditions (*.OFF)

2.21.11 Single run Project file (*.PRO)

2.21.12 Multiple run project file (*.PRM)

2.21.13 File with field data (*.OBS)

2.22 Files with program settings

2.23 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 and seasonal results. The output files with daily data contain information on the:

- 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 parameters of the soil water balance;
- Net irrigation water requirement.

The variables listed in the output files are given in 2.23.1 to 2.23.7. The variables listed in the seasonal output file are given in 2.23.8. The data in the files can be retrieved in spread sheet programs for further processing and analysis.

2.23.1 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	CC	Green canopy cover	%
13	Kc(Tr)	Crop coefficient for transpiration	-
14	Trx	Maximum crop transpiration	mm
15	Tr	Actual crop transpiration	mm
16	T/Tx	Relative transpiration (100 Tr/Trx)	%
17	WP	Crop water productivity adjusted for CO_2, soil fertility and products synthesized	g/m^2

18	StBio	Percent temperature stress affecting biomass production	%
19	Biomass	Cumulative biomass produced	ton/ha
20	HI	Harvest Index adjusted for failure of pollination, inadequate photosynthesis and water stress	%
21	Yield Part	Yield (HI x Biomass)	ton/ha
22	Brelative	: Relative biomass (Reference: no water, no soil fertility, no soil salinity stress)	%
23	WPet	ET Water productivity for yield part (kg yield produced per m3 water evapotranspired)	kg/m^3

2.23.2 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	Ex	Maximum soil evaporation	mm
15	E	Actual soil evaporation	mm
16	E/E	Relative evaporation (100 E/EX)	%
17	Trx	Maximum crop transpiration	mm
18	Tr	Actual crop transpiration	mm
19	T/T	Relative transpiration (100 Tr/Trx)	%
20	ETx	Maximum evapotranspiration	mm
21	ET	Actual evapotranspiration	mm
22	ET/ETx	Relative evapotranspriation (100 ET/ETx)	%

2.23.3 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

2.23.4 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	SaltTot	Salt content in the total soil profile	ton/ha
9	SaltZ	Salt content in the effective root zone	ton/ha
10	Z	Effective rooting depth	m
11	ECe	Electrical conductivity of the saturated soil-paste extract from the root zone	dS/m
12	ECsw	Electrical conductivity of the soil water in the root zone	dS/m
13	StSalt	Salinity stress	%
14	Zgwt	Depth of the groundwater table	m
15	ECgw	Electrical conductivity of the groundwater	dS/m

2.23.5 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

2.23.6 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

2.23.7. 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

2.23.8. 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	
7	GD	Growing degrees	
8	CO2	Atmospheric CO2 concentration	
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	
12	Drain	Water drained out of the soil profile	
13	Upflow	Water moved upward by capillary rise	
14	E	Soil evaporation	mm
15	E/Ex	Relative soil evaporation (100 E/Ex)	%
16	Tr	Crop transpiration	mm
17	Tr/Trx	Relative crop transpiration (100 Tr/Trx)	%
18	SaltIn	Salt infiltrated in the soil profile	
19	SaltOut	Salt drained out of the soil profile	
20	SaltUp	Salt moved upward by capillary rise from groundwater table	
21	SaltProf	Salt stored in the soil profile	ton/ha
22	Cycle	Length of crop cycle: from germination to maturity (or early senescence)	
23	SaltStr	Average soil salinity stress	
24	FertStr	Average soil fertility stress	
25	TempStr	Average temperature stress (affecting biomass)	
26	ExpStr	Average leaf expansion stress	
27	StoStr	Average stomatal stress	
28	Biomass	Cumulative biomass produced	ton/ha
29	Brelative	Relative biomass (Reference: no water, no soil fertility, no soil salinity stress)	
30	HI	Harvest Index adjusted for failure of pollination, inadequate photosynthesis and water stress	%
31	Yield	Yield (HI x Biomass)	
32	WPet	ET Water Productivity for yield part (kg yield produced per m3 water evapotranspired)	kg/m^3
33	DayN	End day of simulation run	-
34	MonthN	End month of simulation run	-
35	YearN	End year of simulation run	-