Chapter 2

Users guide

AquaCrop

Reference Manual
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with contributions of the AquaCrop Network

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Acknowledgments

List of principal symbols

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The FAO crop model to simulate yield response to water

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Chapter 2.
Users guide

Running AquaCrop

2.1 The AquaCrop environment

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

From the ***Main menu*** the user has access to a whole set of menus where input data is displayed and can be updated. Input consists of weather data, crop, management and soil 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. Input can be retrieved from input files. In the absence of input files, default settings are assumed.

When running a simulation the user can in the ***Simulation run*** menu track changes in soil water 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

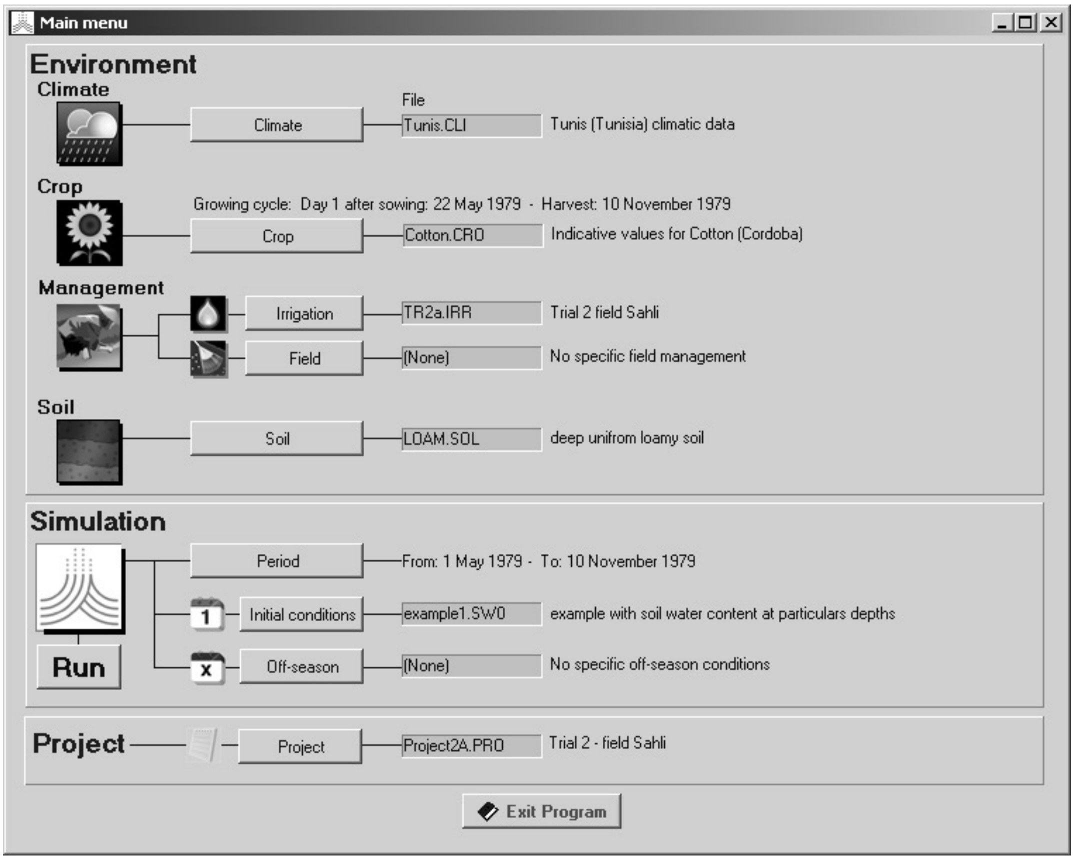


Figure 2.2
Main menu of AquaCrop

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) and Soil profile 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 panel: where project can be saved and project files retrieved.

2.3 Default settings at start

2.3.1 Selected input

When AquaCrop starts it runs with a default crop and soil file. No other files (files are '(None)') are selected. In the absence of climate, irrigation scheduling, field management, initial and off-season conditions files, default settings are assumed. These settings consist of:

- **Climate**: 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, the user has the option to specify other than the default ETo and rainfall data. In the Input panel of the ***Simulation run*** menu the data can be adjusted for each day of the simulation period;
- **Irrigation**: Rainfed cropping is assumed. When running a simulation in this mode, irrigation time and depths can be specified in the Input panel of the ***Simulation run*** menu;
- **Field management**: No specific field management conditions are considered. It is assumed that soil fertility is unlimited, and that field surface practices does not hamper soil evaporation or surface run-off;
- **Initial conditions**: The soil water content in the soil profile at the start of the simulation is assumed to be at field capacity;
- **Off-season conditions**: No specific field management conditions are considered outside the growing period. When running a simulation there are no irrigation events in the off-season and mulches does not cover the field surface.

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

2.3.2 Program settings

2.4 Displaying and updating input characteristics

From the ***Main menu*** the user has access to a whole set of menus where input data retrieved from files is displayed (Fig. 2.4). In the absence of an input file (file is '(None)') the default settings (see 2.3) are assumed. 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).

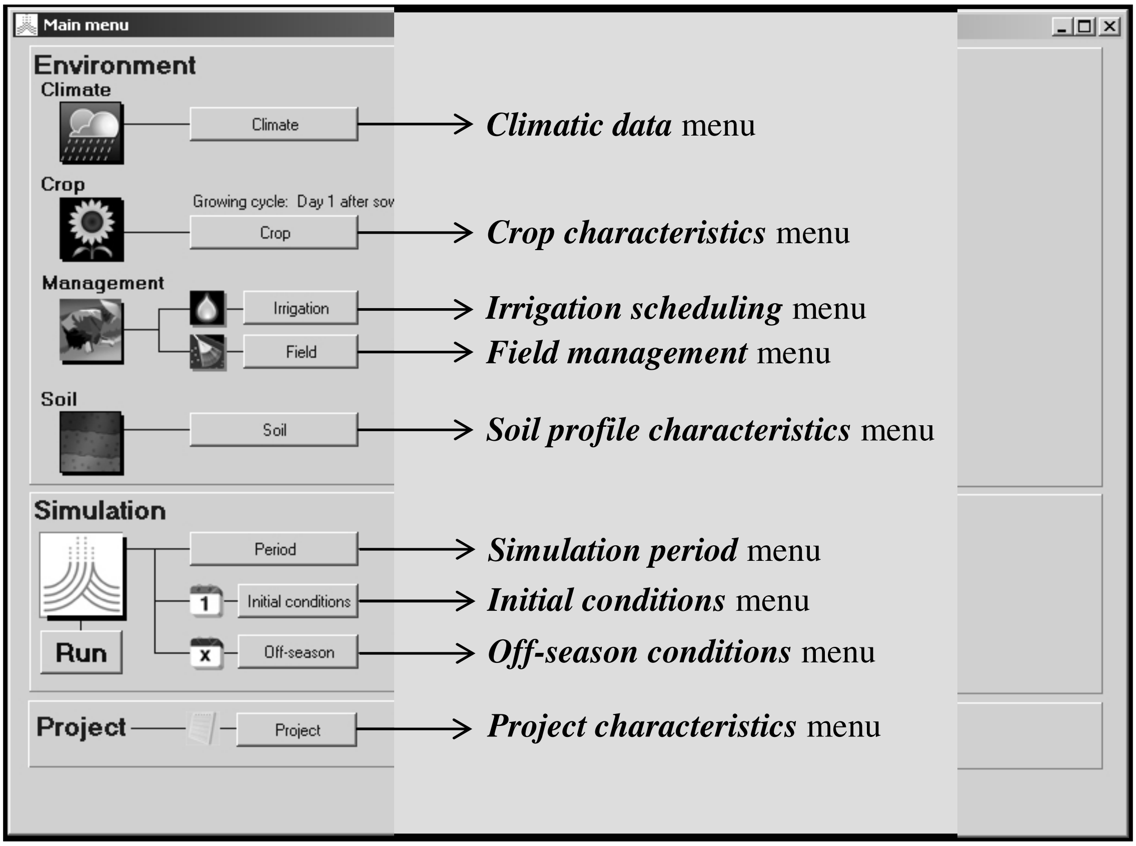


Figure 2.4
Set of menus to display and update input data

In the Menu reference of this Chapter the menus displaying the characteristics of the input data are described (sections 2.8 to 2.17).

2.5 Selecting input files and undoing the selection

From the ***Main menu*** the user has access to the data base(s) where the files are stored (Fig. 2.5). The default data base is the DATA subdirectory of the AquaCrop folder. With the **<Path>** command the user can specify other directories.

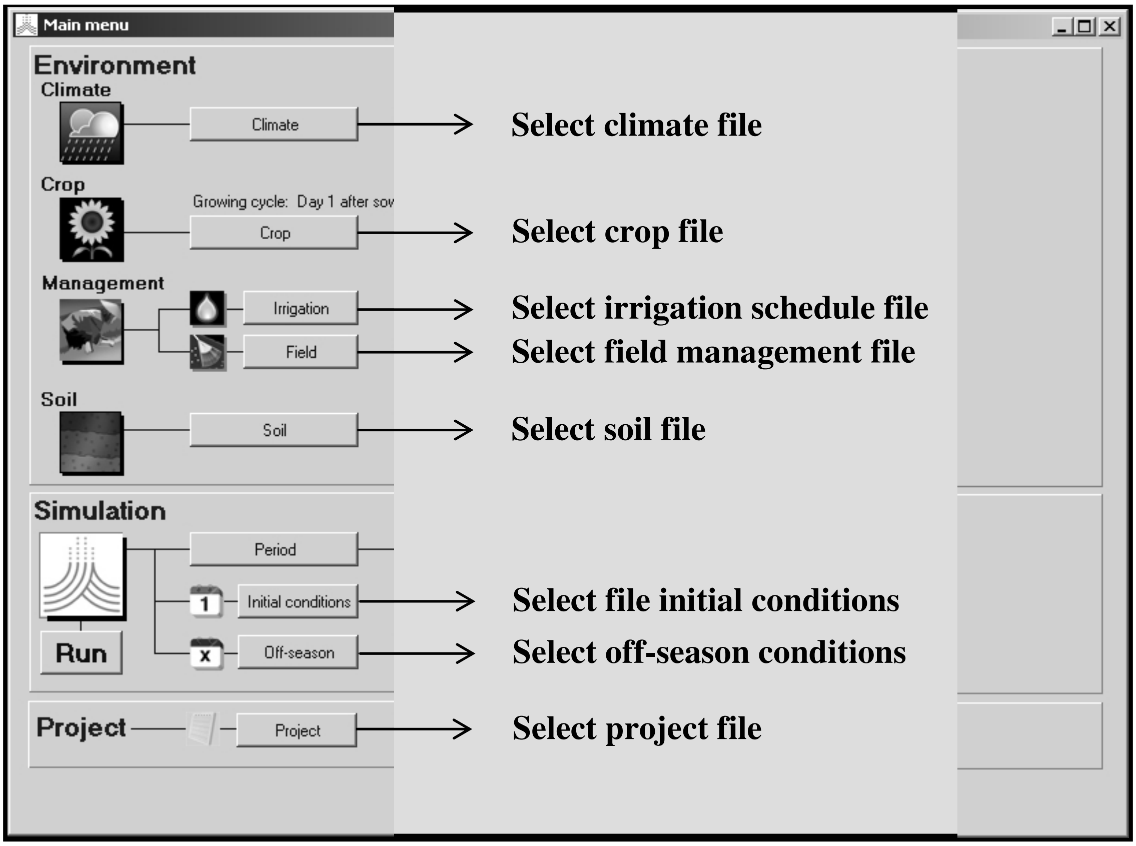


Figure 2.5
Set of menus to retrieve input files from the data base

2.5.1 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. An input file is selected by clicking on its name in the list.

2.5.2 Undo the selection

When a climate, irrigation, field management, initial conditions, off-season conditions, 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 selecting the **<UNDO selection>** command in the ***Select file*** menu.

2.6 Creating input files

After updating the characteristics in one of the menus (see 2.4), an input file is created by selecting the **<Save on disk>** command (Figure 2.6). If the displayed data in the characteristic menu was retrieved from an input file, 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.

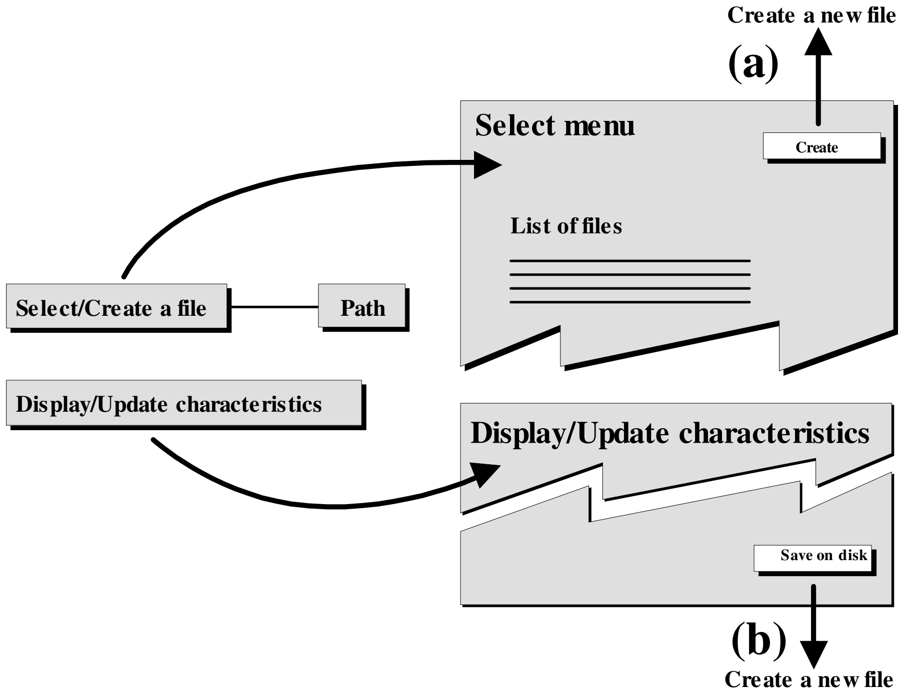


Figure 2.6
Options available to create input files by means of the user interface

Special designed menus to create an input file are only available for climate, crops, irrigation schedules, and soil data. The ***Create file*** menus are displayed by selecting the **<Create new file>** command in the ***Select file*** menu (Fig. 2.6).

- ***Create climate file* menu:** Creating a climate file consists in selecting or creating a Temperature file, ETo file, Rain file and CO_2 file.

- ***Create ETo file*, *Create Rain file* or *Create Temperature file* menu:** 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 2.19).

- ***Create crop file* menu:** 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. 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.

- ***Create irrigation schedule* menu:** When creating an irrigation schedule the user specifies the time and application depth of the irrigation events.

- ***Create soil file* menu:** When creating a soil file, the user has to specify only a few characteristics. With the help of this information AquaCrop generates the complete set of soil parameters. The parameters are displayed and the values can be adjusted in the ***Soil profile characteristics*** menu.

2.7 To exit and close a menu

Commands to exit a menu are available 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 command selected to close the menu. 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 is not retrieved from an input file, 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.

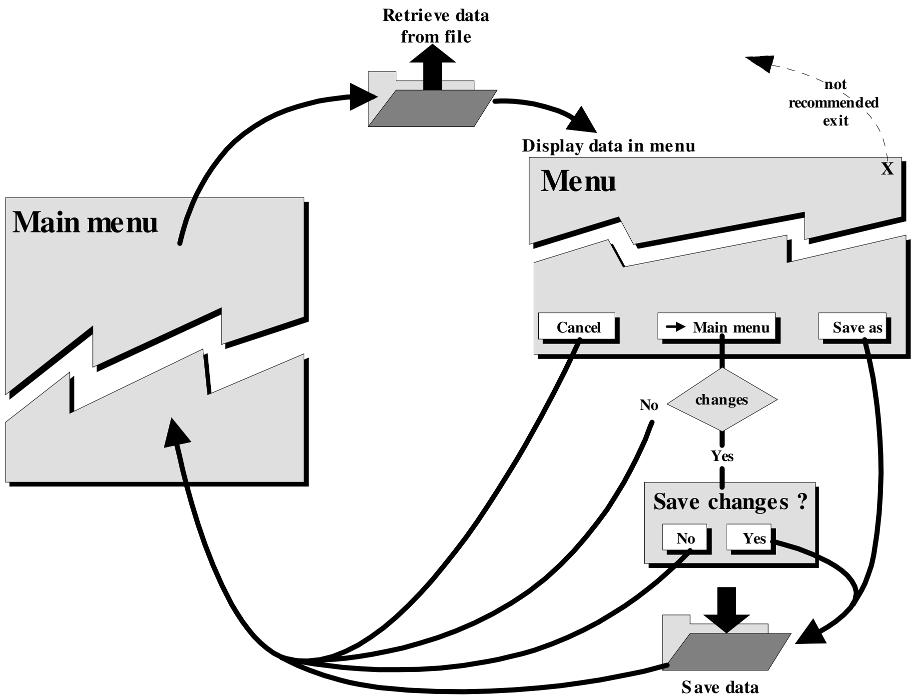


Figure 2.7
Options to exit and close a menu

Menu reference

Main menu

- **Select/Create file**
  - Create climate file
    - Create ETo file
    - Create Rain file
    - Create Temperature file
  - Create crop file
  - Create irrigation schedule
  - Create soil file
  - Set Path
- **Climatic data**
  - Display/Update Temperature data
  - Program settings: Temperature parameters
  - Display/Update ETo data
  - Display/Update Rainfall data
  - Program settings: 10-day or Monthly rainfall
- **Crop characteristics**
  - Estimate plant density
  - Adjustment of harvest index
  - Calibration soil fertility
  - Program settings: Crop parameters
  - **Onset**
- **Irrigation scheduling**
- **Field management**
  - Program settings: Field parameters
- **Soil profile characteristics**
  - List characteristics of soil types
  - Management soil type characteristics
  - Program settings: run-off
- **Simulation period**
- **Initial conditions**
  - Program settings: Simulation run
- **Off-season conditions**
- **Project characteristics**
- **Simulation run**
  - Numerical output
  - Output files
    - Set Path

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 and are plotted 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.

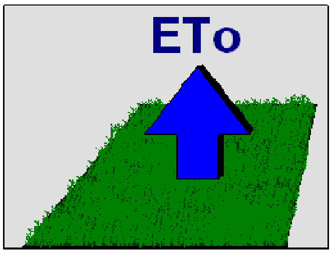
2.8.2 Reference evapotranspiration (ETo)

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 (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
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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. 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

Program settings are available in the ***Climatic data*** menu:

- to select a method to estimate growing degree days from the air and the crop base and upper temperature (see Chapter 3);
- to alter the default minimum and maximum air temperature in the absence of a temperature file.
- to select a procedure to estimate surface runoff and effective rainfall when rainfall data consists of 10-day or monthly totals. More information on the processing of 10-day and monthly rainfall data is given in Chapter 3.

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

2.9 Crop characteristics

The crop characteristics required by the program are displayed and can be adjusted in the ***Crop characteristics*** menu (Fig 2.9a). The number and type of crop parameters varies slightly with the crop types selected when creating a new crop in AquaCrop. 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 (flowering information and yield formation are not considered);
- root and tuber crops (with a yield formation period, starting at root/tuber 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).

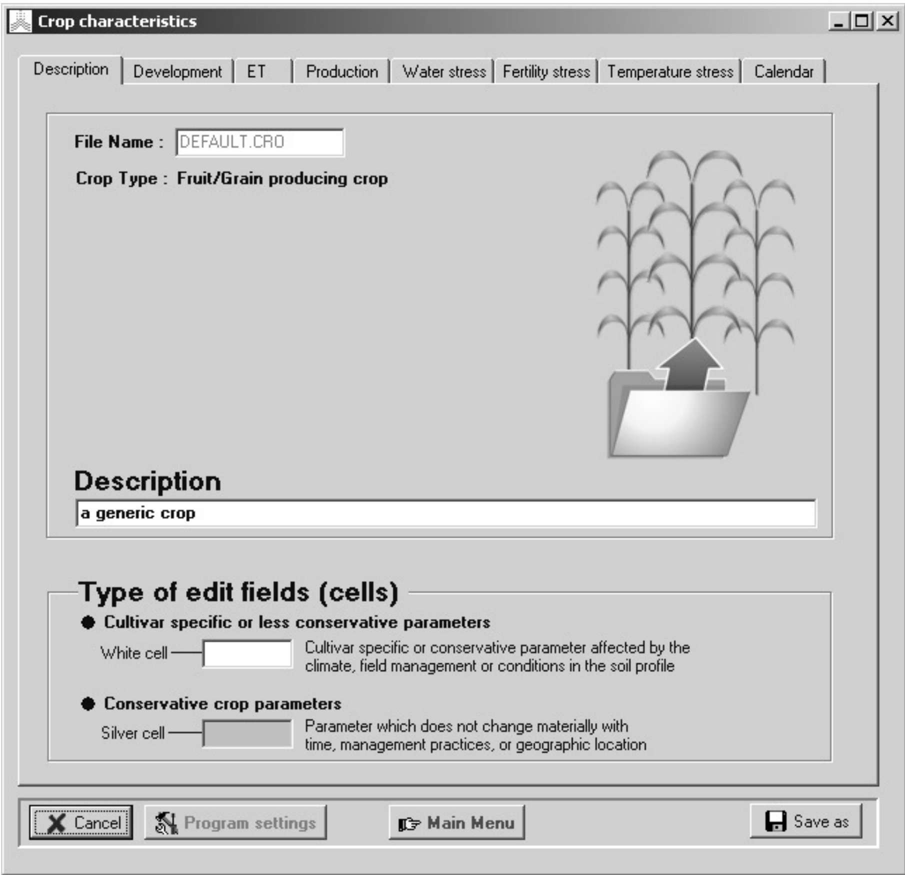


Figure 2.9a
First page of the *Crop characteristics* menu showing different tabs in the top line

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

- Description
- Development
    - Initial canopy cover
    - Canopy development
    - Flowering and yield formation
    - Root deepening
    - Temperatures
- ET
    - Kcb and Ke coefficients
    - Water extraction pattern
- Production
    - Crop water productivity
    - Harvest Index
- Water stress
    - Leaf expansion growth
    - Stomatal closure
    - Early canopy senescence
    - Aeration stress
    - Harvest Index
        - Before flowering
        - During flowering
        - During yield formation
        - Combined effect
- Fertility stress
    - Canopy
    - Water productivity
    - Biomass
    - Ks coefficients
    - Crop parameters
- Temperature stress
    - Biomass production
    - Harvest Index
- Calendar

2.9.1 Conservative and user specific parameters

Crop parameters are conservative or user specific. The conservative parameters 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 are 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 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.

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		
	Soil surface covered by an individual seedling at 90% emergence (cm^2 per plant)	Conservative (2) Management (3)
	Number of plants per hectare	Management (3)
	Time from sowing to emergence (days or GD days)	Management (3)
CGC	Canopy growth coefficient (fraction per day or 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 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 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)
	Excess of potential fruits (%)	Conservative (2)
1.4 Development of root zone		
Z_n	Minimum effective rooting depth (m)	Management (3)
Z_x	Maximum effective rooting depth (m)	Management (3)
	Shape factor describing root zone expansion	Conservative (1)
	Time from sowing to maximum rooting depth (days or GD days)	Cultivar (4) Environment (3)

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

Table 2.9a. continued.

2. Crop transpiration

Symbol	Description	Type (1), (2), (3), (4)
Kcb_x	Crop coefficient when canopy is complete but prior to senescence	Conservative (1)
	Decline of crop coefficient (%/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	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)
	Water productivity normalized for ETo and CO_2 during yield formation (as percent WP* before yield formation)	Conservative (1)

3.2 Harvest Index

HI_o	Reference harvest index (%)	Cultivar (4)
	Building up of HI (period in days or growing degree days)	Cultivar (4)
	Possible increase (%) of HI due to water stress before flowering	Conservative (1)
	Coefficient describing positive impact of restricted vegetative growth during yield formation on HI	Conservative (1)
	Coefficient describing negative impact of stomatal closure during yield formation on HI	Conservative (1)
	Allowable maximum increase (%) of specified HI	Conservative (1)

(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.

4. Stresses		
Symbol	Description	Type [(1), (2), (3), (4)]
4.1 Soil water stresses		
$p_{exp,lower}$	Soil water depletion threshold for canopy expansion - Upper threshold	Conservative [(1)]
$p_{exp,upper}$	Soil water depletion threshold for canopy expansion - Lower threshold	Conservative [(1)]
	Shape factor for Water stress coefficient for canopy expansion	Conservative [(1)]
p_{sto}	Soil water depletion threshold for stomatal control – Upper threshold	Conservative [(1)]
	Shape factor for Water stress coefficient for stomatal control	Conservative [(1)]
p_{sen}	Soil water depletion threshold for canopy senescence – Upper threshold	Conservative [(1)]
	Shape factor for Water stress coefficient for canopy senescence	Conservative [(1)]
	Sum(ETo) during 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 stress		
	Soil fertility stress at calibration (%)	(calibration)
	Shape factor for the Fertility stress coefficient for canopy expansion	Management [(3)]
	Shape factor for the Fertility stress coefficient for Maximum Canopy Cover	Management [(3)]
	Shape factor for the for the Fertility stress coefficient for Crop Water Productivity	Management [(3)]
	Shape factor for the response of Decline of Canopy Cover for limited soil fertility	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

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;
- Root deepening;
- Temperatures (required for the calculation of growing degree days).

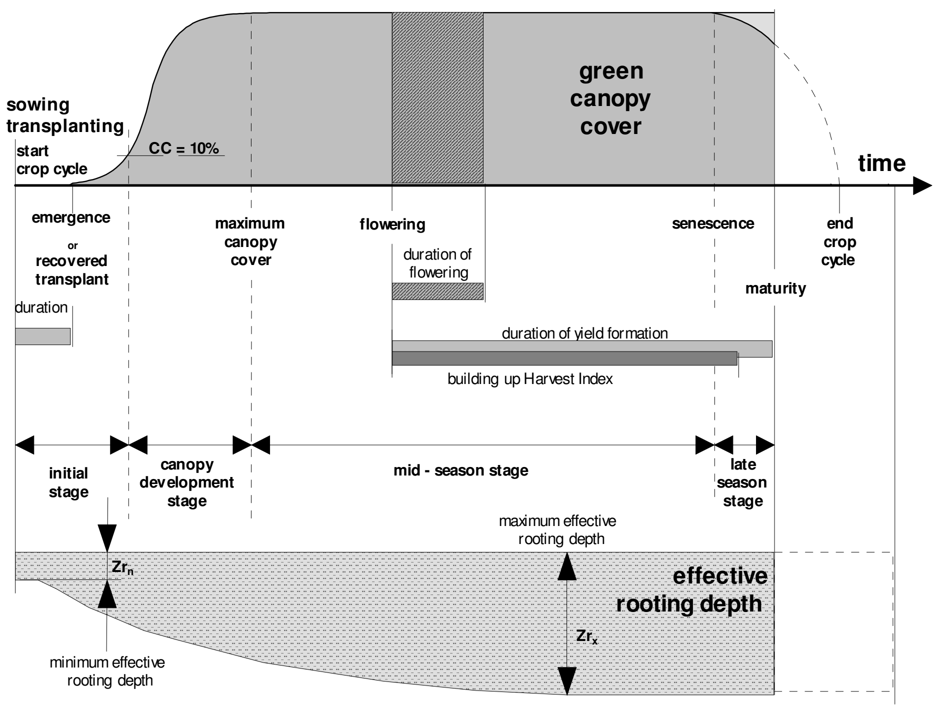


Figure 2.9b1
Schematic representation of crop development for fruit/grain producing crops

- **Initial canopy cover**

The initial canopy cover at 90% emergence (CC_o) is required in the two equations to describe canopy expansion (Chapter 3). It is the product of plant density (number of plants per hectare) and the soil surface covered by an individual seedling at 90% emergence. By clicking on the **<estimate>** command, plant density can be estimated from sowing rate and approximate germination rate, or from plant spacing (Fig. 2.9b2). The initial canopy cover can also be specified by selecting one of the classes ranging from very small to very high cover (Tab. 2.9b1) or by specifying directly the percentage in the ***Crop characteristic*** menu, which would be necessary for transplanted seedlings.

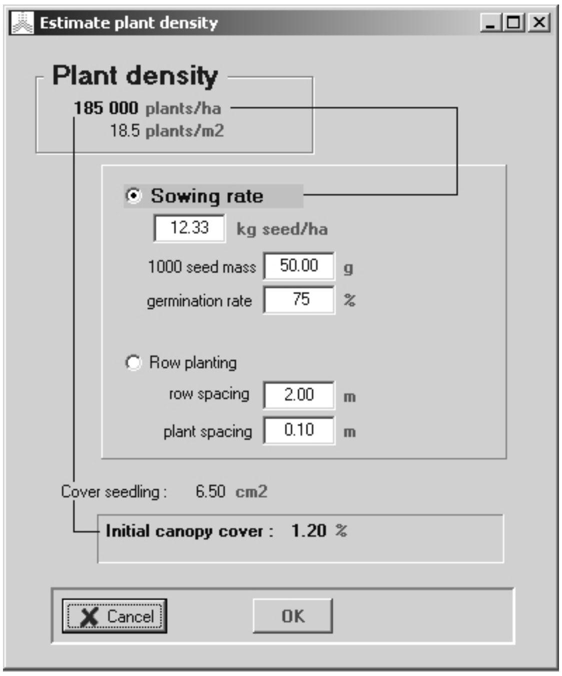


Figure 2.9b2
Estimation of plant density from sowing rate or plant density
in the *Estimate planting density* menu

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) 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, requiring a canopy decline coefficient (CDC) and the starting time. The crop parameters governing canopy expansion and decline are displayed in the canopy development sheet of the ***Crop characteristics*** menu (Fig. 2.9b3).

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

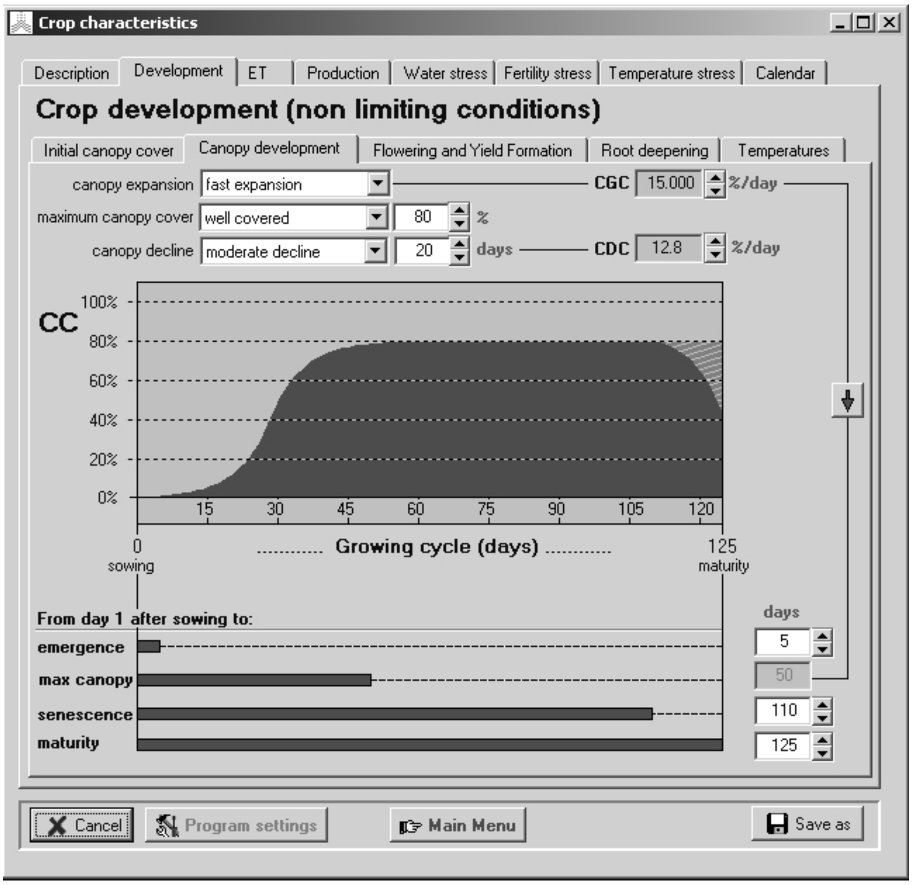


Figure 2.9b3
Specification of canopy development in the *Crop characteristics* menu

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 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).

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 2.9b2
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

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 (start of tuber formation or root enlargement) and yield formation**

The crop parameters to be specified are (i) the time of start of flowering (grain/fruit producing crops), or the start of tuber formation or root enlargement (root/tuber crops) (ii) duration of flowering, (iii) the time required to build up the Harvest Index (HI), (iv) the excess of potential fruits, and (v) the degree of determinancy (Fig. 2.9b4 and 2.9b5). These parameters are mainly cultivar specific.

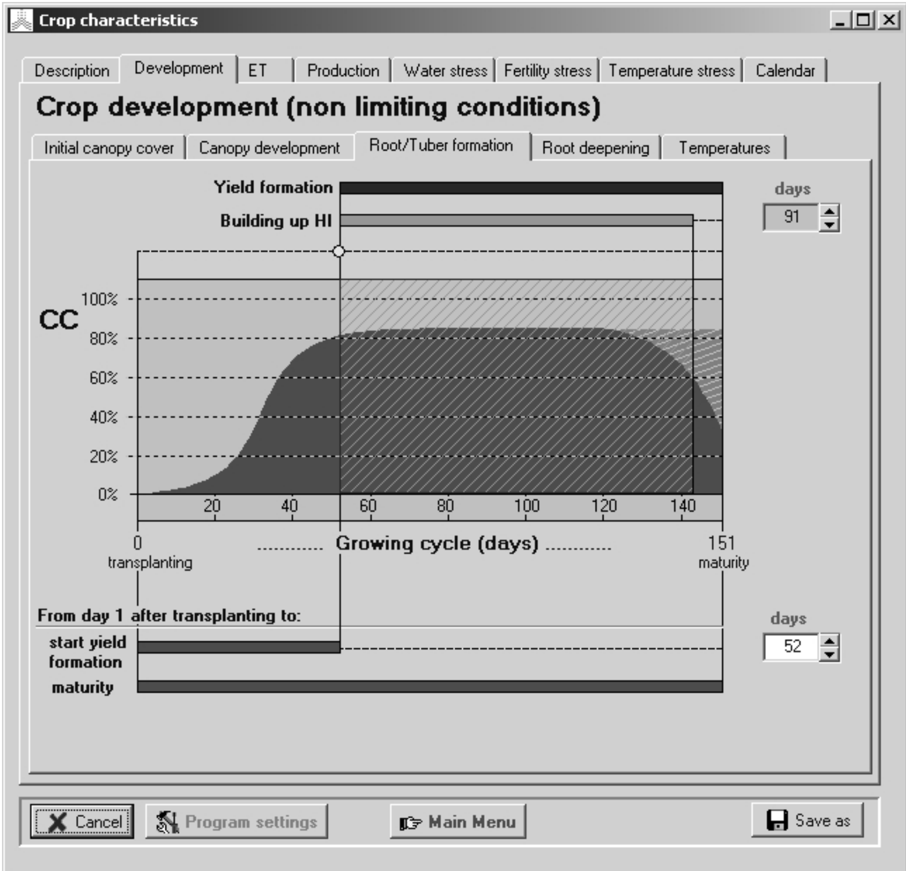


Figure 2.9b4

Specification of flowering and yield information in the *Crop characteristic* menu

If the **<Determinancy linked with flowering>** check button is checked, 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 the canopy development can stretch till canopy senescence.

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. 2.9b5).

Table 2.9b5
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

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.

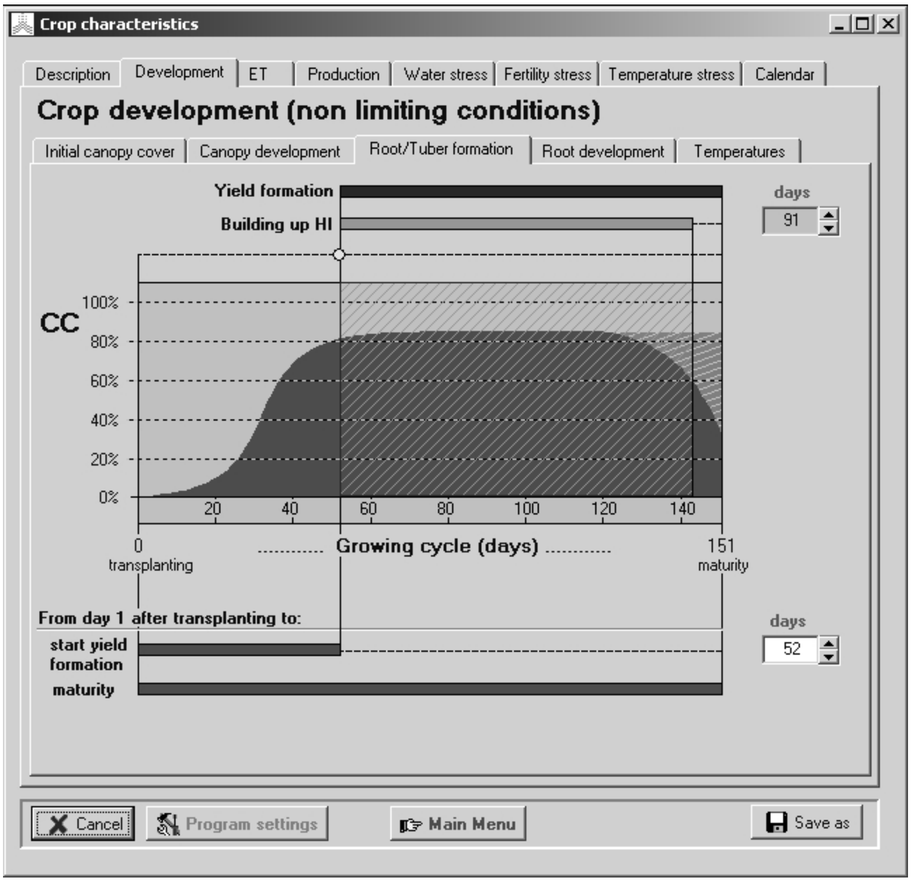


Figure 2.9b5
Specification of the start of yield formation and the yield formation for root/tuber crops in the *Crop characteristic* menu

▪ **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. 2.9b6). These parameters are user specific as root development is strongly impacted by local soil conditions and the life cycle length of the crop.

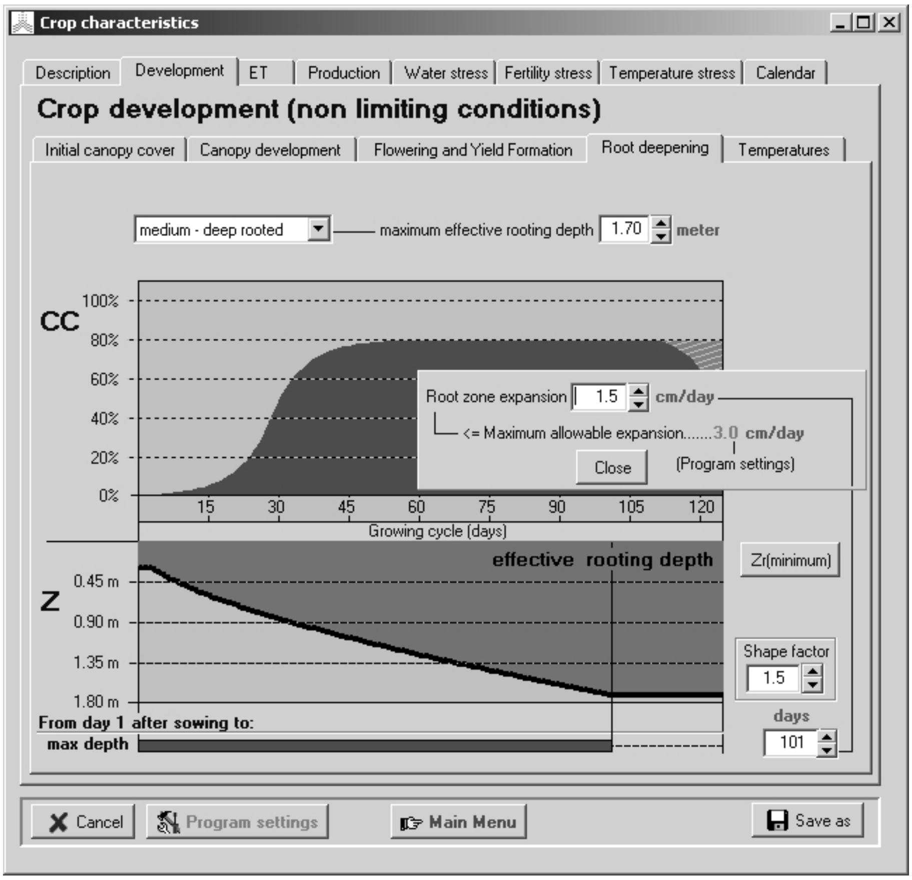


Figure 2.9b6
Specification of root development in the *Crop characteristic* menu

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. 2.9b6). 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 2.9b6
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. 2.9b7). Current version of AquaCrop does not simulate the slowing of root deepening by a restrictive layer.

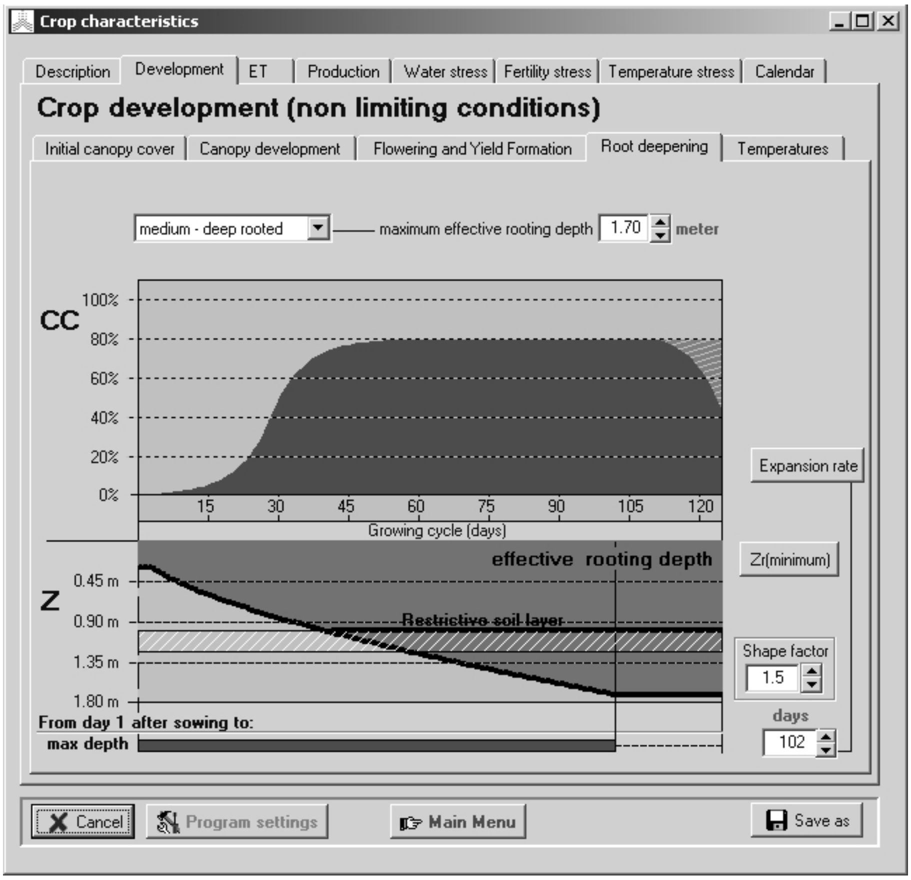


Figure 2.9b7
Restrictive soil layer blocking root development

- **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). 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.2.9b8).

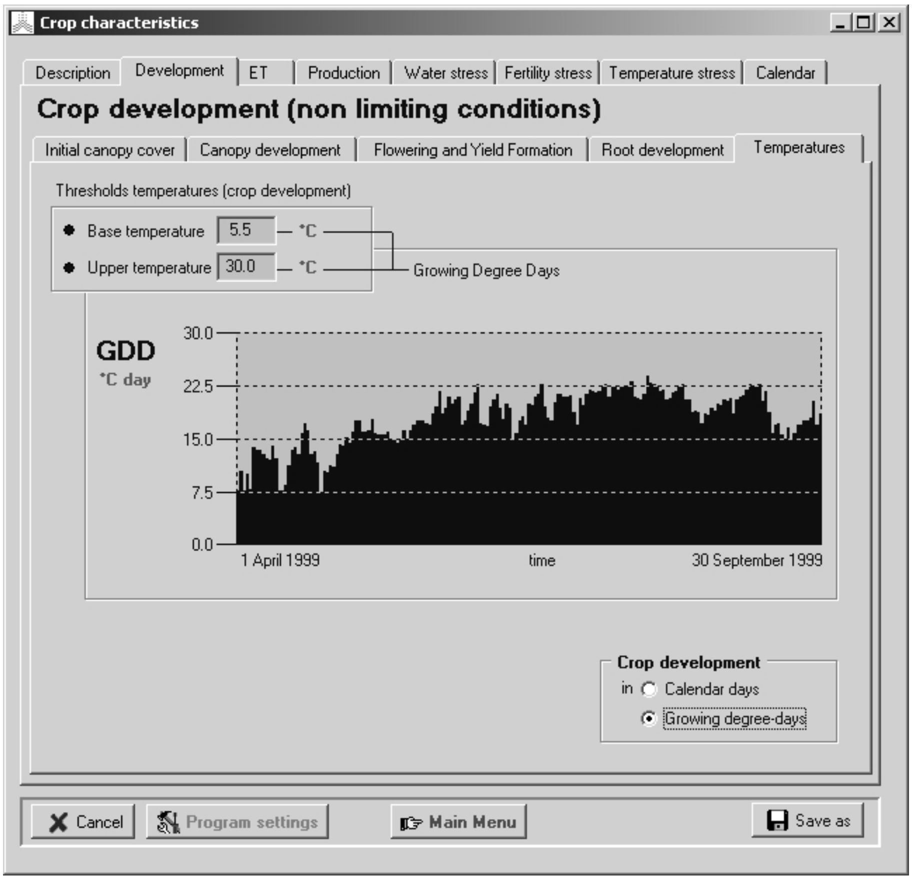


Figure 2.9b8
Specification of the base and upper temperature threshold in the *Crop characteristics* menu

2.9.3 Evapotranspiration

- **Kcb and Ke coefficients**

The soil water evaporation coefficient (for a wet soil surface) and the crop transpiration coefficient (for a well watered soil) are plotted from sowing to maturity (Fig. 2.9c1).

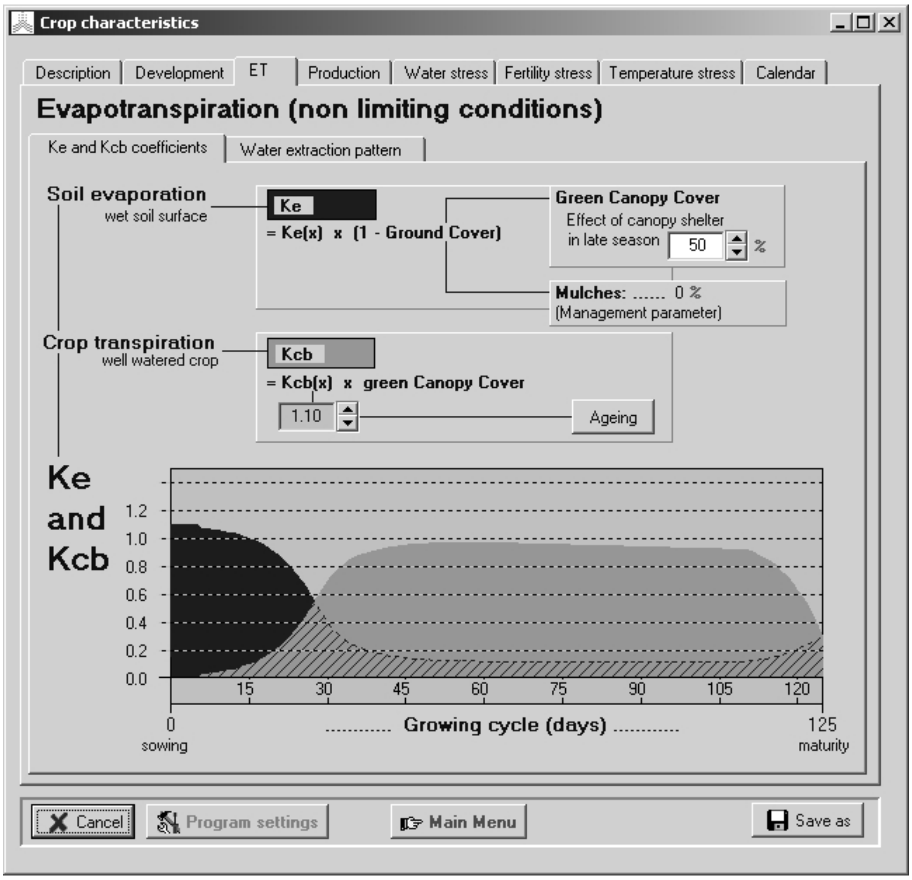


Figure 2.9c1

Response of soil evaporation (Ke) and crop transpiration (Kcb) coefficient to canopy development and decline from sowing to maturity 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 2.9.10 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 or nutrient stress, soil evaporation is 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 (Kcb_x). It is the crop coefficient when canopy cover is complete (CC = 1) and without stresses. Kcb_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 Kcb_x by a constant and very slight fraction per day.

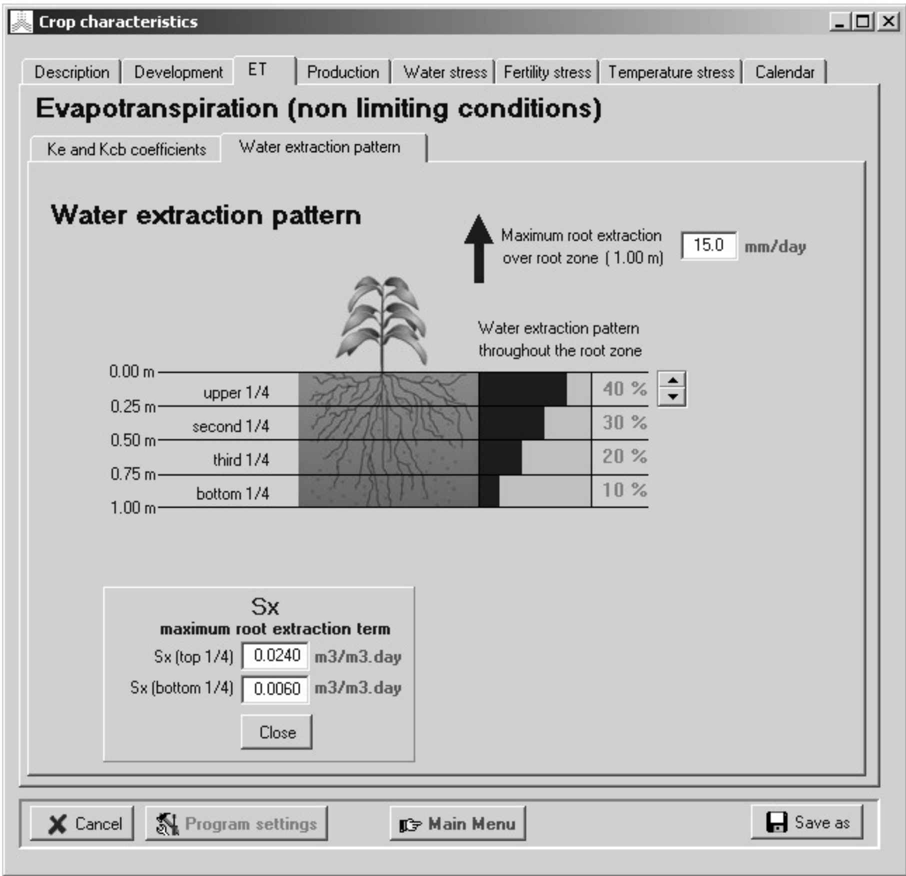


Figure 2.9c2

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 transpiration rate 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).

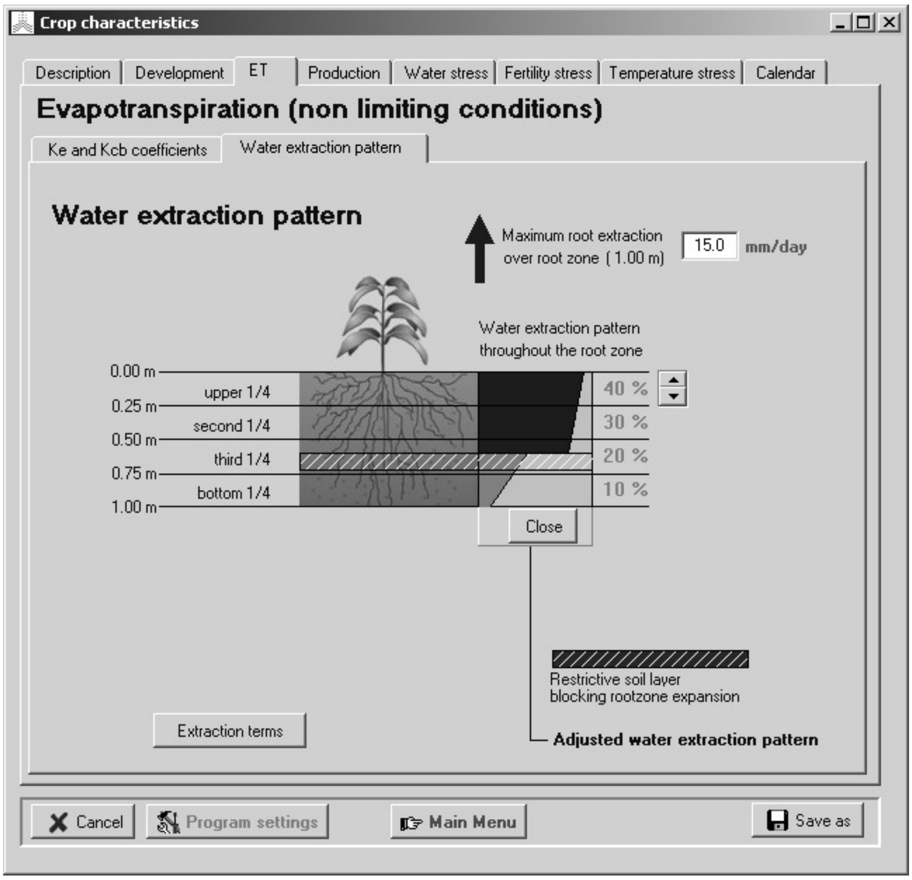


Figure 2.9c3
Adjustment of the water extraction pattern
in the presence of a restrictive soil layer blocking rootzone expansion

2.9.4 Production

- **Normalized crop water productivity (WP*)**

To simulate biomass and yield, the water productivity normalized for ETo 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).

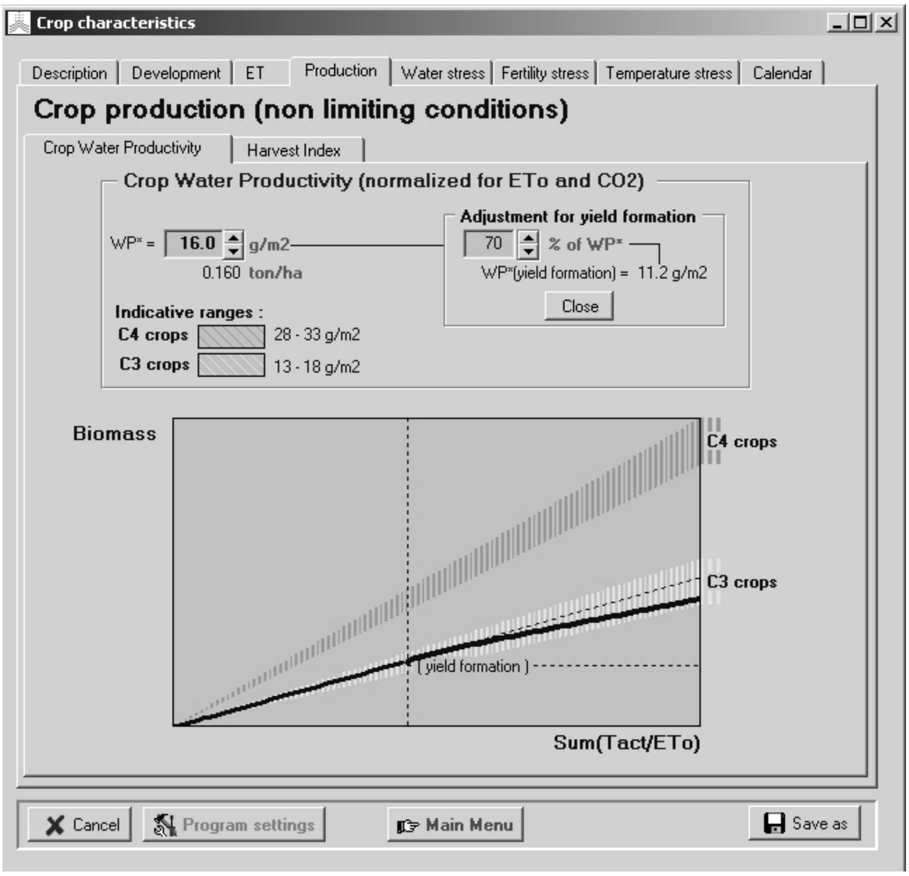


Figure 2.9d1
The water productivity normalized for ETo and air CO_2 and its adjustment if the harvestable organs are rich in oil and/or proteins

- **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. Beginning at the start of flowering or the start of yield formation for root/tuber crops, HI is programmed to increase linearly with time after a lag phase until physiological maturity (Fig. 2.9d2). The value reached at maturity under non-stress conditions is taken as HI_o for that species.

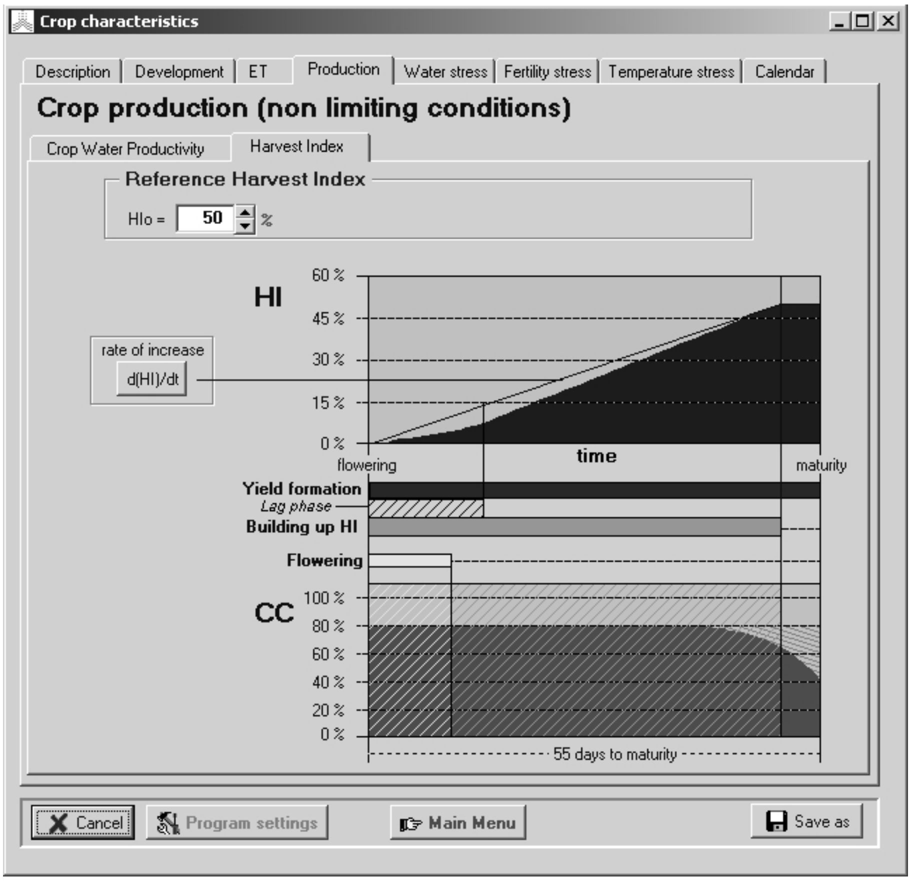


Figure 2.9d2
Specification of the reference harvest index (HI_o)
and the building up of the Harvest Index from flowering to physiological maturity

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.

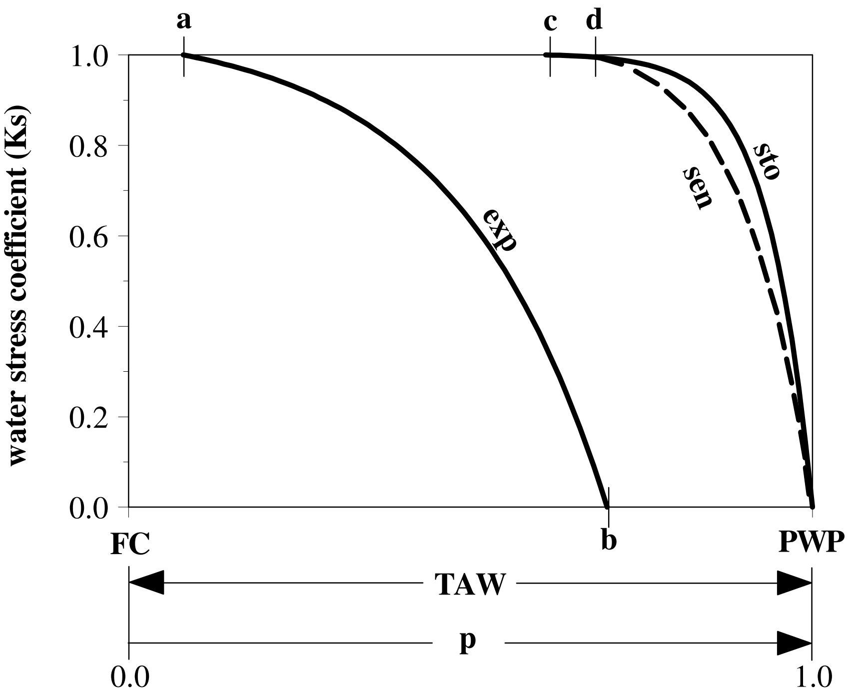


Figure 2.9e1
Examples of the variation of the water stress coefficient for leaf expansion (exp), stomatal conductance (sto) and canopy senescence (sen) for various soil water depletions

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, and rarely possibly concave (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 -6 (strongly concave).

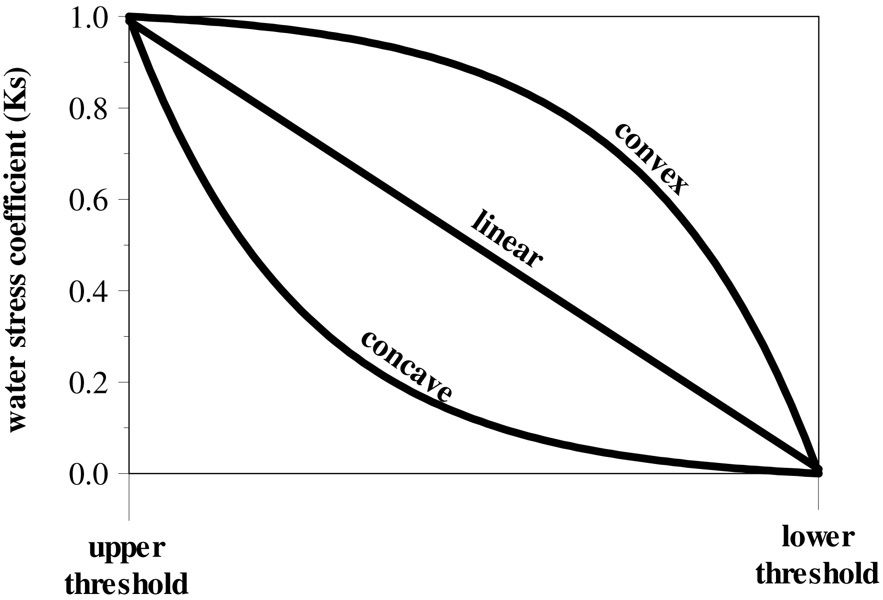


Figure 2.9e2
Concave, linear and convex shapes of the Ks curve

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

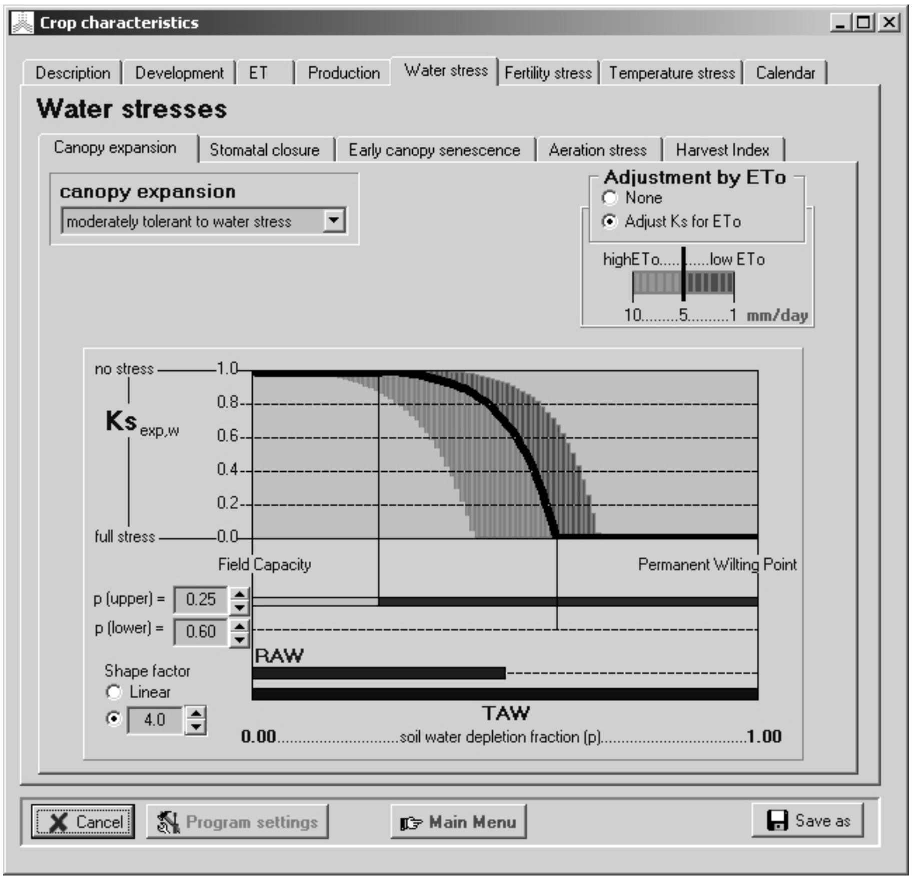


Figure 2.9e3
Specification of the upper and lower thresholds and the shape of the Ks curve for the effect of water stress on canopy expansion ($Ks_{exp,w}$)

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

- **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 2.9e4), the aeration of the root zone will be deficient, resulting in a decrease of crop transpiration.

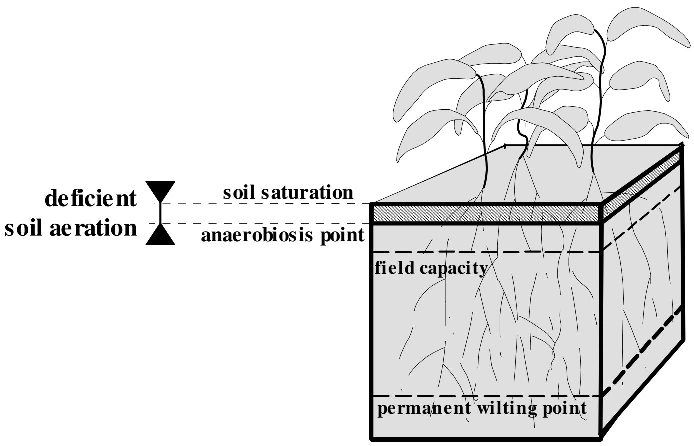


Figure 2.9e4
Zone (dark area) of restricted soil water extraction as a result of deficient soil aeration

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. 2.9e5). 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

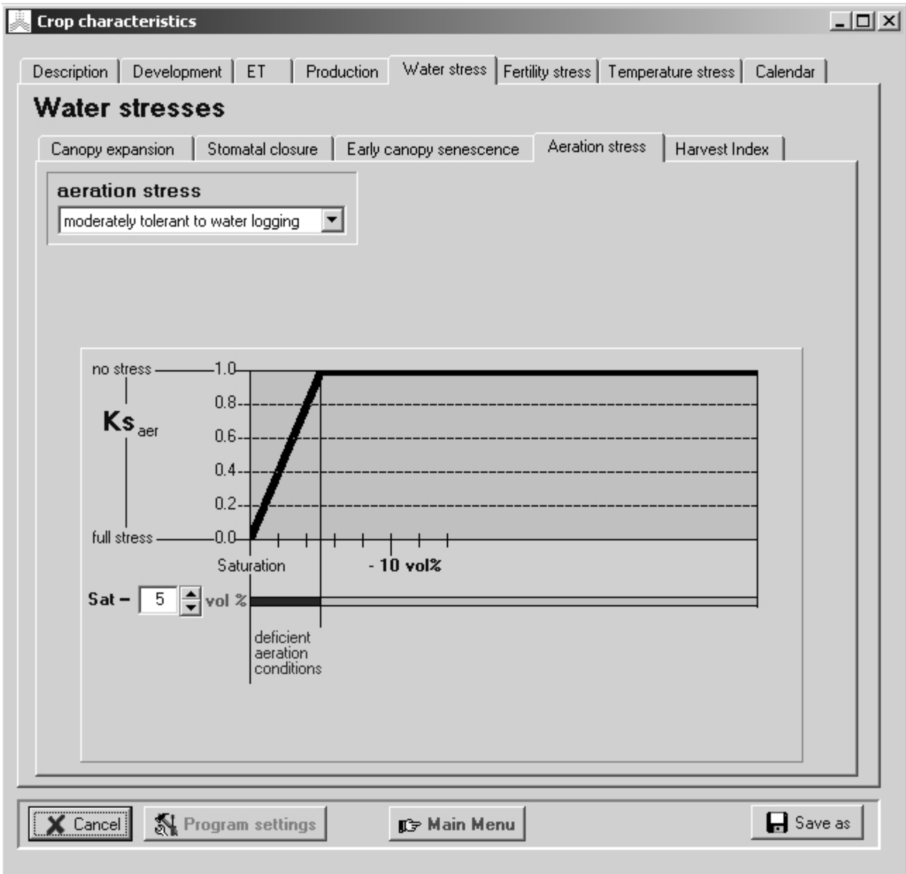


Figure 2.9e5
Specification of the soil water content below saturation at which poor aeration no longer limits transpiration

- **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. 2.9e6) or select a class graded for the effect of pre-anthesis water stress (Tab. 2.9e5).

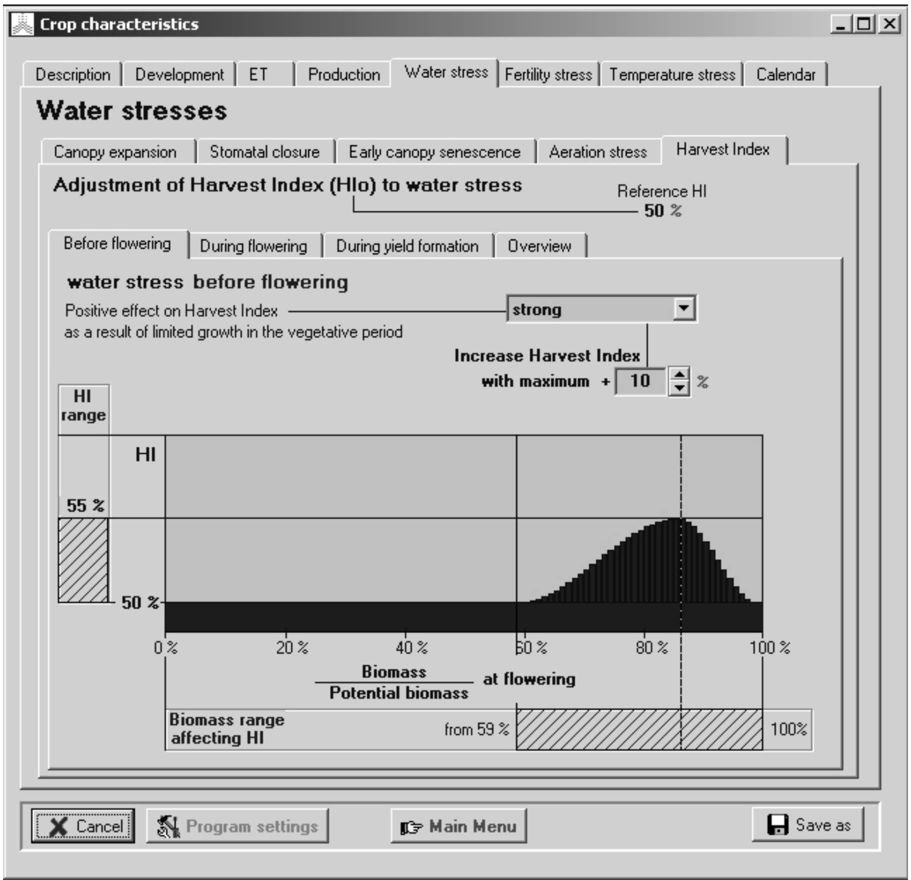


Figure 2.9e6
Positive effect on Harvest Index of pre-anthesis water stress affecting biomass production

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. 2.9e7, Tab 2.9e6). In addition to the Ks value, the user specifies the extent of excessive potential fruits in the Flowering and Yield formation sheet of Development (see 2.9.2).

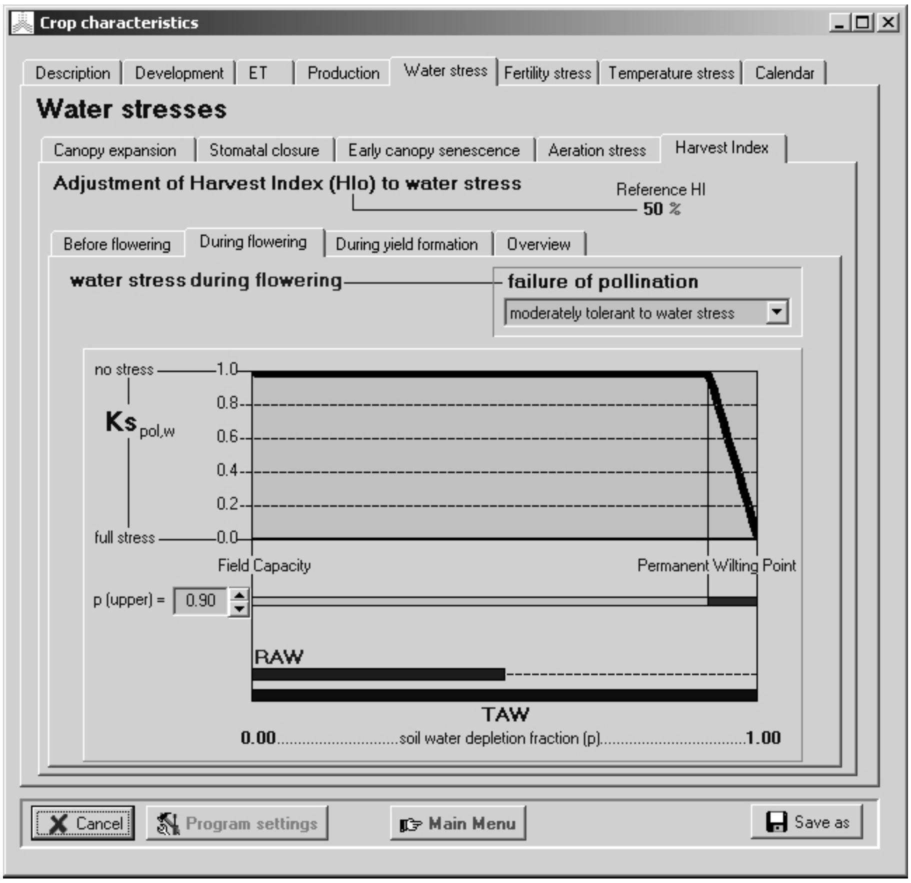


Figure 2.9e7
Specification of the upper thresholds
for the effect of water stress on failure of pollination

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	Soil water depletion fraction for failure of pollination (p_{pol})	
	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	Soil water depletion fraction for failure of pollination (p_{pol})	
	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

By selecting the **<view corresponding HI adjustment>** command, the user can study the combined effect on the Harvest Index of water stress during yield formation in the ***Adjustment of Harvest Index*** menu (Fig 2.9e8). The combined effect on HI can be displayed for various root zone depletions and evaporative demands.

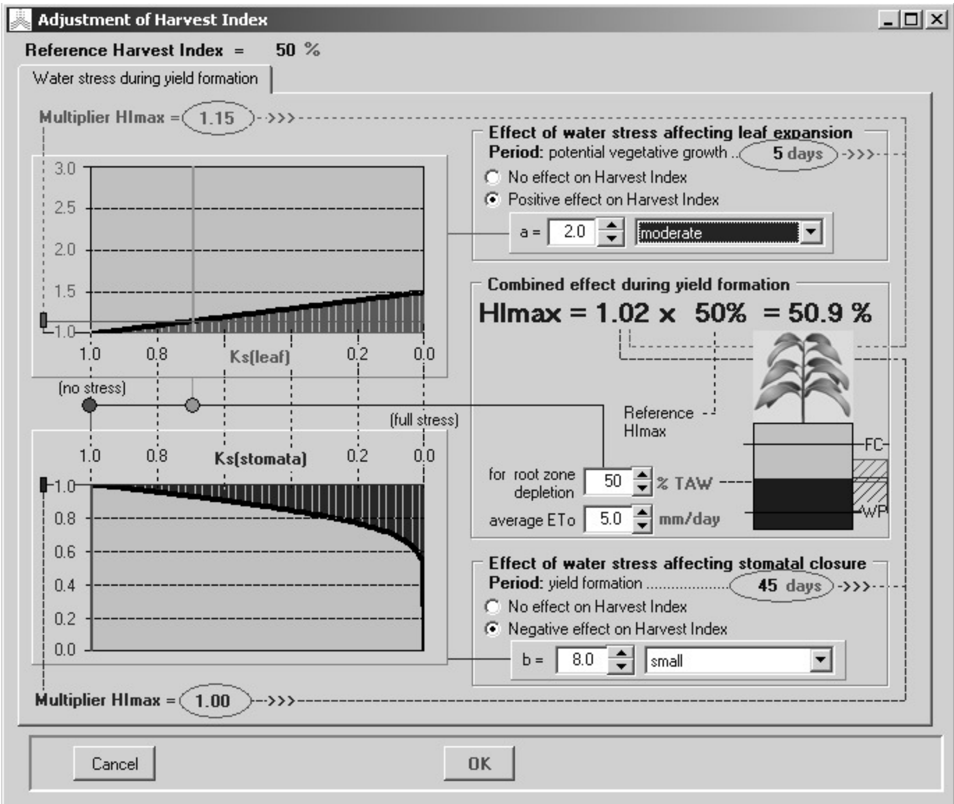


Figure 2.9e8.
Combined effect on Harvest Index of water stress during yield formation for the selected "a" and "b" coefficient, root zone depletion and evaporative demand

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. 2.9e9).

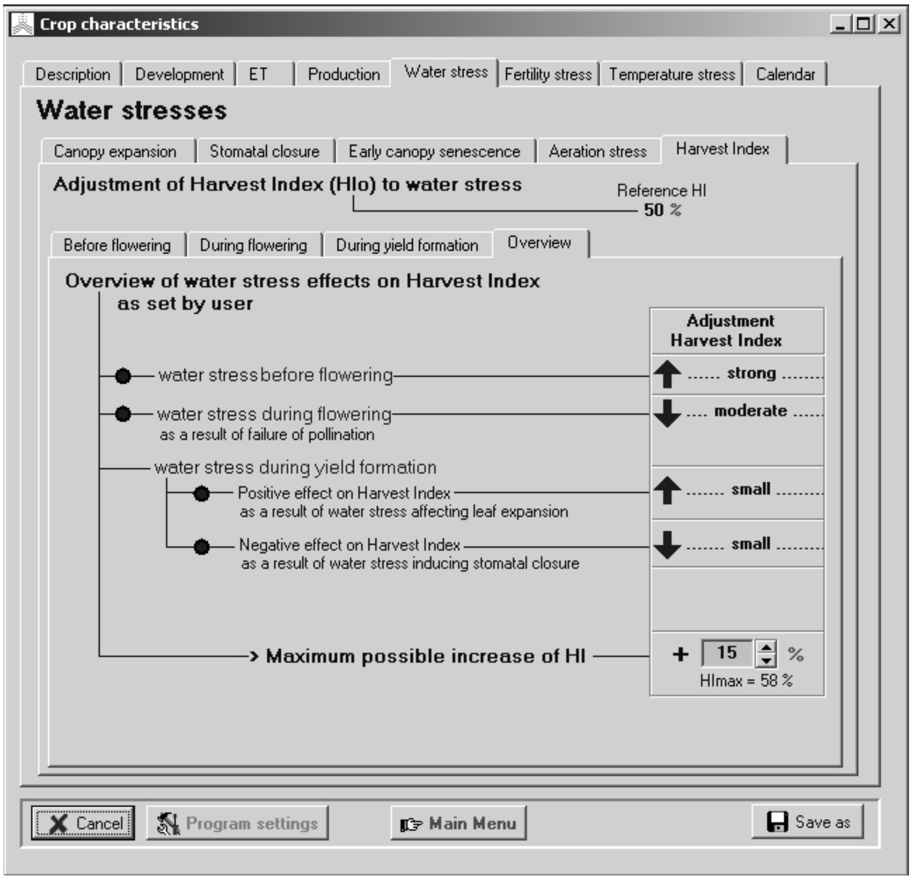


Figure 2.9e9
Combined effect of water stress on harvest index

2.9.6 Fertility stress

Mineral nutrient stress, particularly the lack of nitrogen, can reduce canopy expansion, the maximum canopy cover that can be reached (CC_x) and the water productivity (WP*). In addition, under long-term nutrient stress CC normally undergoes steady decline once the adjusted CC_x is reached at mid season. AquaCrop does not simulate nutrient cycles and balance, but provides categories of soil fertility levels ranging from non-limiting to severely limiting. The user can choose one of the categories when specifying Field Management but calibrates the crop response in the ***Crop characteristic*** menu (See 2.9.7 Calibration for soil fertility).

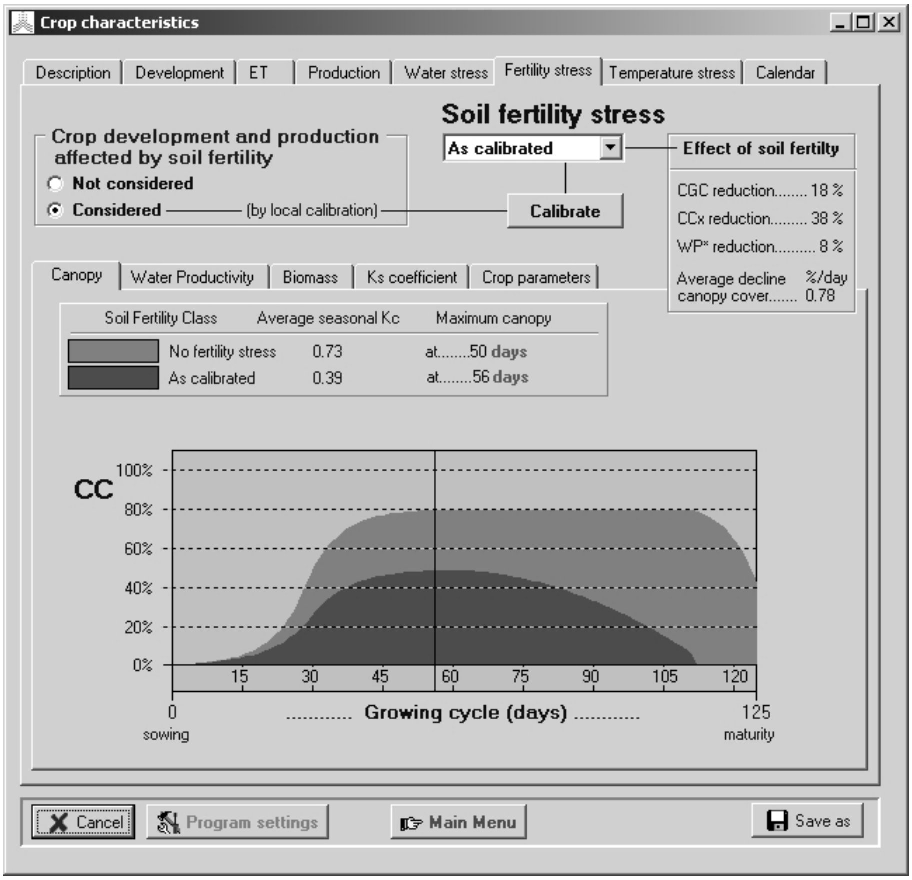


Figure 2.9f
The effect of soil fertility stress on canopy development

Once calibrated the user can see the effect of 4 predefined classes on crop development, water productivity and biomass production (Fig. 2.9f). The 4 predefined fertility levels (next to the calibrated response) considered in AquaCrop are:

- Non limiting;
- Near optimal (20% soil fertility stress);
- Moderate (40% soil fertility stress), and
- Poor (60 % soil fertility stress).

2.9.7 Calibration for soil fertility

The calibration consists of specifying the canopy decline and the reductions in canopy growth coefficient (CGC), maximum canopy cover (CC_x) and water productivity (WP*) for a specific stress level. This is not done directly but through a calibration process explained below.

- **Soil fertility stress and decline coefficients**

The effect of limited soil fertility on crop development and production is described with a set of 3 soil fertility stress coefficients (Ks) and one decline coefficient (f). The set consists of :

- $Ks_{exp,f}$: soil fertility stress coefficient for canopy expansion (≤ 1);
- Ks_{CCx} : soil fertility stress coefficient for the maximum canopy cover (≤ 1);
- Ks_{WP} : soil fertility stress coefficient for the water productivity (≤ 1);
- $f_{CDecline}$: average daily decline of the canopy cover once maximum canopy cover is reached (≥ 0).

For non-limiting soil fertility (i.e. soil fertility stress is zero) the 3 soil fertility stress coefficients (Ks) are 1. When the soil fertility stress is complete (100% fertility stress), crop production is no longer possible and the Ks coefficients are zero. Between the upper and lower limits for soil fertility the Ks coefficients vary between 1 and 0 (Fig. 2.9g1).

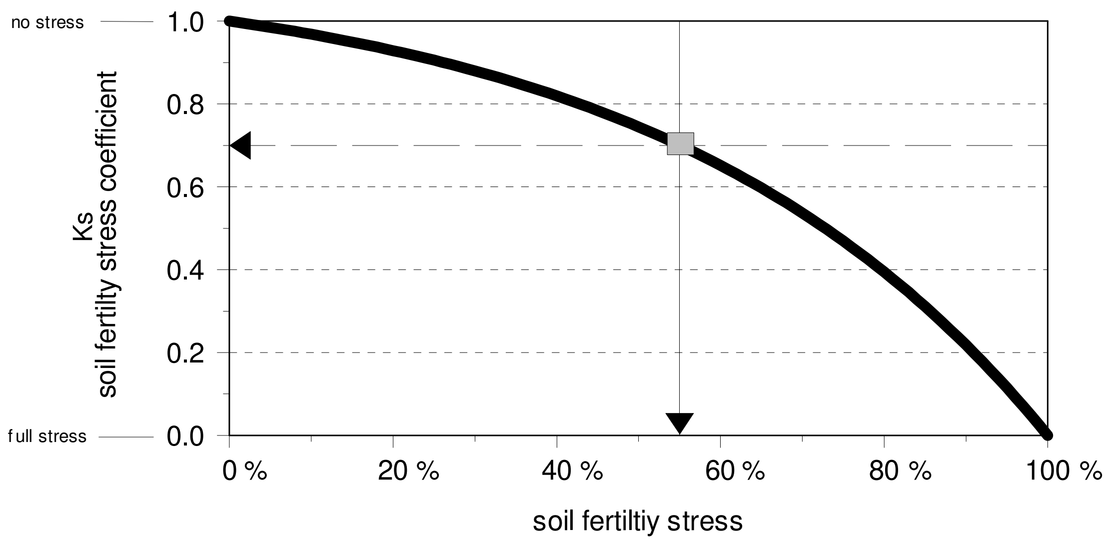


Figure 2.9g1
Soil fertility stress coefficient for various soil fertility stress level (full line) with indication of the Ks and soil fertility stress used for calibration (square)

The shape of the Ks curves can be convex, linear or concave and may differ between the 3 Ks curves. The shape of each of the curves is determined at calibration by specifying a Ks value between 1 and 0 for the particular soil fertility stress at which the crop response is calibrated. Once a curve is calibrated, the Ks corresponding to other soil fertility stresses is obtained from the curve.

The calibration for the average daily decline of the canopy cover ($f_{CDecline}$) follows the same approach. For non-limiting soil fertility (i.e. soil fertility stress is zero) the decline is zero. When the soil fertility stress is complete (100% fertility stress), a maximum decline of 1 % per day is assumed. Between the upper and lower limits for soil fertility $f_{CDecline}$ varies between 0 and 1 % per day. The shape of the decline coefficient curve is determined at calibration by specifying a $f_{CDecline}$ between 0 and 1 % per day for the particular soil fertility stress at which the crop response is calibrated. (Fig. 2.9g2).

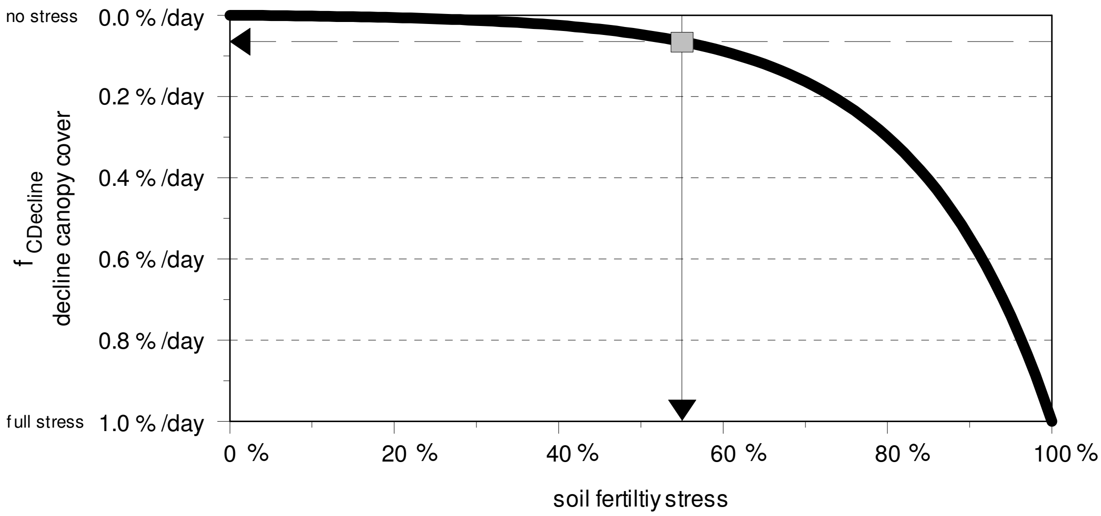


Figure 2.9g2
Decline canopy coefficient for various soil fertility stress level (full line) with indication of the $f_{CDecline}$ and soil fertility stress used for calibration (square)

- **Calibration process**

The calibration consists of 3 steps and requires access to observed data from two well watered fields (no water stress) one with and the other without soil fertility stress. The field with unlimited soil fertility is the reference field, while the field with limited soil fertility is used to calibrate the shape of the Ks and decline coefficients curves. The calibration requires that the crop on the calibration field shows a well noted response to the limited soil fertility.

Step 1. Selection of the soil fertility stress for calibration

The biomass harvested at the end of the crop cycle on the calibration field ($B_{calibration\ field}$), expressed as a percentage of the biomass of the reference field ($B_{reference\ field}$), is specified as the percentage of the soil fertility stress used for calibration.

$$soil\ \ fertility\ \ stress = 100\frac{B_{calibration\ field}}{B_{reference\ field}} \qquad \text{(Eq. 2.9g1)}$$

Step 2. Calibration of canopy development (Ks_{CCx}, $Ks_{exp,f}$, $f_{CDdecline}$)

Observed differences in canopy development between the calibration and reference field are used to calibrate some of the Ks coefficients. Depending on the quality of the data one or more coefficients can be calibrated (Fig. 2.9g3):

a. The maximum canopy cover (CC_x) observed on the calibration field is expressed as a percentage of the CC_x obtained on the reference field. By specifying the observed reduction in CC_x (for the soil fertility stress fixed in step 1) AquaCrop determines the corresponding shape of the Ks_{CCx} curve; and/or
b. By knowing the time required to reach CC_x (in days or growing degrees counting from sowing), the corresponding reduction in CGC at the calibration field can be obtained (AquaCrop displays for that purpose both the time required to reach CC_x and the corresponding reduction in CGC). Once the reduction in CGC is known at the soil fertility stress fixed in step 1, AquaCrop determines the corresponding shape of the $Ks_{exp,f}$ curve; and/or
c. For good quality data, the observed decline in canopy development starting at mid season can be used to specify the average $f_{CDecline}$ at the soil fertility stress fixed in step 1. AquaCrop determines the corresponding shape of the $f_{CDecline}$ curve.

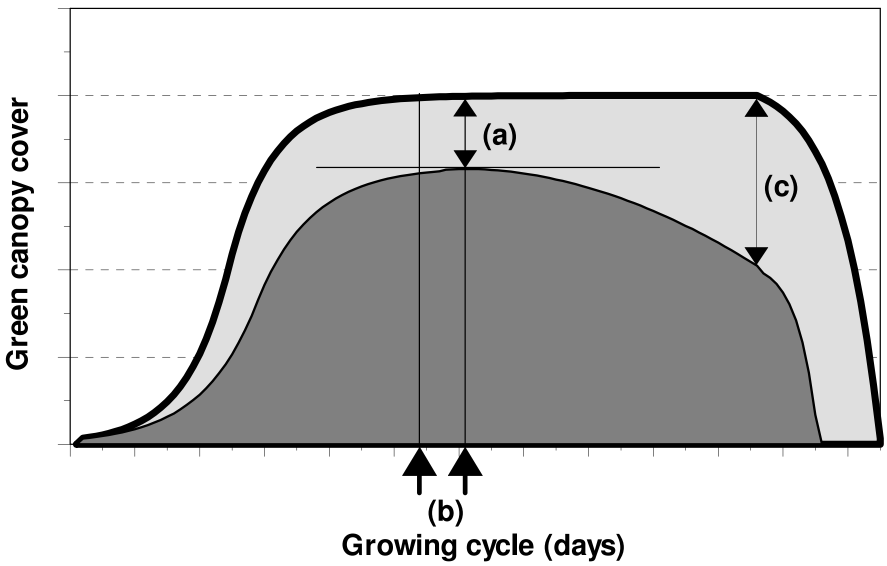


Figure 2.9g3
Canopy cover observed on the reference field (light area) and calibration field (dark area) with indication of (a) the reduction in CC_x, (b) the delay in time to reach CC_x and (c) the canopy decline once CC_x is reached

Step 3. Calibration of water productivity for biomass (Ks_{WP})

By simulating the canopy development for limited soil fertility ($CC_{limited}$), as determined by the reference CC_o, CGC and CC_x and the calibrated Ks_{CCx}, $Ks_{exp,f}$ and $f_{CDdecline}$ in step 2, AquaCrop estimates the corresponding biomass production that can be expected on the calibration field for well watered conditions at the soil fertility stress used for calibration:

$$B_{calibration\,field} = \left(Ks_{WP}\ WP^{*}\right)\ \left(Kcb_x\ CC_{limited}\right) \qquad \text{(Eq. 2.9g2)}$$

where WP* is the reference water productivity. By adjusting Ks_{WP}, the simulated drop in biomass production (100 $B_{calibration}/B_{reference}$) can be matched with the observed relative biomass production (which was taken as the soil fertility stress used for calibration in step 1 (Eq. 2.9g4). If required, the soil fertility stress coefficients affecting canopy development (Ks_{CCX}, $Ks_{exp,f}$, and $f_{CDecline}$) can also be altered in this process (especially if good calibration data was lacking) until a good match between observed and simulated biomass production is obtained (Fig. 2.9g5).

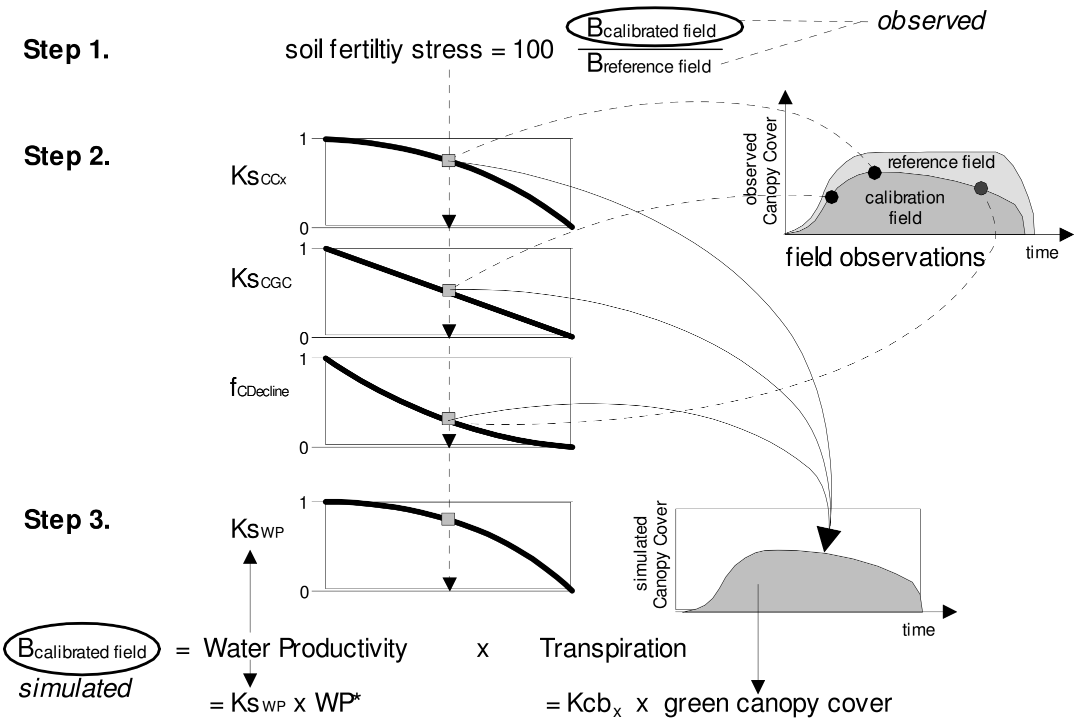


Figure 2.9g4
Visual representation of the calibration process for soil fertility

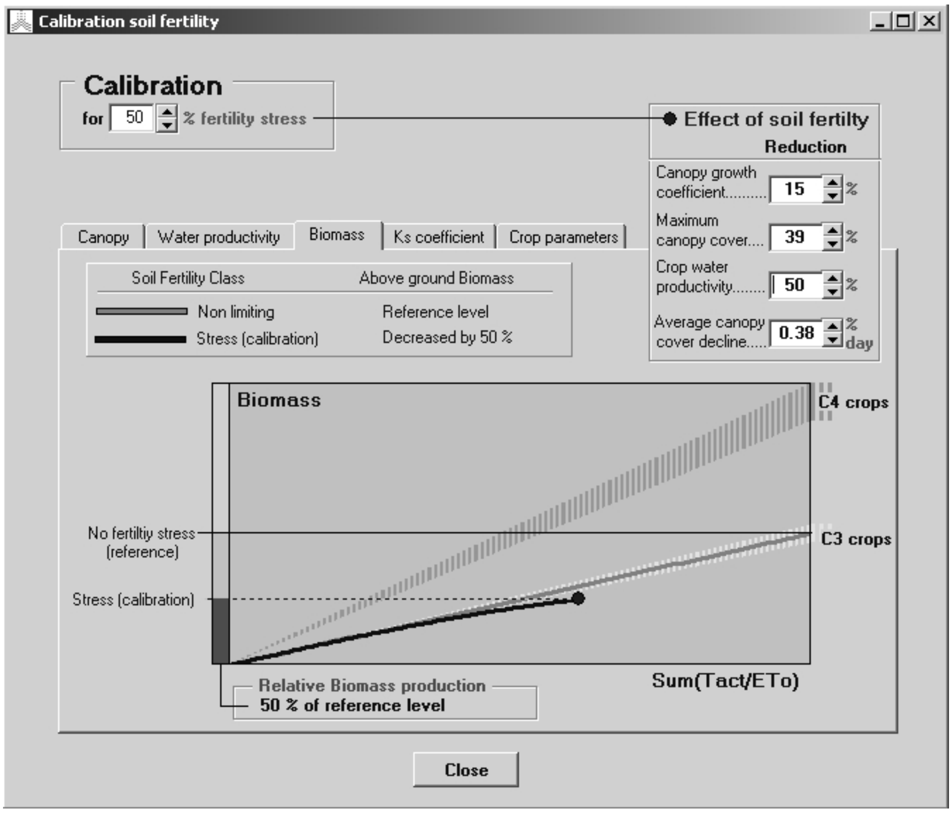


Figure 2.9g5
Display of the simulated relative biomass when calibrating soil fertility stress

2.9.8 Temperature stress

In AquaCrop temperature stresses affecting biomass production and pollination are 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. 2.9h1). The lower threshold is fixed at 0 °C-day. Between the upper and lower threshold the shape of the Ks curve is logistic.

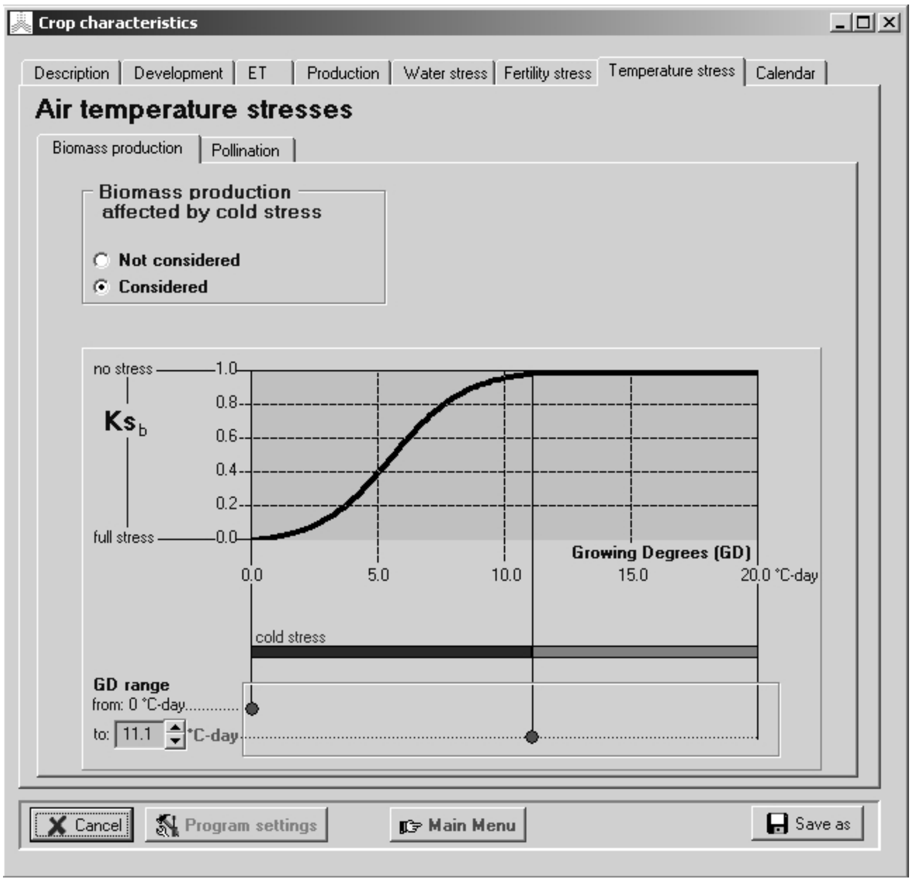


Figure 2.9h1
Specification of the threshold for temperature stress on biomass production

▪ **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 the upper temperature threshold. For the heat stress Ks is 1 at the upper threshold and 0 at the lower threshold temperature (Fig. 2.9h2). Between the upper and lower thresholds the shapes of the Ks curves are logistic.

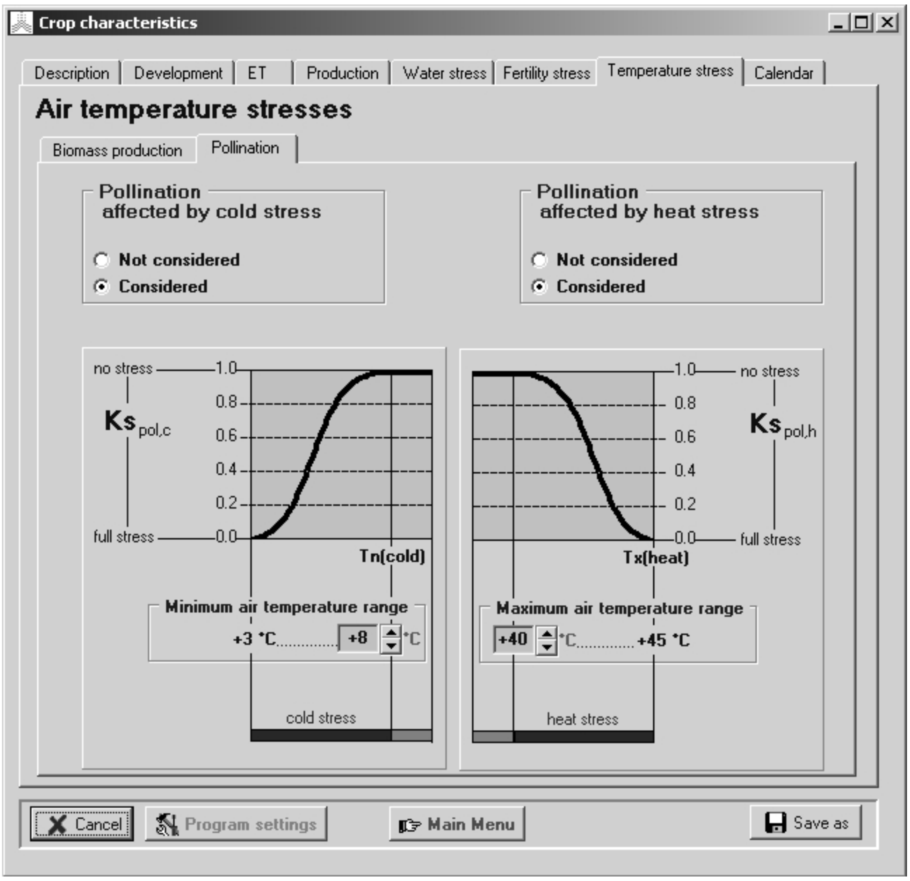


Figure 2.9h2
Specification of the thresholds for cold and heat stress on pollination

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 8 °C below (cold stress) or above (heat stress) the specified threshold air temperature.

2.9.9 Calendar

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

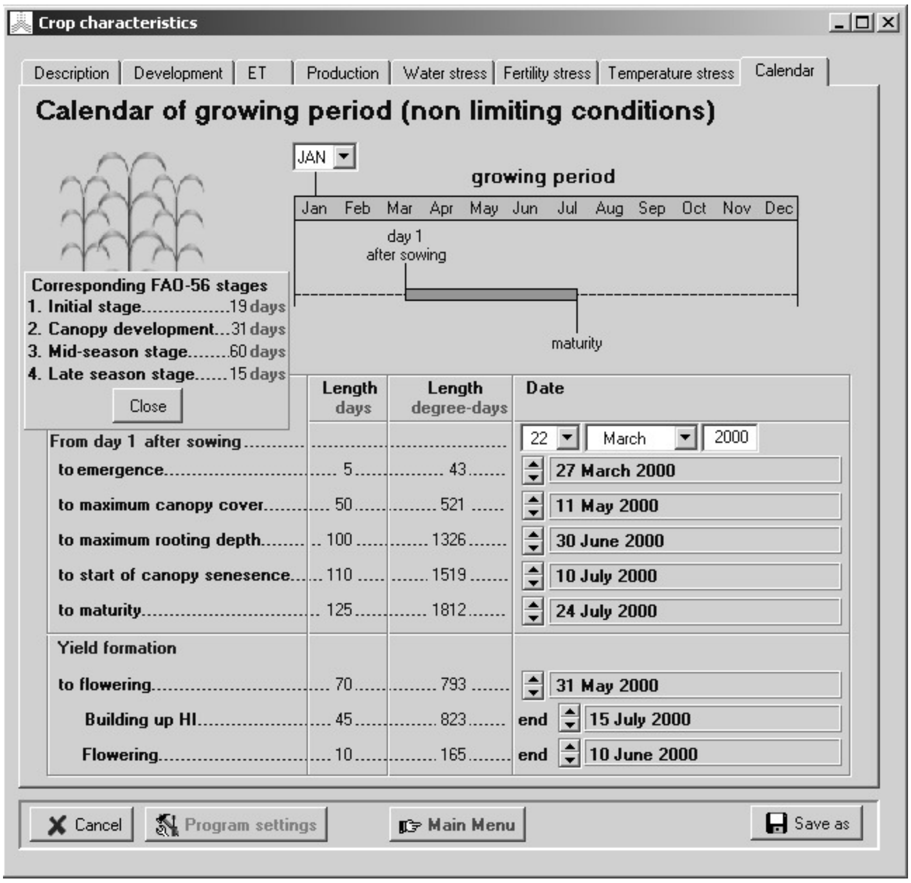


Figure 2.9i
Crop calendar with indication of the FAO-56 growth stages

In the calendar the length of crop growth stages for the described crop development 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.

2.9.10 Program settings

From the ***Crop characteristics*** menu the user has access to the program settings listed in Table 2.9j. 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 2.9j
Program settings affecting evapotranspiration, crop development and the effect of water stresses

Symbol	Program parameter	Default
f_K	Evaporation decline factor for stage II	4
Ke_x	Soil evaporation coefficient for fully wet and non-shaded soil surface	1.10
	Threshold for green CC below which HI can no longer increase (% cover)	10 %
Z_o	Sowing depth (% of minimum effective rooting depth)	70 %
	Maximum for root zone expansion (cm/day)	3 cm/day
	Shape factor for effect water stress on root zone expansion	-6
	Required soil water content at sowing depth for germination (% TAW)	20 %
	Adjustment factor for FAO-adjustment soil water depletion (p) by ETo	1
	Number of days after which deficient aeration is fully effective	3 days
	Exponent of senescence factor adjusting drop in photosynthetic activity of dying crop	1
β	Decrease of p(sen) once canopy senescence is triggered (% of p(sen))	12 %

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
- generate onset based on rainfall.

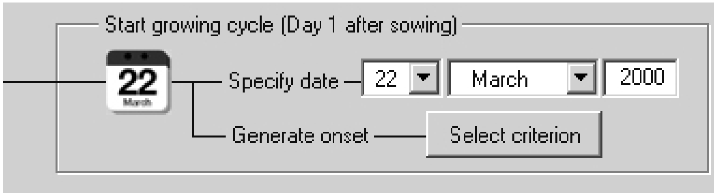


Figure 2.10a
Panel in *Main menu* where the start of the growing cycle is specified

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 Generate onset

In rainfed cropping, sowing or planting is typically determined by rainfall events. By clicking on the **<Select criterion>** command, the ***Onset*** 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 onset date is the first date for which the selected criterion holds. The next 12 onset days are displayed when clicking on the **<Next days>** command.

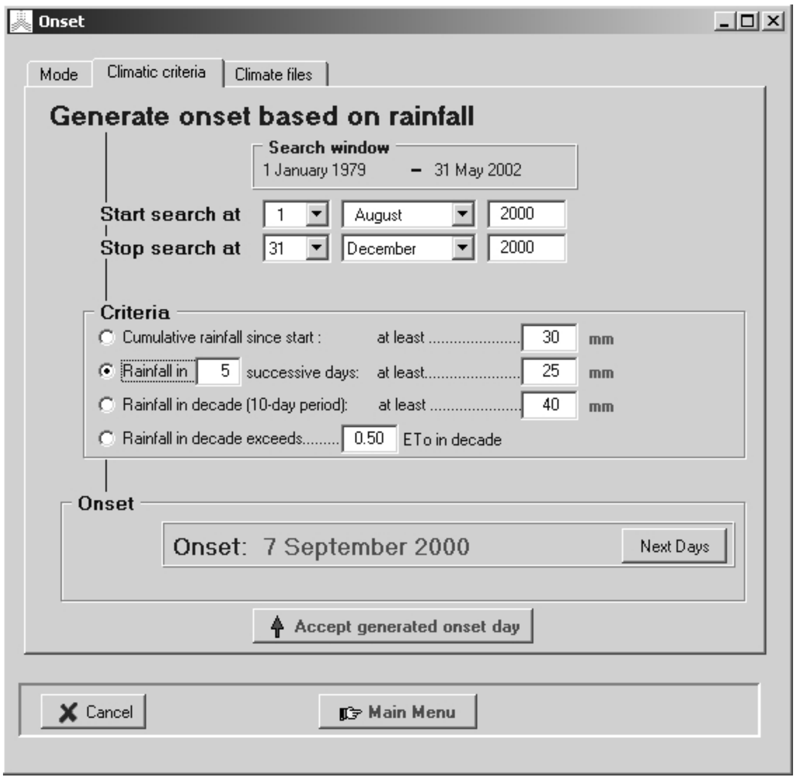


Figure 2.10b
***Onset* menu where the onset of the growing period is determined by the exceedance of 25 mm of rainfall in a period of 5 successive days, counting from 1 August 2000 (start of the search window)**

2.11 Irrigation scheduling

Various irrigation modes can be selected in the ***Irrigation scheduling*** menu (Fig. 2.11a). 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 scheduling* 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 and application depth 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.

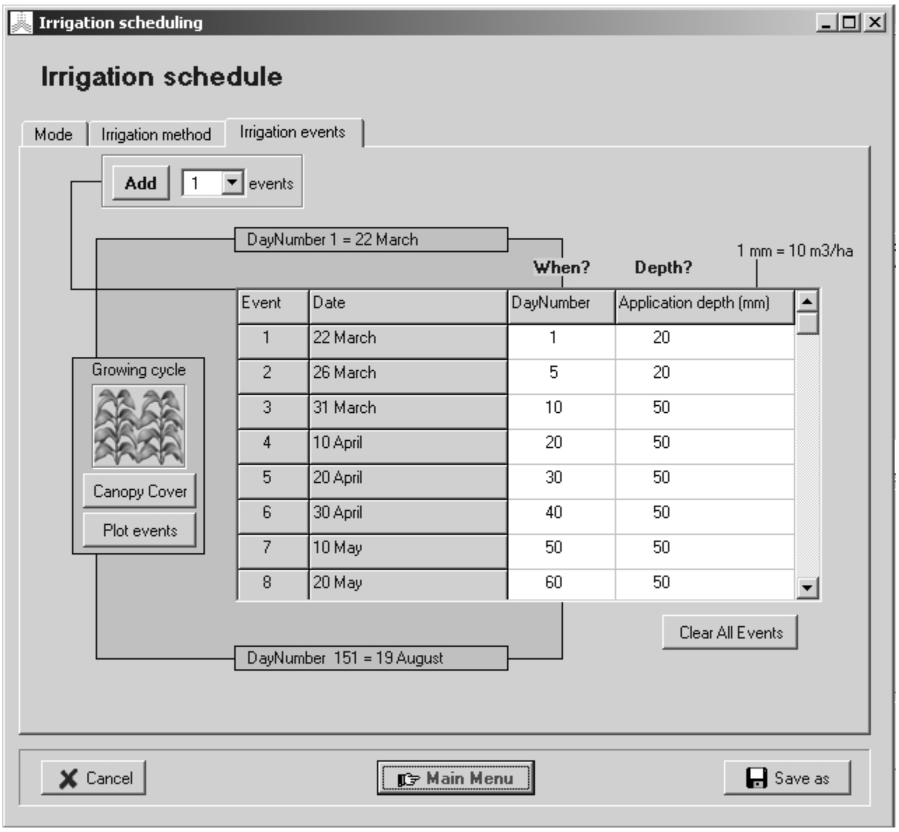


Figure 2.11b
Specification of the time and application depth for irrigation events

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 and depth criteria has to be specified. The value 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 linked with the criteria to crop development (Fig. 2.11c). The time and depth criteria with their corresponding parameters that need to be specified are listed in Tables 2.11a and 2.11b.

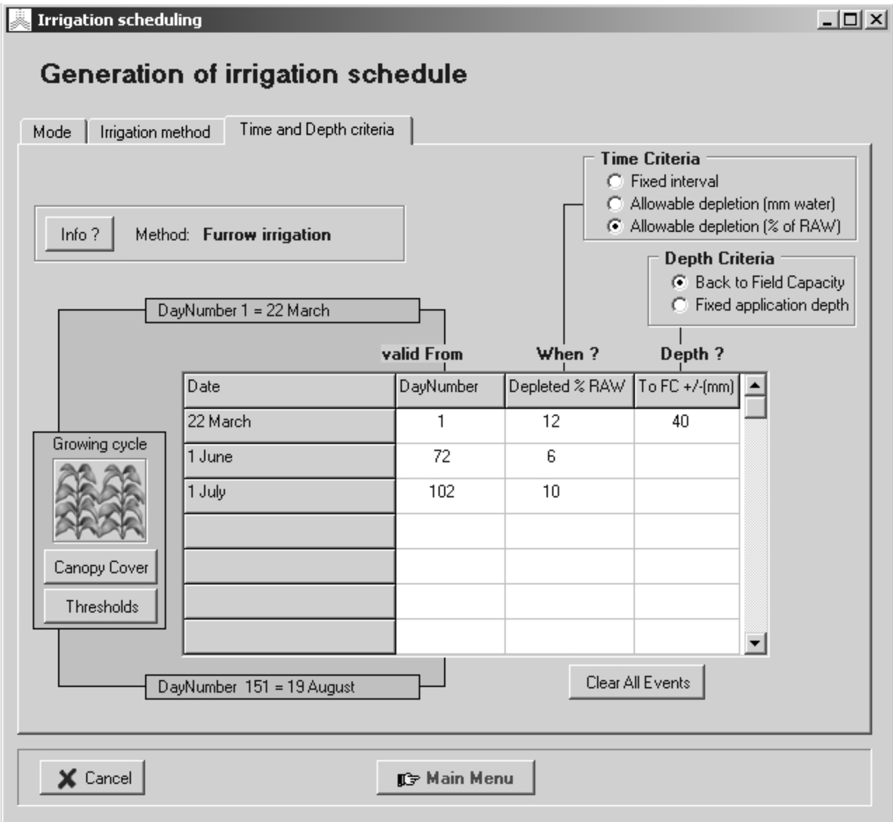


Figure 2.11c
Specifying an irrigation schedule
where the fixed irrigation interval (time criterion) varies over the season
while the fixed irrigation application depth (depth criterion) remains constant

Table 2.11a
Time criteria with corresponding parameter

Criterion	Parameter
Fixed interval	Interval between irrigations (for example 10 days)
Allowable depletion (mm water)	Amount of water that can be depleted from the root zone (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 water on top of the amount of irrigation water required to bring the root zone back to Field Capacity. The 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	Net irrigation application depth

2.11.5 Irrigation method

Many types of irrigation systems wet only a fraction of the soil surface (Table 2.8d). 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. The user can alter the value if more specific information is available from field observations.

Table 2.11d
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

2.12 Field management

Characteristics of general field management can be specified in the ***Field management*** menu (Fig. 2.12a). Choices 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

Limited soil fertility might hamper canopy development, result in a steadily decline of the canopy in mid season, and reduce crop water productivity. The selected soil fertility level and the calibration (see 2.9.7) determine the crop response. Four predefined soil fertility levels can be selected:

- non limiting (no soil fertility stress);
- near optimal (mild soil fertility stress of 20%);
- moderate (moderate soil fertility stress of 40%);
- poor (severe soil fertility stress of 60%).

Additionally one can select the soil fertility level for which the crop response was calibrated (user defined).

AquaCrop displays for the selected soil fertility level (i) the canopy development, (ii) the water productivity corresponding to the amount of biomass produced, (iii) the expected biomass production and (iv) the adjusted values for particular cop parameters (Fig. 2.12b). The crop response on soil fertility will be different if additionally water or temperature stress occurs during the season.

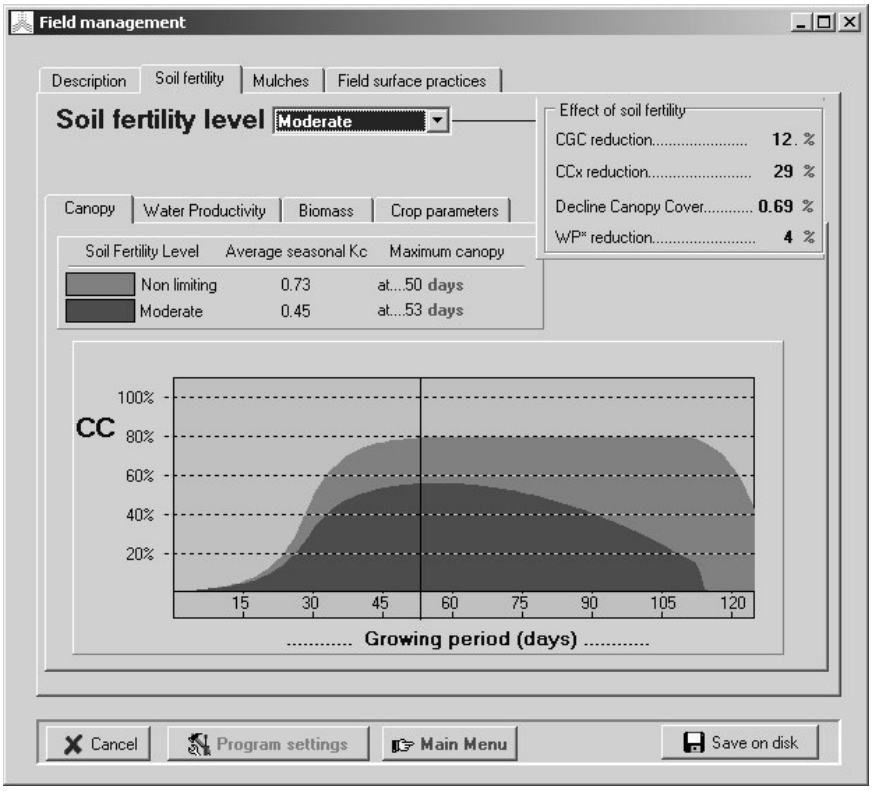


Figure 2.12b
Display of the crop response
for the selected soil fertility level in the *Field management* menu

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 effect of mulches on the reduction of soil evaporation. Plastic mulches substantially reduce the evaporation of water from the soil surface (50 to 80 % depending on their soil cover). Organic mulches may consists of unincorporated plant residues or foreign material imported to the field such as a straw (reduction of the soil evaporation by about 50%)

The corresponding total reduction in soil evaporation is displayed (Fig. 2.12c).

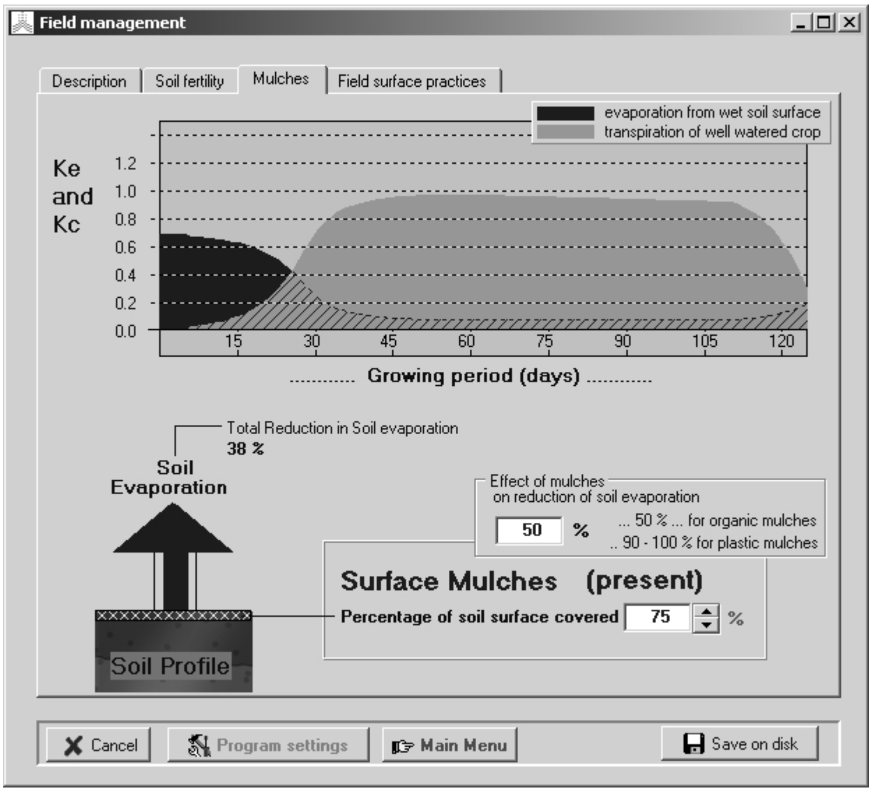


Figure 2.12c
Display of the effect of mulches on soil evaporation

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.

2.12.4 Program settings

The soil depth from which evaporation can extract water out of the top of the soil profile is fixed in the program. With the Program settings the user can alter its default value of 0.30 meter.

2.13 Soil profile characteristics

The characteristics of the various soil horizons and of the soil surface layer are displayed and can be adjusted in the ***Soil profile characteristics*** menu (Fig. 2.13). The user specifies also in this menu the occurrence of a restrictive soil layer that might block the root zone expansion.

Figure 2.13
***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.

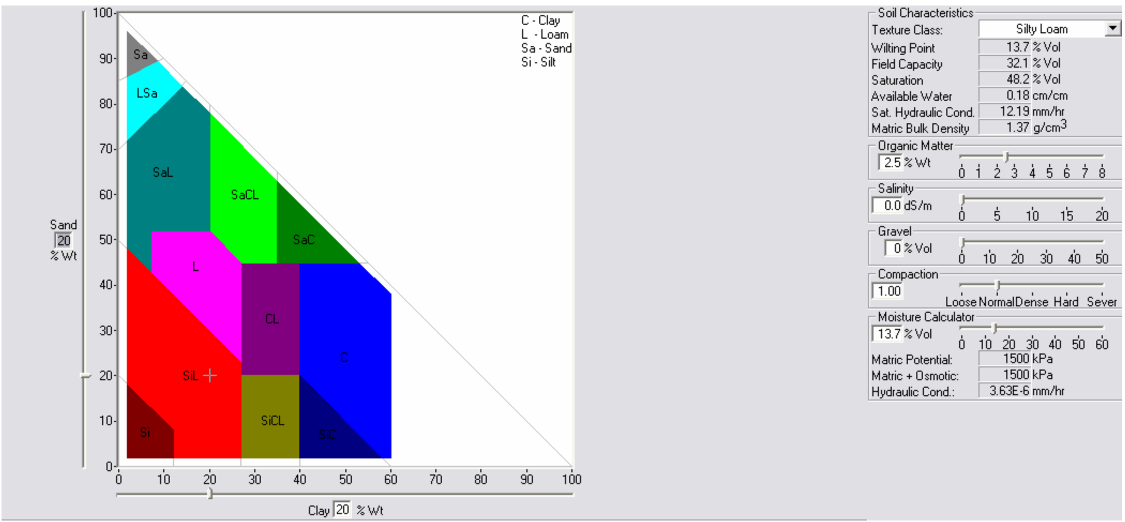
The user can make use of indicative values provided by AquaCrop for various soil textural classes (Tab. 2.13a), or import locally determined or derived data from soil texture with the help of pedo-transfer functions (Box 2.13). The values presented in Table 2.13a or derived with the help of pedo-transfer 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.

- 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).

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

2.13.4 Restrictive soil layer

If an impermeable soil layer blocks root development, the user specifies its depth. The root zone expansion is halted once the restrictive soil layer is reached (Chapter 3).

2.13.5 Program settings

With the Program settings the user can

– switch on/off the 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.
– alter the default thickness of the topsoil that will be considered for the determination of its wetness (required for the determination of AMC).

2.14 Simulation period

In the ***Simulation period*** menu the user can adjust the simulation period for a simulation run (Fig. 2.14). The length of the growing cycle is given as a reference in the Simulation period sheet and the range of the climatic data available in the climate files is displayed in the Climatic data sheet.

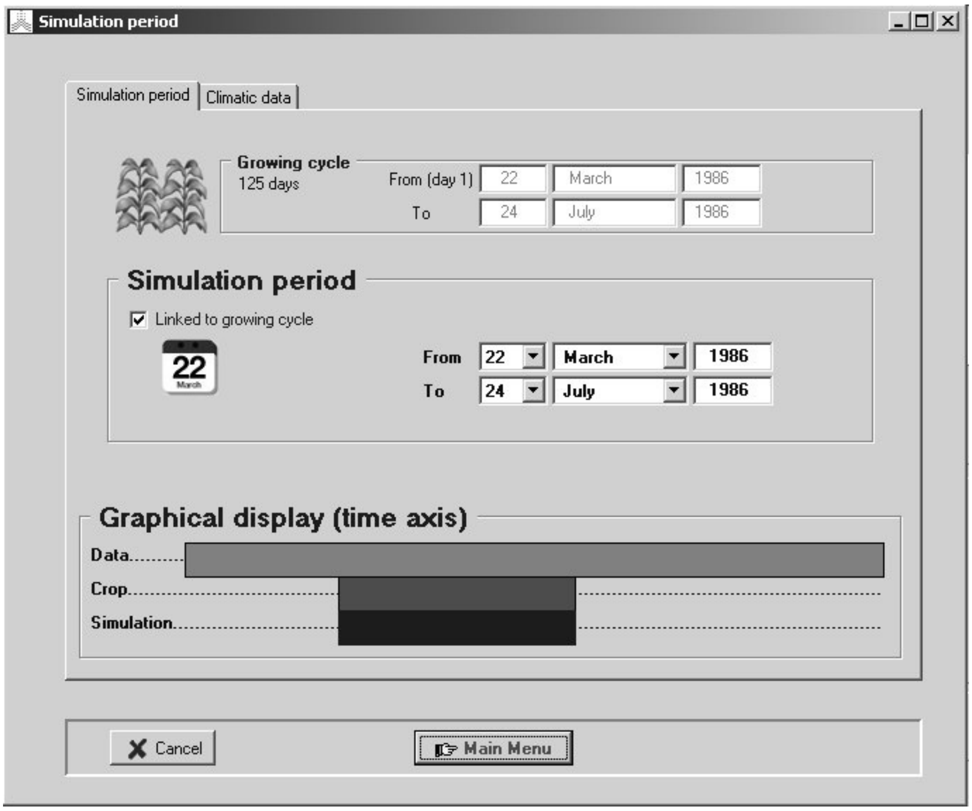


Figure 2.14
Specification of the simulation period in the *Simulation period* menu

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

2.15 Initial conditions

The information used by AquaCrop at the start of each simulation run can be adjusted in the ***Initial conditions*** menu (Fig. 2.15).

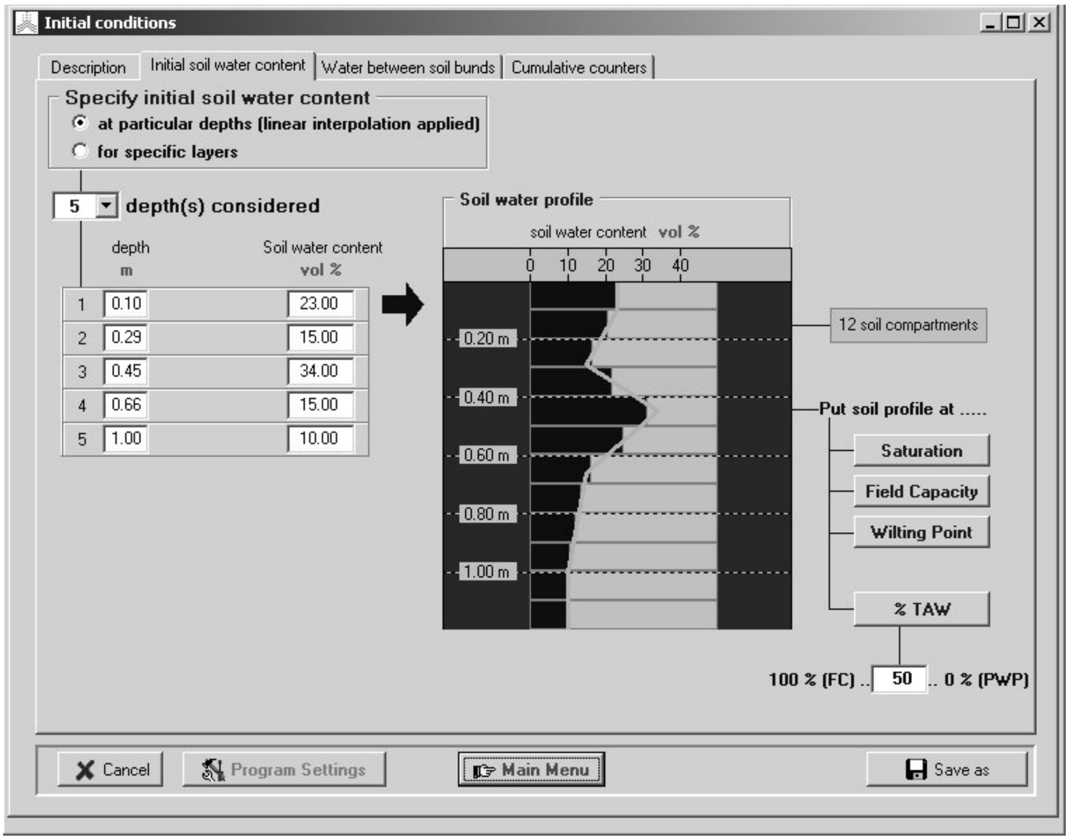


Figure 2.15
Specification of the initial soil water content in the *Initial conditions* menu

2.15.1 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.

2.15.2 Water between soil bunds

If the field is surrounded by soil bunds (see 2.12 Field management) the amount of water on top of the soil surface at the start of the simulation run can be specified.

2.15.3 Cumulative counters

Cumulative counters keep track of the sum of the daily values of parameters of the soil water balance during a simulation run: rainfall and irrigation amount, amount of water lost by surface runoff, amount of water evaporated, transpired, infiltrated into the soil profile and drained out of the profile. These counters are, by default, automatically reset at zero at the start of each simulation run. If the default option is not selected (see 2.15.4 Program settings) the values are kept for the next run and the 'Cumulative counters' sheet is displayed. In the sheet the user can reset the counters at any time to their initial value.

2.15.4 Program settings

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

- **Soil compartments**

To describe accurately the retention, movement and uptake of water 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.

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

When starting a new simulation run, the soil water conditions in a soil profile are by default reset to the specified initial conditions (see 2.15.1) and the cumulative counters (see 2.15.3) are reset to zero. 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 at the end of a simulation run becomes the soil water content 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. Also the values for the cumulative counters can be kept between the simulation runs.

2.16 Off season conditions

If the simulation period (see 2.14 Simulation period) is not fully linked with the growing cycle but starts before the planting of the crop or finishes after the moment of maturity, management conditions outside the growing cycle needs to be considered. In the ***Off-season conditions*** menu (Fig. 2.16) the user can specify the presence of mulches and the occurrence of irrigation events outside the growing cycle.

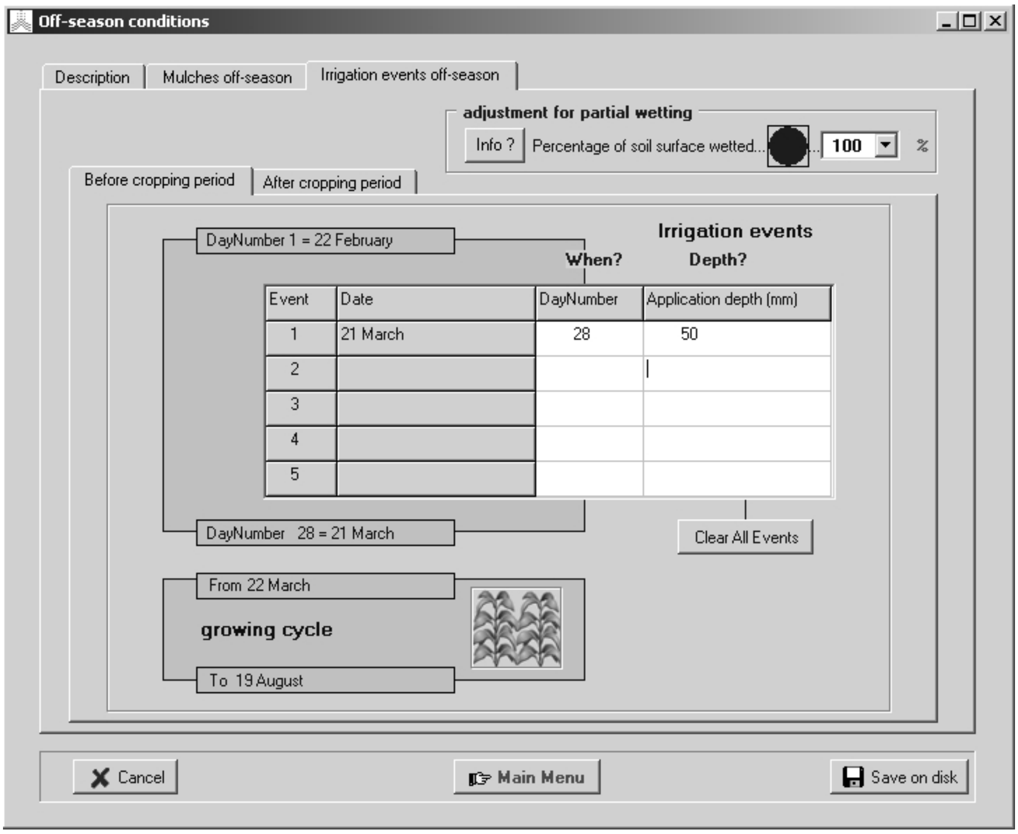


Figure 2.16
Specification of a pre-irrigation in the *Off-season conditions* menu

2.16.1 Mulches in the off-season

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

2.16.2 Irrigation events in the off-season

Irrigation events can be scheduled before and after the growing cycle. 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.

2.17 Project characteristics

Project characteristics consist of (i) the file names containing the characteristics of the selected environment (climate, crop, management and soil), and of the initial and off-season conditions, (ii) the growing cycle and simulation period and (iii) the program settings. The characteristics can be saved in a project file and are displayed in the ***Project characteristic*** menu (Fig. 2.17).

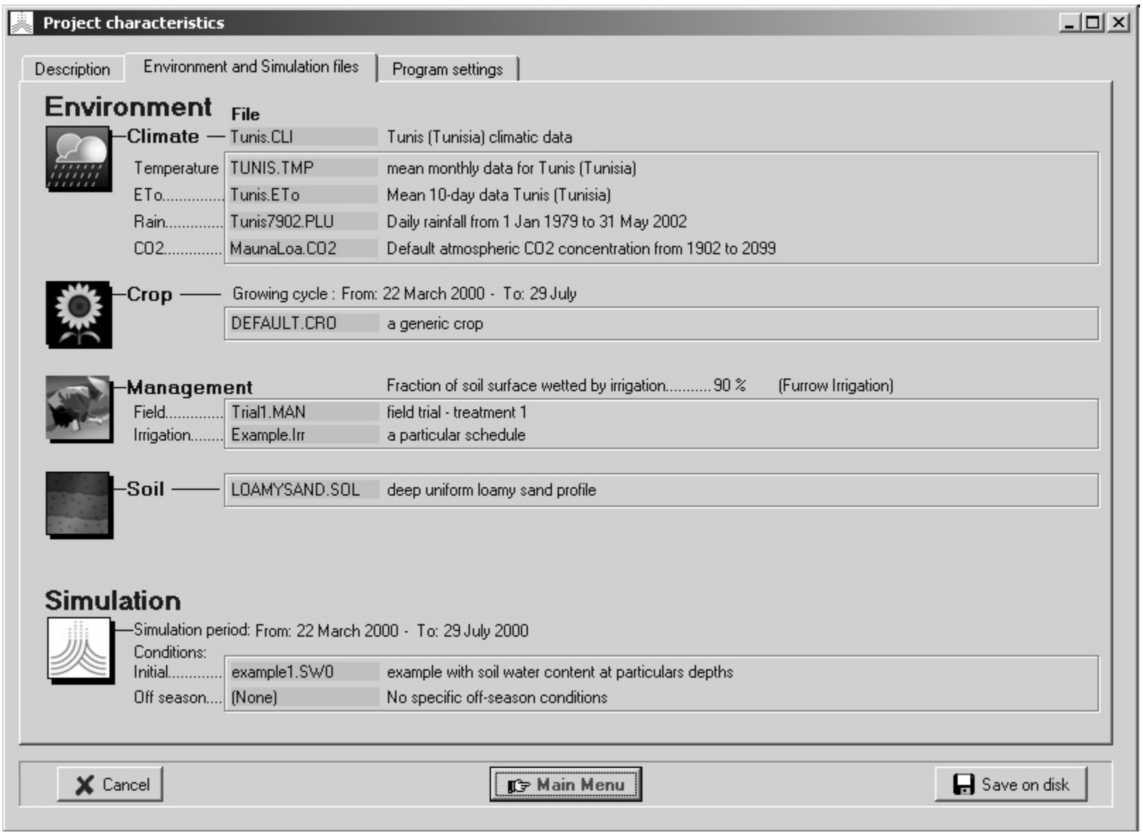


Figure 2.17
Display of the file names containing the characteristics of the selected environment and of the initial and off-season conditions in the *Project characteristic* menu

Characteristics of the environment and of the initial and off-season conditions can be specified in AquaCrop without retrieving them from a file (file is '(None)'). If a project containing '(None)' files is saved, the default settings listed in 2.3 (Default settings at the start) will be assumed when retrieving such a project file. If the characteristics do not correspond with the default setting, it is strongly advised to save the characteristics in a file, before saving the project characteristics.

2.18 Simulation run

2.18.1 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. 2.18a and 2.18b). From such plots the user can follow throughout the simulation run the effects of water 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.

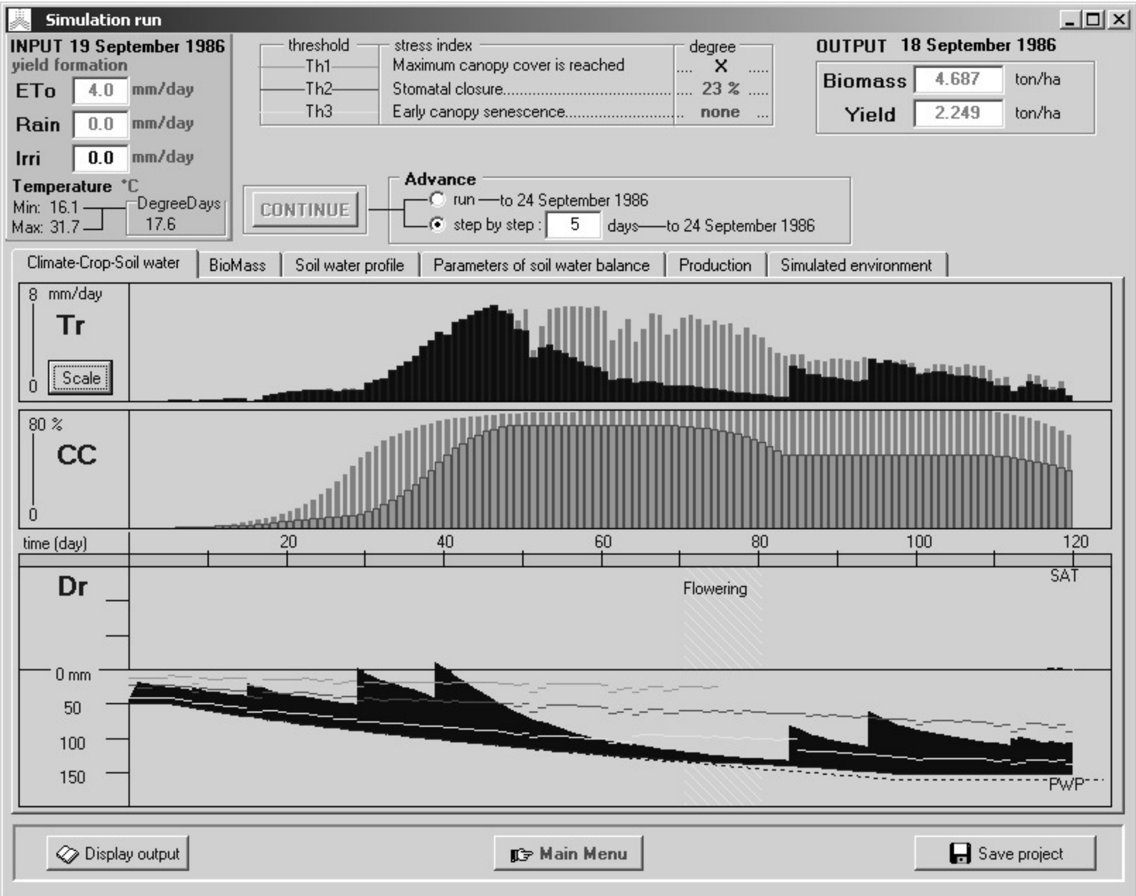


Figure 2.18a.
Graphical displays of Climate-Crop-Soil water output in the *Simulation run* menu

The Climate-Crop-Soil water sheet (Fig. 2.18a) 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 (Th1) affecting canopy expansion. This will result in a slower canopy development than expected (0-30 days after planting in Fig. 2.18a). In the canopy cover graph (CC) the canopy cover without water stress is plotted in light gray in the back portion of figure as a reference. More severe water stress will result in stomata closure, resulting in reduced crop transpiration (45-95 days after planting in Fig. 2.18a). 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 (70-85 days after planting in Fig. 2.18a).

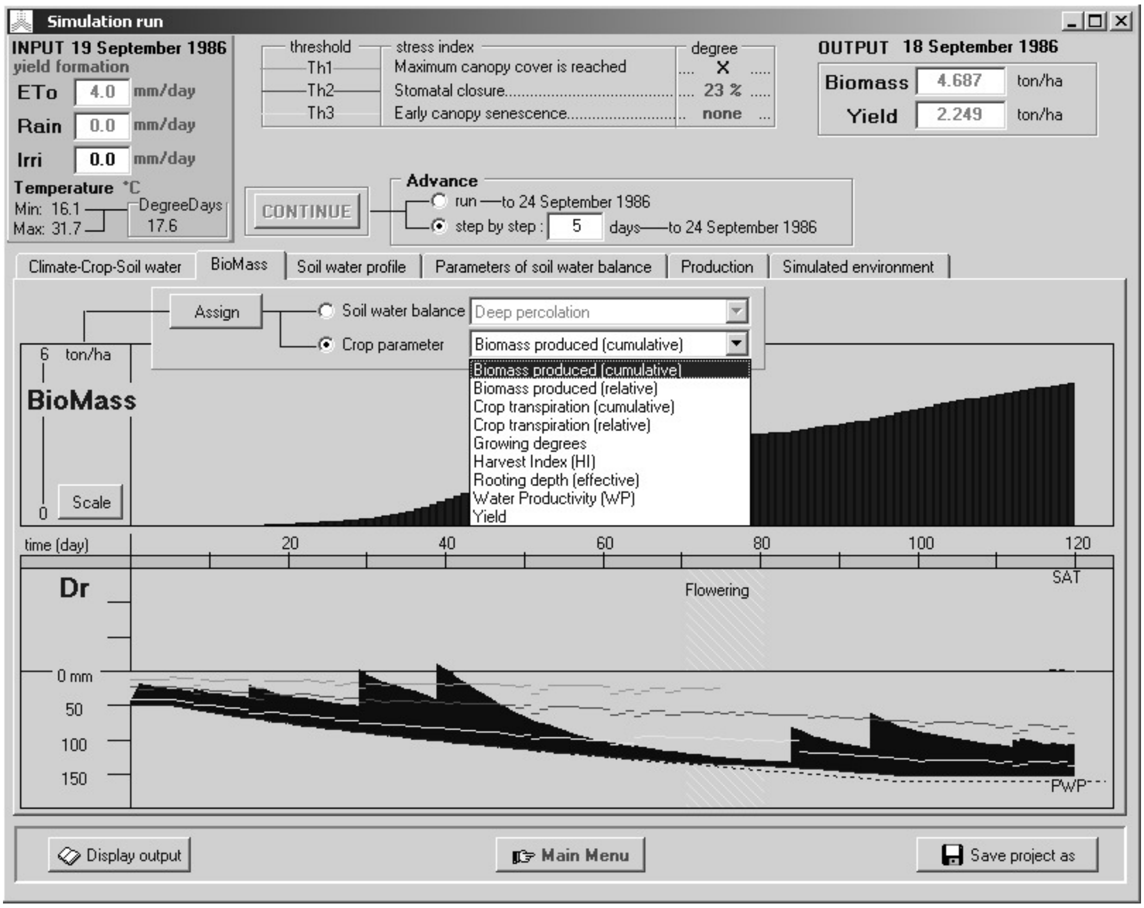


Figure 2.18b.
Selection of a parameter for display in the *Simulation run* menu

In the second sheet of the ***Simulation run*** menu, the user can select particular parameters for further analysis (Tab. 2.18). Several crop parameters and parameters of the soil water balance can be selected and the scale for the plot can be adjusted (Fig. 2.18b).

Table 2.18
Parameters of the soil water balance and crop parameters that can be selected for display in the Simulation run menu

Parameters of the soil water balance	Crop parameters
Deep percolation	Biomass produced (cumulative)
Deep percolation (cumulative)	Biomass produced (relative)
Evapotranspiration	Crop transpiration (cumulative)
Evapotranspiration (cumulative)	Crop transpiration (relative)
Evapotranspiration (maximum)	Growing degrees
Evapotranspriation (relative)	Harvest Index (HI)
Infiltrated water	Rooting depth (effective)
Infiltrated water (cumulative)	Water Productivity (WP)
Irrigation	Yield
Irrigation (cumulative)	
Rainfall	
Rainfall (cumulative)	
Soil evaporation	
Soil evaporation (cumulative)	
Soil evaporation (maximu)	
Soil evaporation (relative)	
Surface runoff	
Surface runoff (cumulative)	

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 every day of the simulation period. In the Parameters of soil water balance sheet, values are given for soil evaporation, crop transpiration, surface runoff, infiltrated water, and drainage.

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 2.18c). The simulated amount of biomass produced and the biomass that could have been produced in the absence of water and soil fertility stress are displayed as well. Information is also given on the amount of biomass and of yield produced per unit of transpired water (actual water productivity in ton per m^3).

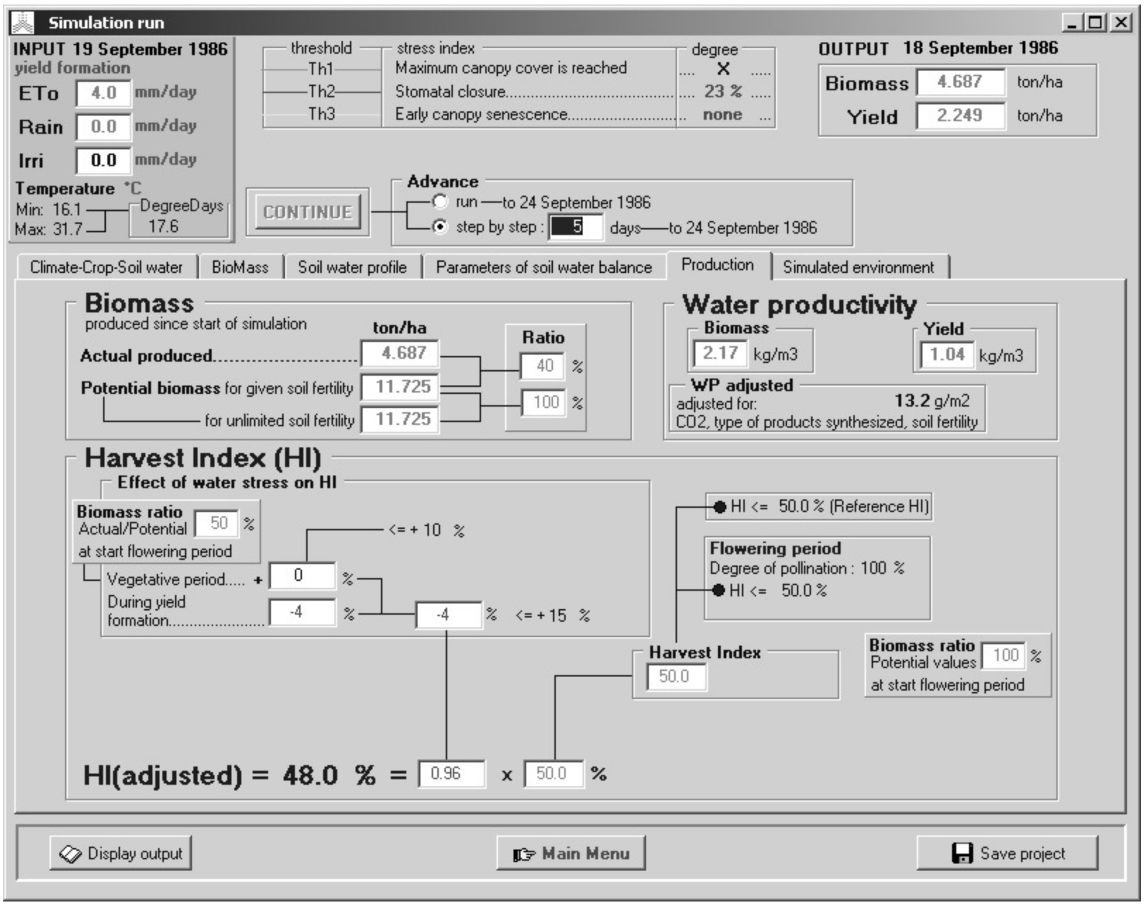


Figure 2.18c.
Information on biomass production, actual water productivity, and the ante and post-anthesis impact of water stress on the adjustment of HI in the *Simulation run* menu

2.18.2 Save project

By selecting the **<Save project>** command in the ***Simulation run*** menu, the characteristics of the environment, the initial and off-season conditions and program settings can be saved as a project file. This is an alternative way of creating a project file (see 2.6).

2.18.3 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. 2.18d). The data can be aggregated in 10-day, monthly or yearly data.

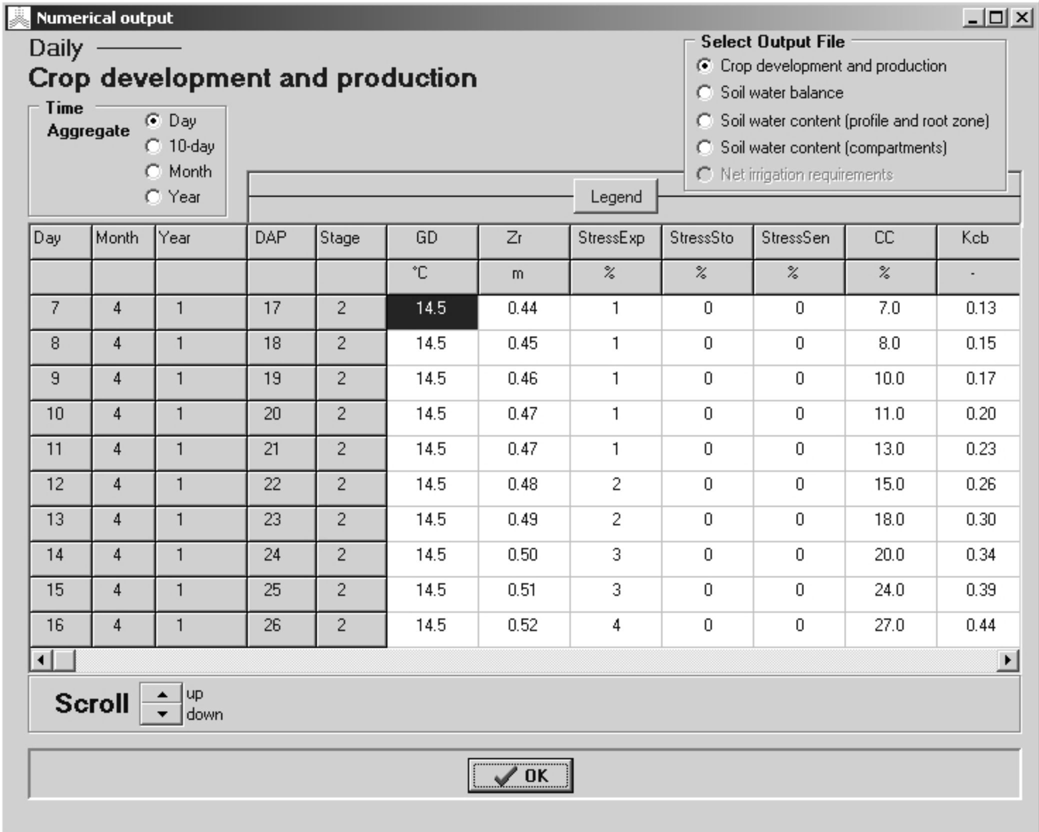


Figure 2.18d.
Display of data recorded in output files

2.18.4 Output files

On exit of the ***Simulation run*** menu, the option is available to save the output on disk. The output consists of 5 files containing:

- 18 key variables for crop development and production (ProjectCROP.OUT)
- 16 key variables for soil water balance (ProjectWABAL.OUT)
- 10 key variables for soil water content – profile (ProjectPROFILE.OUT)
- 12 key variables for soil water content – compartments (ProjectCOMP.OUT)
- 5 key variables for net irrigation requirement (ProjectINET.OUT)

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 not overwritten at each run.

The data in the files can be retrieved in spread sheet programs for further processing and analysis.

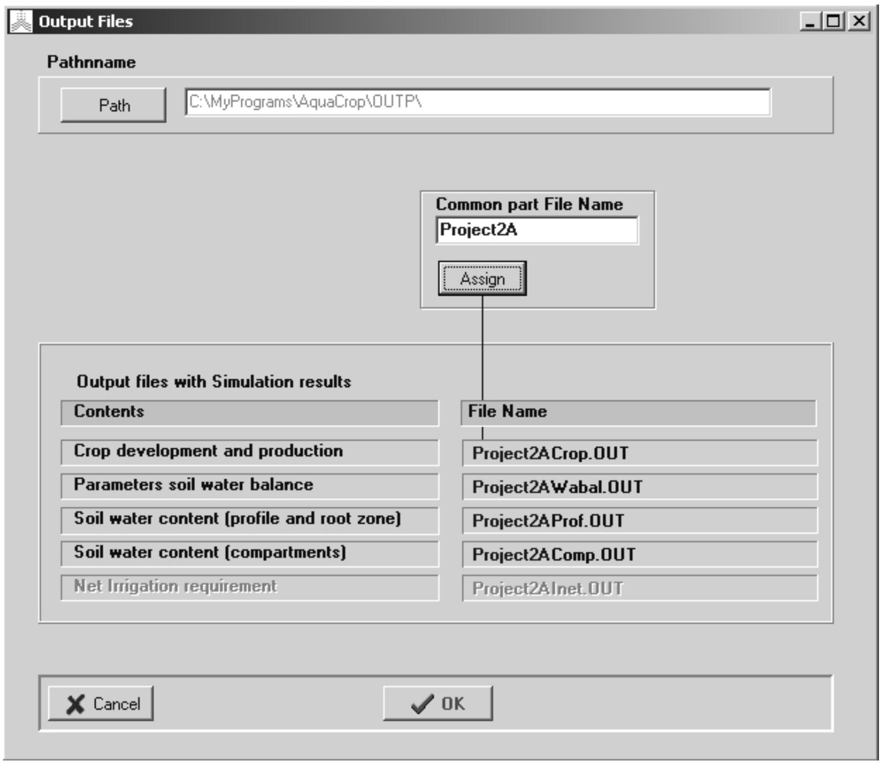


Figure 2.18c
Specification of the path and file name for the Output files

Input/Output and program settings Files

If AquaCrop is correctly installed, the main directory (default " C:\ProgramFiles\FAO\ AquaCrop ") should contain:

(i) the following files:

- AquaCrop.EXE (the executable file);
- Files with default project settings (*.PAR): Default.PAR, General.Par, Planting.par, Onset.par, Runoff.par, Showers.par, Crop.par, Field.Par, Temperature.PAR;
- Files with default Crop and Soil parameters: DEFAULT.CRO, DEFAULT.SOL;
- SOILS.DIR (a file with default values for soil characteristics)

(ii) and three subdirectories:

- DATA (default subdirectory for the input files);
- OUTP (default subdirectory for the output files);
- SIMUL (subdirectory for simulation purposes, containing between other files the MaunaLoa.CO2 file).

2.19 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 the timing and applied irrigation amounts of an irrigation schedule;
- Field management files (*.Man) containing characteristics of the field on which the crop is cultivated;
- Soil files (*.SOL) containing characteristics of the soil profile;
- 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
- 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.

2.19.1 Climate file (*.CLI)

A climate file (Tab. 2.19a) 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 2.19a.
Example of a climate file (files with extension CLI)

Tunis (Tunisia) climatic data
3.0 : AquaCrop Version (January 2009)
Tunis.TMP
Tunis.ETo
Tunis7902.PLU
MaunaLoa.CO2

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

Temperature (Tab. 2.19b), ETo (Tab. 2.19c) and Rainfall files (Tab. 2.19d) 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 2.19b.
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 2.19c.
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 2.19d.
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

2.19.3 CO2 file

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. 2.19e).

Table 2.19e.
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

2.19.4 Crop file

2.20 Files with program settings

2.21 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. The output files contain daily data of:

- Crop development and production;
- Soil water content at various depths of the soil profile;
- Soil water content in the root zone;
- Various parameters of the soil water balance;
- Net irrigation water requirement.

The variables listed in the output files are given in 2.18.1 to 2.18.5. The data in the files can be retrieved in spread sheet programs for further processing and analysis.

2.21.1 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	Zr	Rooting depth	m
8	StExp	Water stress affecting leaf expansion	%
9	StSto	Water stress inducing stomatal closure	%
10	StSen	Water stress triggering early canopy senescence	%
11	CC	Green canopy cover	%
12	Trx	Maximum crop transpiration	mm
13	Tr	Actual crop transpiration	mm
14	T/Tx	Relative transpiration (100 Tr/Trx)	%
15	WP	Crop water productivity adjusted for CO2, soil fertility and products synthesized	g/m^2
16	StBio	Temperature stress affecting biomass production	%
17	BioMass	Cumulative above ground biomass	ton/ha
18	HI	Harvest Index adjusted for failure of pollination, inadequate photosynthesis and water stress	%
19	Yield Part	Yield (HI x BioMass)	ton/ha
20	Br(w)	Percent biomass produced (Reference: given soil fertility but well watered soil)	%

21	Br(wsf)	Percent biomass produced (Reference: well watered and well fertilized soil)	%
22	WPbiom	Water Productivity for biomass	kg/m^3
23	WPyield	Water Productivity for yield part	kg/m^3

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

2.21.3 Soil water content (profile)

Default file name: ProjectProfile.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	WCZx	Water content in maximal root zone	mm
8	Zr	Rooting depth	m
9	Wr	Water content in actual root zone	mm
10	Wr(SAT)	Water content in actual root zone if saturated	mm
11	Wr(FC)	Water content in actual root zone at field capacity	mm
12	Wr(exp)	Water content in actual root zone at upper threshold for leaf expansion	mm
13	Wr(sto)	Water content in actual root zone at upper threshold for stomatal closure	mm
14	Wr(sen)	Water content in actual root zone at upper threshold for early canopy senescence	mm
15	Wr(PWP)	Water content in actual root zone at permanent wilting point	mm

2.21.4 Soil water content (compartments)

Default file name: ProjectComp.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

2.21.5. 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