Food and Agriculture Organization
of the United Nations

AquaCrop update and new features

Version 6.0

March 2017

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Contents

Abstract

In AquaCrop Version 6.0 (i) some simulation processes are updated and fine-tuned, (ii) an extra field management characteristic is considered, (iii) extra soil characteristics are introduced, (iv) the water thresholds for stomatal closure of some crops in the data base are harmonized, and (v) dry beans were calibrated.

I. Updated and fine-tuned simulation processes:

Because earlier versions of AquaCrop did not simulate well crop performance in very dry environments, having simulated crop failures that did not occur in reality, some calculation procedures were re-examined and improved:

1. **Simulation of the early development of the canopy cover under water stress**: When the crop germinates, the expansion rate of the canopy cover (CC) of the seedling is no longer limited by water stress in Version 6.0. Assuming that sufficient reserves are available in the seed, the expansion of the canopy cover is now simulated at its maximum rate (given by the Canopy Growth Coefficient, CGC). Any reduction of leaf expansion or inducing of early senescence due to water stress, are not considered until CC is 25% above the initial canopy cover. The protection of the seedling avoids an instantaneous killing of the seedling too soon after germination;
2. **Simulation of root deepening in a dry subsoil**: If the soil water depletion at the front of root zone expansion exceeds a specific threshold, the root deepening will slow down in Version 6.0, and can even become inhibited if the soil water content at the front is at permanent wilting point. The limited root deepening in a dry subsoil results in a smaller root zone and reduces the simulated water stress;
3. **Simulation of soil water stress**: The update in Version 6.0 consists in comparing at each time step, the depletion in the total root zone with the depletion in the top soil. This determines which part of the soil profile is the wettest and will determine the degree of water stress. This modification and update is more realistic for the simulation of situations where a light rain occurs and reduces the simulated water stress of deep rooted crops in those situations.
4. **Simulation of canopy cover decline**: The update of the equation describing the canopy cover decline, makes the simulation of senescence duration less divergent for the different maximum canopy covers that could be reached at the start of senescence. The slower canopy decline of a crop, where the maximum crop canopy cover was not yet reached, will stretch the time of early senescence, and might allow the crop to (partly) recover if rain or irrigation occurs in this period.

The updates 1 to 4, hardly affect the simulation of crop development and production outside very dry environments.

5. **Simulation of cold stress**: The effect of cold stress was simulated in previous AquaCrop versions by considering a temperature stress coefficient affecting the normalized biomass water productivity (WP*) as the target crop parameter. The update in Version 6.0 consists in assigning the crop transpiration coefficient (Kc_{Tr}) as the target parameter for the cold stress coefficient. As such, emphasis is given on the reduction in stomatal conductance at low temperature, which in turn affects crop transpiration. In simulations with version 6.0, the crop transpiration during cold periods will be less than in previous AquaCrop versions.

This will also keep the root zone relatively wetter, and might reduce water stress later in the season.

Additionally, the calibration and simulation of salinity stress was updated.

6. **Calibration and simulation of salinity stress:** The calibration of the crop for soil salinity stress in Version 6.0 is unlinked with the calibration for soil fertility. Further-on, the simulation of salinity stress, does not only consider ECe (Electrical Conductivity of the saturated soil-paste extract), which is the indicator for soil salinity, but also ECsw (Electrical Conductivity of the soil water). When the soil dries out, the increase of ECsw results in the increase of osmotic effects causing a stronger closure of the stomata, and the simulation of a stronger reduction of crop transpiration.

II. Introduction of an extra field management characteristic:

7. **Possibility to specify the degree of weed management:** Insufficient weed management results in the occurrence of weeds. The weeds (specified as relative cover) affect crop development and production trough competition for the available resources (water, light, and nutrients). Weeds reduce directly the canopy cover of the crop in the field, and as such the crop transpiration and crop production. Additionally, weeds affect the soil water balance and might affect the timing and magnitude of soil water stress in the season. This might indirectly affects crop development and production.

III. Introduction of extra soil characteristics:

8. **Possibility to specify the penetrability of a soil horizon:** In previous AquaCrop versions, a restrictive soil layer always blocked completely the root deepening. In Version 6.0 of Aquacrop, the penetrability (given as a percentage) specifies the expansion rate of the root zone in a horizon. Outside restrictive soil horizons, the root zone expansion is normal. There will be situations where, due to the delay in the root zone expanding in the restrictive horizon(s), the effective rooting depth can no longer reach its maximum value;
9. **Possibility to specify gravel in a soil horizon:** Gravel (specified as a mass percentage) reduces the volume of the fine soil fraction in the soil profile. This affects the soil physical characteristics, has effects on the simulation of the soil water and salt balance, and might affect crop development and production.

IV. Update of crop parameters:

10. **Update of soil water thresholds for soybean, sorghum, potato and cotton.** Values more in line with those reported in the literature, were introduced in the revised database of Version 6.0.
11. **Update of soil water extraction terms.** Values more in line with those reported in the literature, were introduced in the revised database of Version 6.0 for all crops.

V. Calibration of AquaCrop for new crops:

12. **Calibration of AquaCrop for dry beans.**

Part 1. Updated and fine-tuned simulation processes

1. Simulation of the early development of the canopy cover under water stress

1.1 General procedure of germination

A seed will germinate when the soil water content in the top soil is above a specified threshold. The value for the threshold is a program parameter which can be altered by the user. The default value for germination is set at 20 % of the Total Available soil Water (i.e. 0.2 TAW).

1.2 Update in AquaCrop version 6.0

When the crop germinates, the expansion rate of the canopy cover (CC) of the seedling is no longer limited by water stress in Version 6.0. Thanks to nutrients available in the seed, it is assumed that the expansion of the canopy cover is its maximum rate (given by the Canopy Growth Coefficient, CGC). Any reduction of leaf expansion or inducing of early senescence due to water stress, are disregarded till CC is 25% above the initial canopy cover (i.e. CC > 1.25 CCo). Although water stress does not affect the early expansion, the growth rate of the seedling will be slow in cool weather, when growing degrees limit a quick increase of CC. On days where the mean air temperature is at or below the base temperature (i.e. zero growing degree day), the expansion is inhibited completely.

Once CC is above 1.25 of CCo, the protection of the germinating seedling is switched off, and the further expansion of the canopy cover is directed by the soil water content in the root zone and the available growing degrees. If the water stress is severe, early senescence can be triggered.

2. Simulation of root deepening in a dry subsoil

The expansion of the root zone is affected by the soil water content in the soil profile, and soil physical characteristics of the horizons.

As in previous AquaCrop versions:

- The unhindered expansion of the root zone in a well-watered soil profile without soil physical constraints;
- The restricted expansion when the root zone becomes depleted;

New in version 6.0:

- The limited expansion of the root zone in a dry subsoil;

Updated in version 6.0:

- The simulation of the expansion of the root zone in a soil profile with restricted soil horizon(s).

2.1 Unhindered expansion of the root zone in a well-watered soil

as in previous AquaCrop versions

The root deepening rate is a function of crop type and time (Fig. 2.1). In AquaCrop the development of the rooting depth is simulated by considering the n^{th} root of time. Once half of the time required for crop emergence (or plant recovery in case of transplanting) is passed by ($t_0/2$), the rooting depth starts to increase from an initial depth Z_o to the maximum effective rooting depth Z_x:

$$Z = Z_o + (Z_x - Z_o)\sqrt[n]{\frac{\left(t - \frac{t_0}{2}\right)}{\left(t_x - \frac{t_0}{2}\right)}} \quad \text{(Eq. 2.1)}$$

where
- Z effective rooting depth at time t [m];
- Z_o starting depth of the root zone expansion curve [m];
- Z_x maximum effective rooting depth [m];
- t_o time to reach 90 % crop emergence [days or growing degree days];
- t_x time after planting when Zr_x is reached [days or growing degree days];
- t time after planting [days or growing degree days];
- n shape factor.

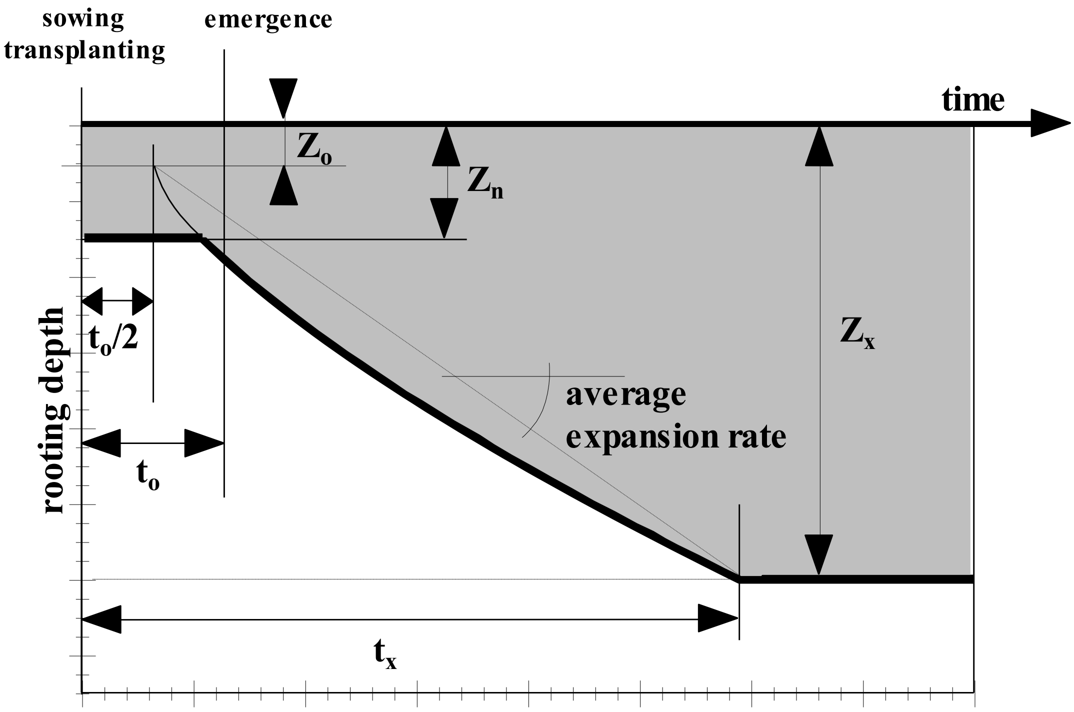


Figure 2.1 – Development of the effective rooting depth (shaded area) from sowing till the maximum effective rooting depth (Z_x) is reached.

The starting depth of the root zone expansion curve Z_o is a program parameter and expressed as a fraction of Z_n (Fig. 2.5). The development of the effective root zone starts when Z exceeds the minimum effective rooting depth (Z_n) and advances till the maximum effective rooting depth (Z_x) is reached (Fig. 2.1 and 2.2). At any time the effective rooting depth Z is given by

$$Z_n \leq Z \leq Z_x \qquad \text{(Eq. 2.2)}$$

The maximum and minimum effective rooting depth, and the shape factor (n) are specified in the ***Crop characteristics*** menu (Fig. 2.2). The shape factor n, which is crop specific, determines the decreasing speed of the root zone expansion in time. For values larger than 1, the expansion of the root zone is more important just after planting than later in the season. The larger the value of n, the stronger the discrepancy between the expansion rates at the beginning and end of the period for root zone expansion. The expansion of the effective root zone is constant (linear) when n is 1.

The time to reach the maximum effective rooting depth can be specified by selecting the average root zone expansion or by specifying explicitly the time in either calendar days or growing degree days (Fig. 2.2).

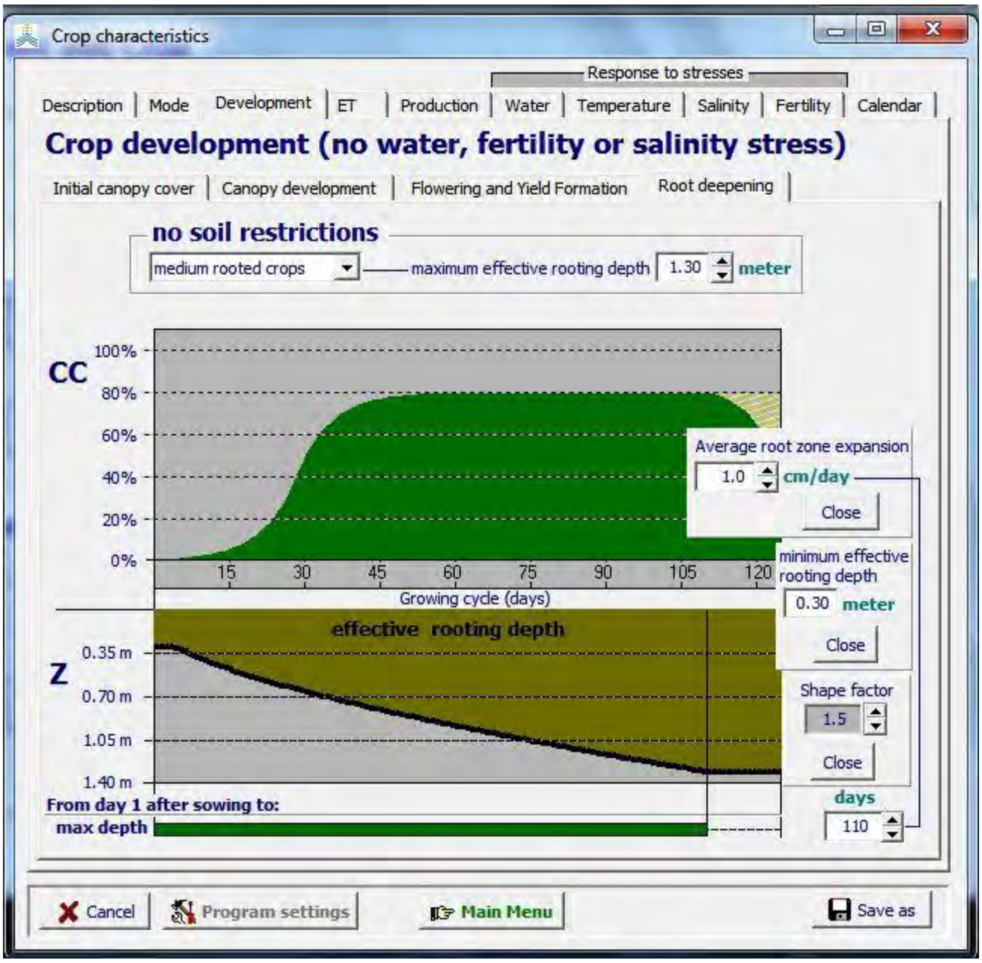


Figure 2.2 – Root deepening in a well-watered soil with no soil restrictions as specified in the *Crop characteristic*s menu.

In Version 6.0, the default values for the classes of the maximum effective rooting depth are updated (Tab. 2.1).

Table 2.1 – Updated classes, corresponding default values, and ranges for the maximum effective rooting depth of the fully developed crop under optimal conditions

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

2.2 Restricted expansion of the root zone when the root zone becomes depleted

as in previous AquaCrop versions

Water stress affects crop development. Leaf expansion can already be reduced at small root zone depletions. The development of the root zone starts to be affected when the average root zone depletion (Dr) exceeds the upper threshold for stomatal closure (Dr > p_{sto} TAW). At this depletion the water stress coefficient for stomatal closure (Ks_{sto}) becomes smaller than 1 (Fig. 2.3).

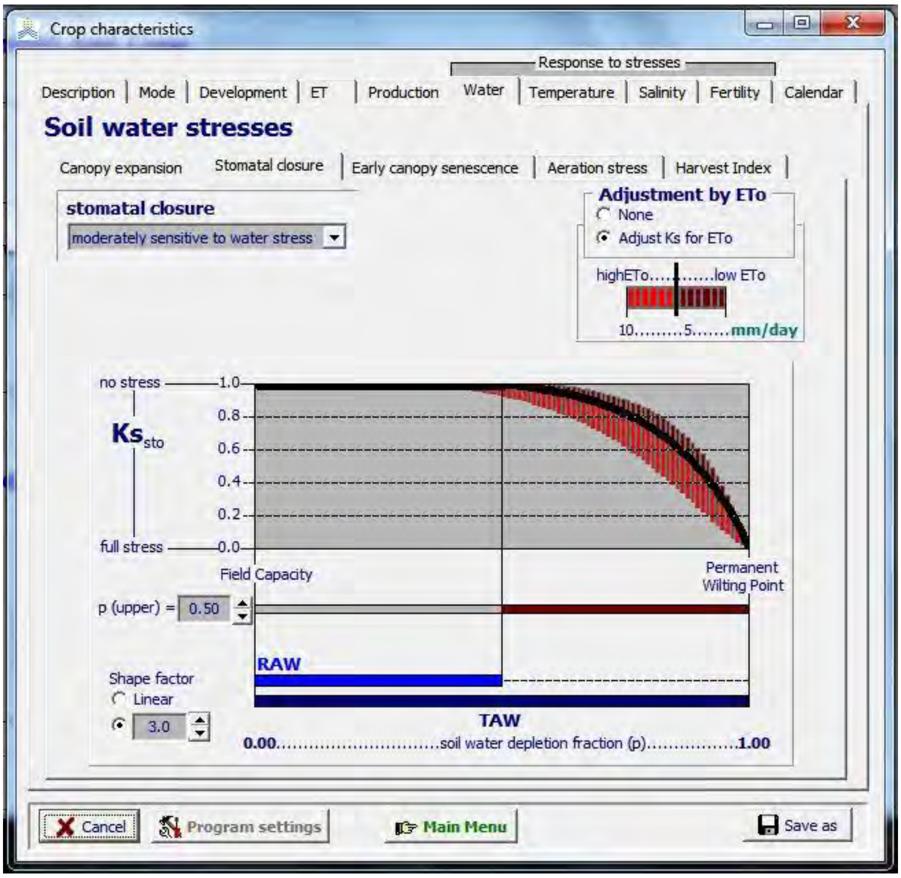


Figure 2.3 – The threshold and shape for the soil water stress coefficient for stomatal closure (Ks_{sto}) as specified in the *Crop characteristics* menu.

The reduction in the expansion of effective rooting depth is determined by the magnitude of the Ks_{sto} (Fig. 2.3) and a (negative) shape factor, f_{shape} (Fig.2.4). The shape factor, f_{shape}, is a program parameter which can be adjusted by the user (Fig. 2.5). The effect of water stress on the reduction of the root zone expansion is:

- **strong** for f_{shape} = 0, and given by the linear relationship:

$$dZ_{adj} = Ks_{sto}\ dZ \qquad \text{(Eq. 2.3)}$$

- **small to medium** for -1 ≤ f_{shape} ≤ -8, and given by an exponential relationship:

$$dZ_{adj} = dZ\ \frac{e^{Ks_{sto}\ f_{shape}} - 1}{e^{f_{shape}} - 1} \qquad \text{(Eq. 2.4)}$$

Making f_{shape} (default is -6.0) more negative minimizes the effect of water stress on root zone development, whereas root zone development is slowed significant in the early period of stress development if f_{shape} is close to -1.0 (Fig. 2.4).

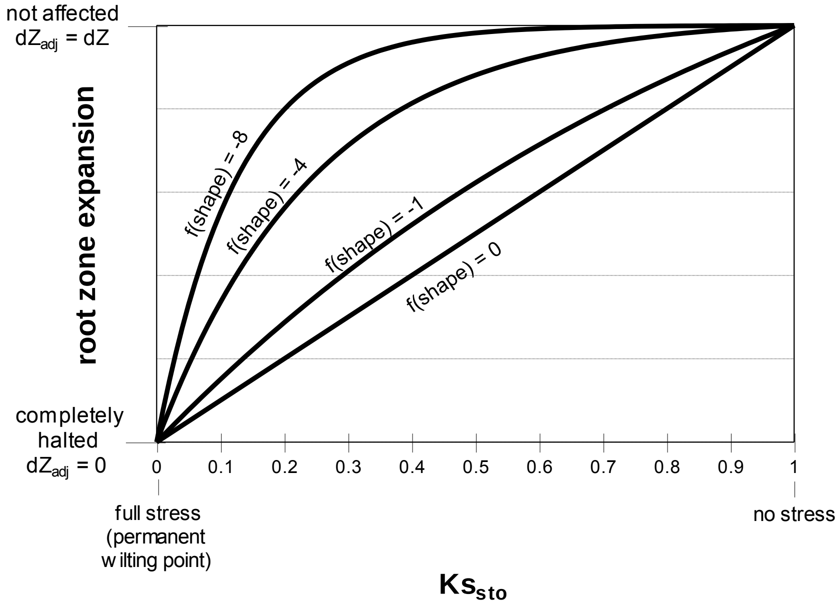


Figure 2.4 – The effect of water stress on the reduction of root zone expansion for various shape factors (f_{shape}) and water stress in the root zone (Ks_{sto})

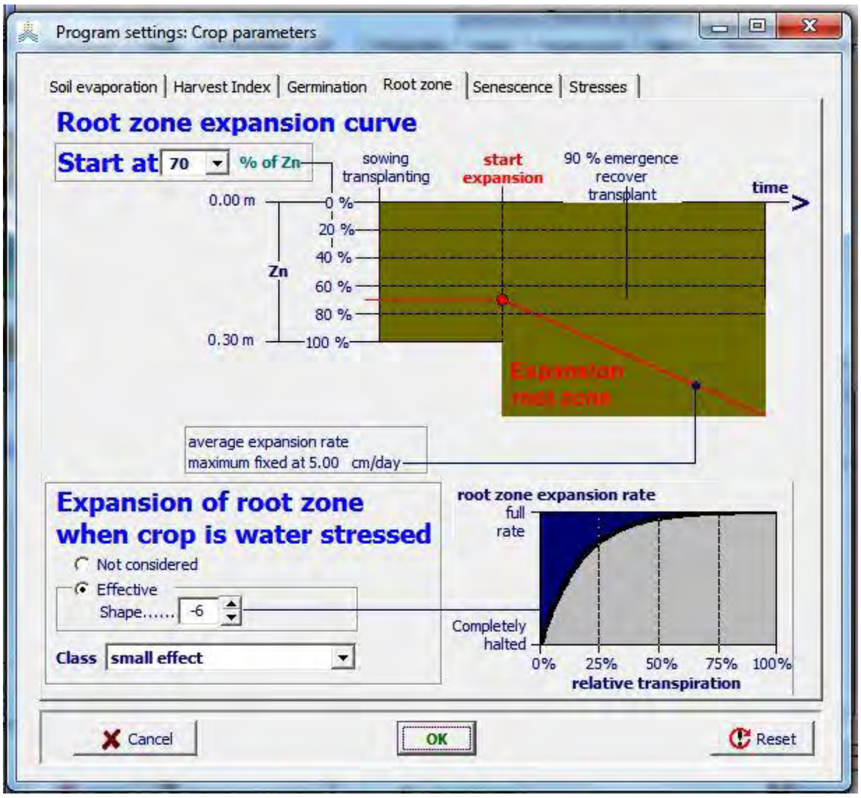


Figure 2.5 – The starting depth (Zo) of the root zone expansion curve and the shape factor (f_{shape}) for the expansion of root zone when the crop is water stressed, as specified in the *Program settings: Crop parameters* menu.

2.3 Limited expansion of the root zone in a dry subsoil

New in Version 6.0

To avoid root zone expansion in a dry subsoil, an extra restriction on root zone development is implemented in Version 6.0. If the soil water depletion at the front of root zone expansion exceeds a specific threshold ($p_{Zr,exp}$ TAW), the root deepening will slow down, and can even become inhibited if the soil water content at the front is at permanent wilting point (Fig. 2.6). To avoid excessive parametrization and in the absence of published data, $p_{Zr,exp}$ is derived from the root zone depletion at which stomata starts to close (p_{sto}):

$$p_{Zr,exp} = p_{sto} + \frac{1 - p_{sto}}{2} \qquad \text{(Eq. 2.5)}$$

This makes that the root zone expansion remains unrestricted when the stomata starts to close, but also that the soil water depletion at which the expansion starts to be limited is linked with the sensitivity of the crop to water stress. Root deepening in a dry subsoil is more restrictive for sensitive crops to water stress than for more tolerant crops. The root zone expansion curve (Zr_{exp}) and the Ks_{sto} curve have the same shape factor (Fig. 2.6). The correction for ETo of the threshold for stomatal closure (Fig. 2.3) is however disregarded when deriving $p_{Zr,exp}$ in Eq. 2.5.

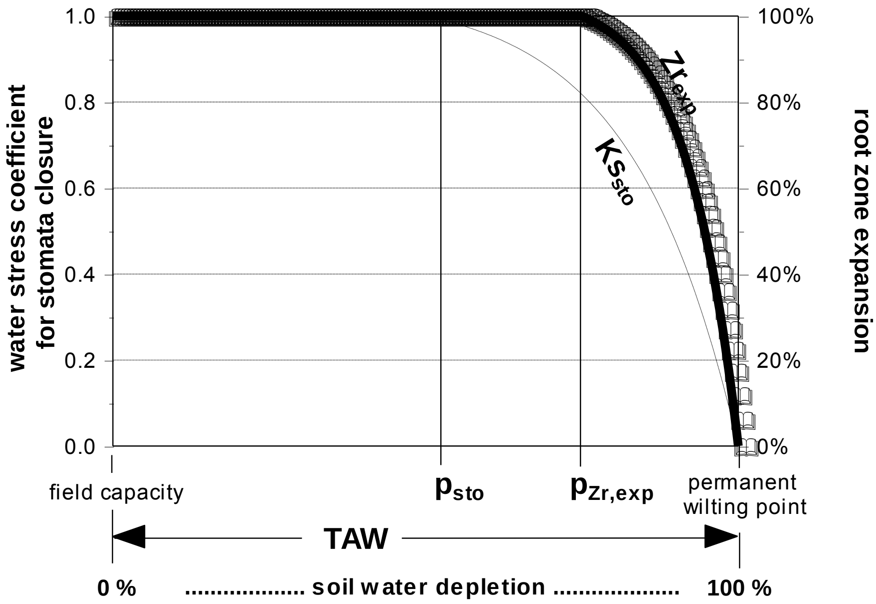


Figure 2.6 – Root zone expansion (Zr_{exp}) at the expansion front (bold line) and water stress coefficient for stomata closure, Ks_{sto} (dotted line) for various soil water depletions.

If the soil water depletion at the expansion front exceeds $p_{Zr,exp}$ TAW, the root zone deepening is slowed down. This is the case at the start of the season in the simulation showed in Fig. 2.7, and at the end of the season in Fig. 2.8. In the simulation illustrated in Fig. 2.7, rainfall and/or irrigation wetted sufficiently the subsoil later in the season so that the root deepening rate became at full speed. However, due to the initial delay in expanding, the effective rooting depth could no longer reach its maximum value.

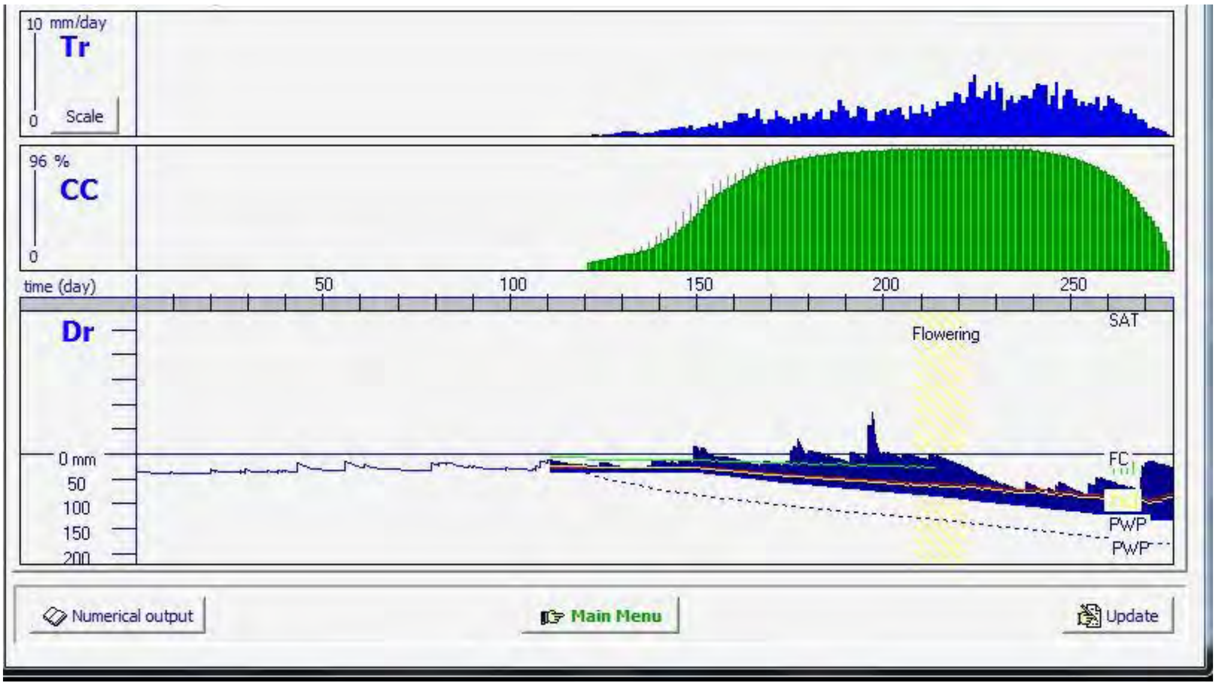


Figure 2.7 – Simulation whereby the initial very dry soil profile was insufficient wetted by rainfall at the start of the crop cycle. This limited root zone expansion in the first part of the season. Later, the subsoil got wetted by rainfall and the deepening rate became at full speed. However, due to the initial delay in expanding, the effective rooting depth could no longer reach its maximum value (given by the dotted line in the Dr graph).

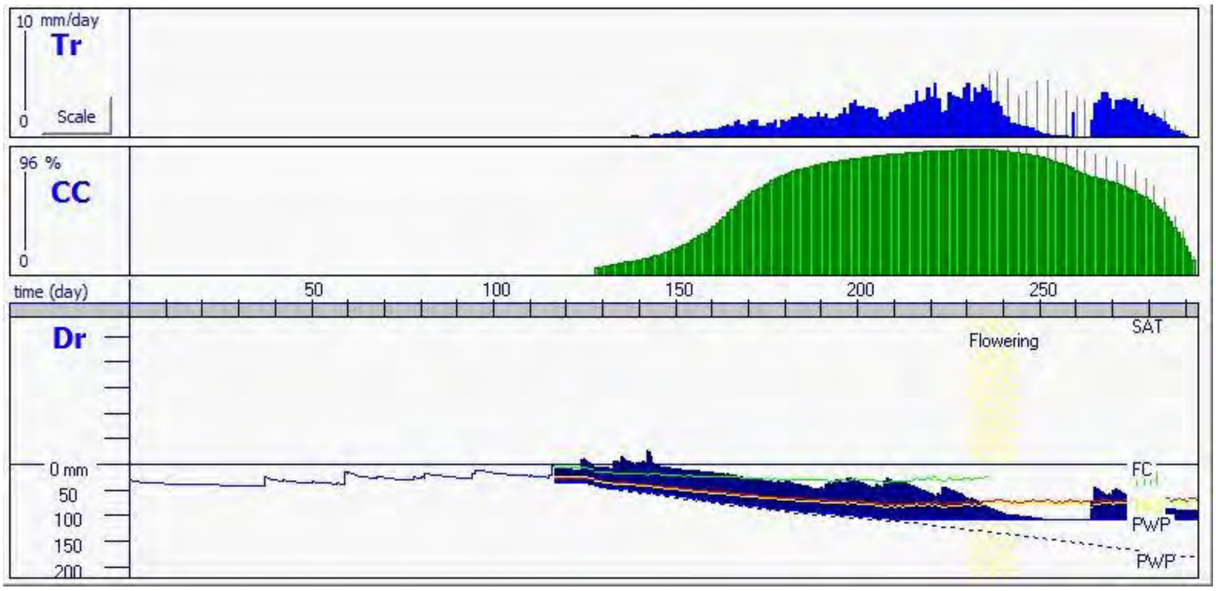


Figure 2.8 – Simulation whereby initially the top of the very dry soil profile was sufficient wetted by rainfall to allow full expansion of the root zone. When rain ceased later in the season the subsoil at the expansion front of the root zone remained dry, and root deepening became inhibited at that depth.

2.4 Expansion of the root zone in a soil profile with restrictive soil layer(s)

Updated in Version 6.0

The effective rooting depth cannot reach its maximum value (line 1, in Fig. 2.9) if restrictive soil layers limit root development or when the exploitable soil depth is smaller than Z_x.

The distinct layer can be a hardpan, formed by deposits in the soil that fuse and bind the soil particles. Hardpans limits or inhibited the expansion of the root zone and are also largely impervious to water. A restrictive soil layer may also be the result of soil compaction which increases its bulk density. Practices that can lead to poor bulk density are listed in Table 2.2. Whenever the bulk density exceeds a certain level, root growth is restricted (Tab. 2.3). Compacted soil layers with high bulk densities, do not only restrict root growth, but may also inhibit the movement of air and water through the soil.

Table 2.2 – Practices that can lead to poor bulk density

- Consistently ploughing or disking to the same depth;
- Allowing equipment traffic, especially on wet soil;
- Using a limited crop rotation without variability in root structure or rooting depth;
- Incorporating, burning, or removing crop residues;
- Overgrazing forage plants, and allowing development of livestock loafing areas and trails;
- Using heavy equipment for building site preparation, or land smoothing and levelling

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

Table 2.3 – Ideal and root restricting bulk densities

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

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

The root deepening rate is described by Eq.2.1 as long as the expanding front is in a non-restrictive layer. In the restrictive soil layer, the expansion is slowed down (line 2b, in Fig. 2.9) or inhibited (line 2a, in Fig 2.9) depending on its penetrability. Below the restrictive soil layer, the root zone expansion is normal again, and no longer restricted (Fig. 2.10). However, due to the delay in expanding, the effective rooting depth can no longer reach its maximum value.

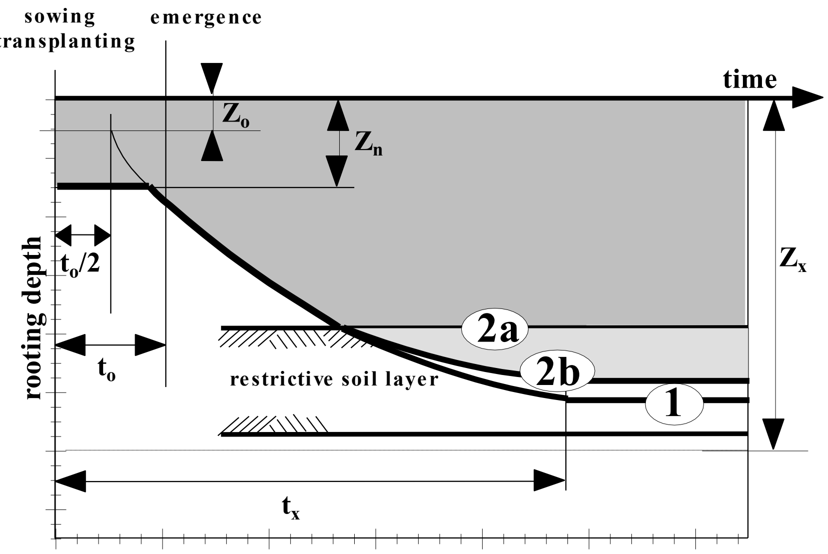


Figure 2.9 – Development of the effective rooting depth (1) in the absence and (2) in the presence of a restrictive soil layer (2a) which inhibits the expansion of the root zone; and (2b) which slows down the expansion of the root zone

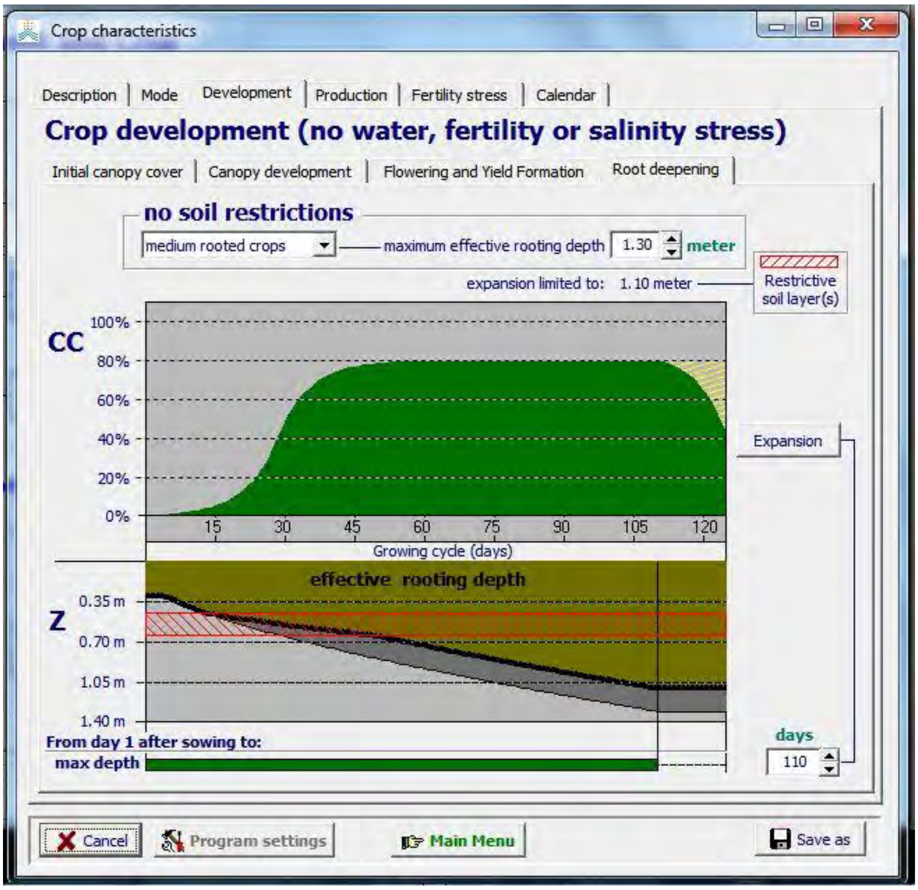


Figure 2.10 – Display of the effective rooting depth in the *Crop characteristics* menu, when a restrictive soil layer (red shaded area), as specified in the *Soil profile characteristics* menu (Fig. 2.11), limits the root zone expansion. Above or below the restrictive layer (0.45 – 0.65 m), the root zone expansion rate is normal and not affected.

The presence of a restrictive soil layer in the soil profile is a soil characteristic. By specifying the presence as a distinct soil horizon, the depth and thickness of the restrictive layer can be specified (Fig. 2.11). Its penetrability describes the effect on the expansion rate of the root zone.

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

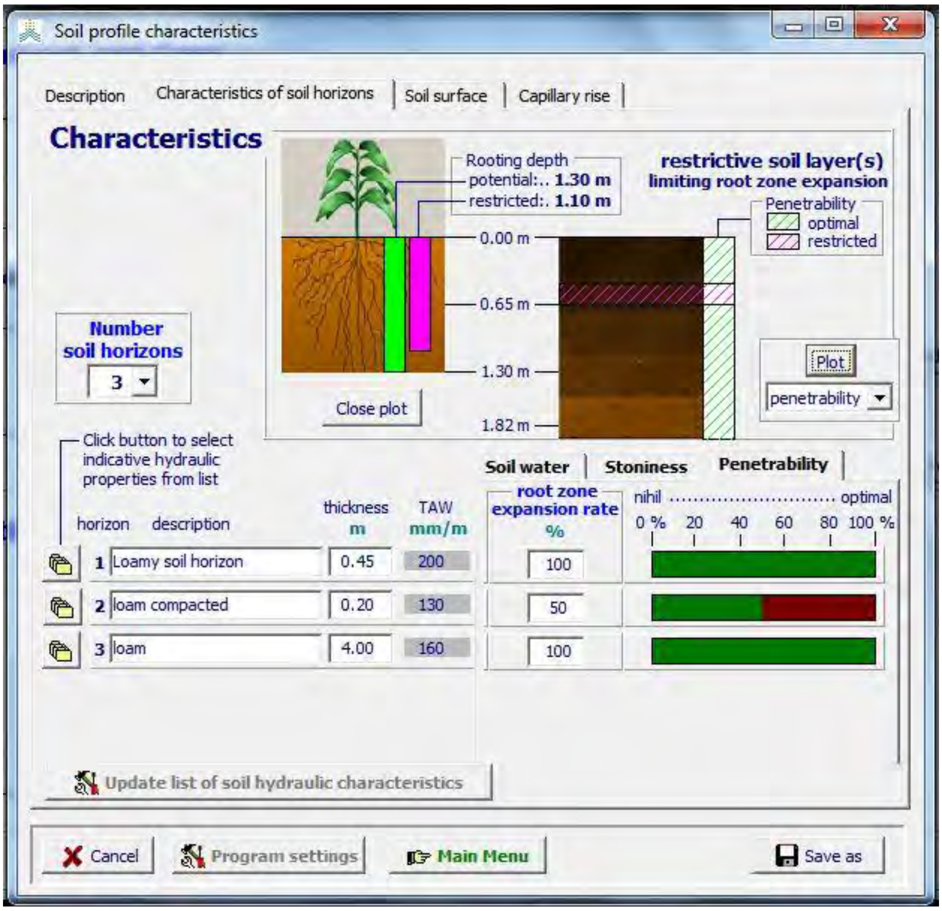


Figure 2.11 – Specification of the depth and thickness of the restrictive soil layer (soil horizon 2: 0.45 – 0.65 meter) and its effect on the expansion rate of the root zone (50% penetrability) in the *Soil profile characteristics* menu. The corresponding development of the effective rooting depth is given in the *Crop characteristics* menu (Fig. 2.10).

3. Simulation of soil water stress

The update in Version 6.0 consist in comparing at each time step, the root zone depletion with the depletion in the top soil, to determine which part of the soil profile is the wettest and controls the water stresses.

3.1 Soil water content and depletion in the root zone

To describe accurately the retention, movement and uptake of water in the soil profile, AquaCrop divides the soil profile into soil compartments (12 by default) with thickness Δz (Fig. 3.1). The soil water content in the root zone at time t, is given by the sum of the soil water content in the individual compartments of the root zone (Zr_t):

$$Wr_t = \sum_{1}^{n} \left(1000 \;\; \theta_{i,t} \;\; [\alpha \;\; \Delta z_i]\right) \qquad \text{(Eq. 3.1)}$$

where Wr_t is the actual soil water content in mm(water) at time step t, $\theta_{i,t}$ the soil water content (m^3(water)/m^3(soil)) in compartment i, Δz_i the thickness of the compartment in meter, α a dimensionless correction factor to account for partial rooted compartments, and n the number of soil compartments which are rooted at time step t (Fig. 3.1). For partial rooted compartments α is the fraction of the compartment which is rooted. For fully rooted compartments, α is one.

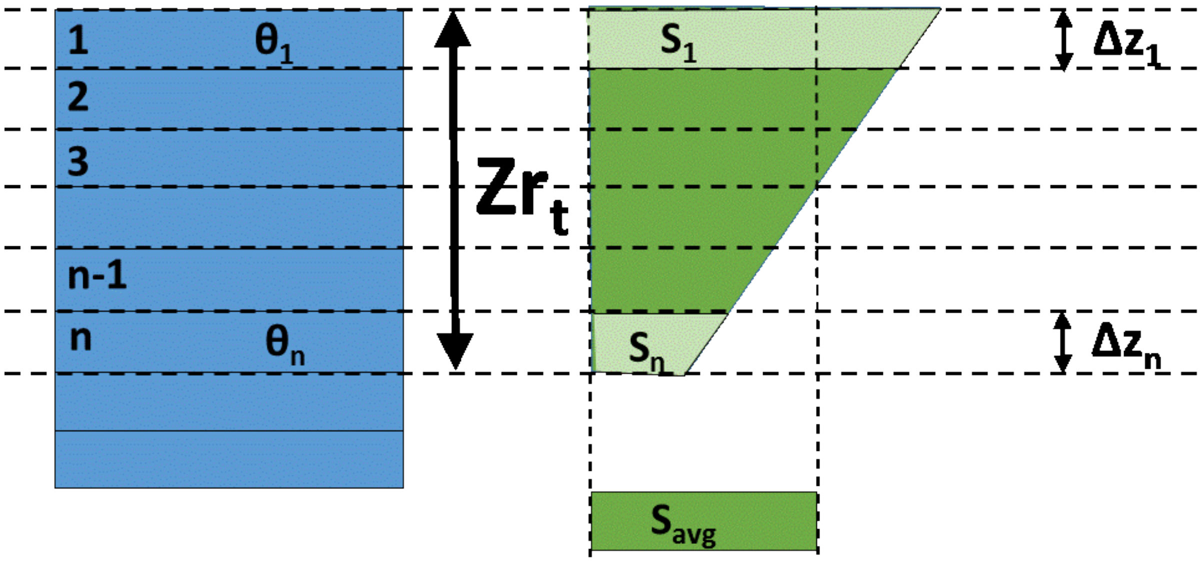


Figure 3.1 – The soil water content (θ), thickness (Δz) and sink term for water extraction by roots (S) of the soil compartments (1 to n) composing the root zone (Zr_t) at time t.

Depletion (D) expresses the amount of soil water retained in the soil profile, as a shortage versus a reference (Fig. 3.2). At the reference (for which Field Capacity is selected) the depletion is zero (D = 0). The depletion in the root zone (Dr) at time step t is given by:

$$Dr_t = Wr_{FC} - Wr_t \quad \text{(Eq. 3.2)}$$

$$Wr_{FC} = \sum_{1}^{n} \left(1000\ \theta_{FC,i}\ [\alpha\ \Delta z_i]\right) \quad \text{(Eq. 3.3)}$$

where Wr_{FC} is the soil water content in the root zone at Field Capacity.

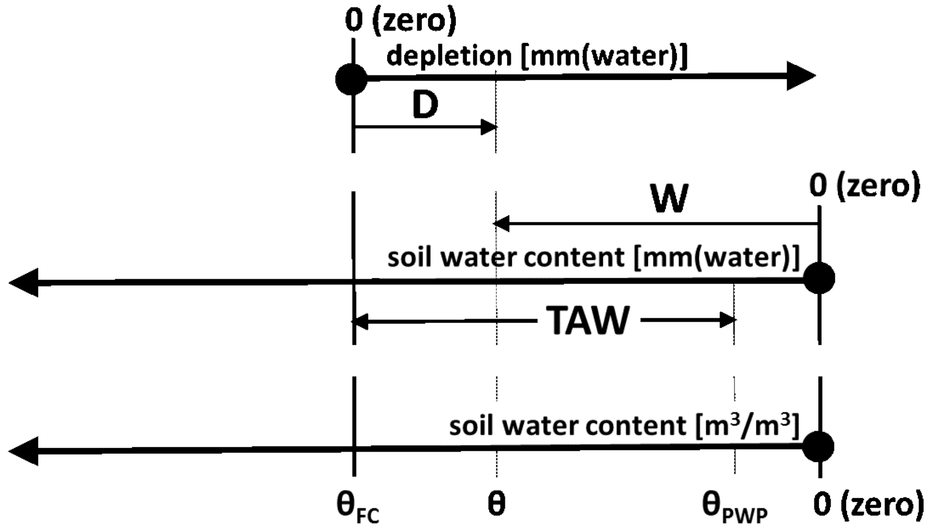


Figure 3.2 – Depletion (D), soil water content (W) and Total Available soil Water (TAW) in mm(water), and soil water content at Field Capacity (θ_{FC}) and at Permanent Wilting Point (θ_{PWP}) in m^3(water) per m^3(soil).

3.2 Soil water content and depletion in the top soil

The root zone depletion ($D_{Ztop,t}$) and soil water content ($W_{Ztop,t}$) in the top soil expressed in mm(water) and at time step t are given by:

$$D_{Ztop,t} = W_{Ztop,FC} - W_{Ztop,t} \quad \text{(Eq. 3.4)}$$

$$W_{Ztop,t} = \sum_{1}^{p} \left(1000\ \theta_i\ [\alpha\ \Delta z_i]\right) \quad \text{(Eq. 3.5)}$$

$$W_{Ztop,FC} = \sum_{1}^{p} \left(1000\ \theta_{FC,i}\ [\alpha\ \Delta z_i]\right) \quad \text{(Eq. 3.6)}$$

where $W_{Ztop,FC}$ is the soil water content in the top soil expressed in mm(water) at Field Capacity, Ztop is the thickness of the top soil in meter, $\theta_{i,t}$ is the soil water content (m^3(water)/m^3(soil)) in compartment i of the top soil at time t, p is the number of soil compartments which compose Ztop, and α is a dimensionless correction factor which is less than 1 if the p^{th} compartment is only part of Ztop. Eq. 3.4, 3.5 and 3.6 are only computed in the part of the simulation period where the actual rooting depth at time t (Zr_t) is larger than Ztop.

The thickness of the top soil, is a program parameter, which can be altered by the user by selecting the **<Program settings>** command in the ***Crop characteristics*** menu (Fig. 3.3). The default value for Ztop is 0.10 m, and its value can range between 0.10 up and 0.50 m.

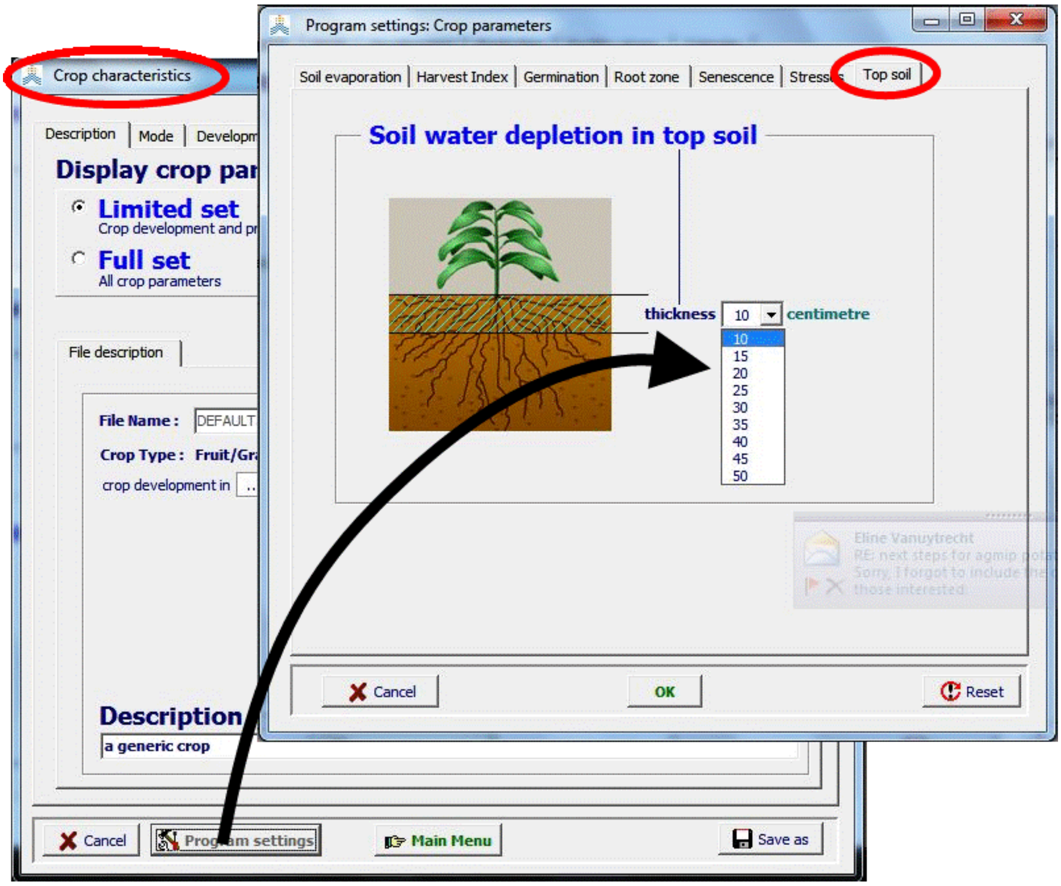


Figure 3.3 – Specifying the thickness of the top soil (Ztop) in centimetre in the *Program settings: Crop parameters* menu.

3.3 Determination of the soil water stress

To determine which part of the soil profile is the wettest and controls the water stress, the root zone depletion (Dr_t) is compared with the depletion in the top soil ($D_{Ztop,t}$) at each time step t in which the rooting depth (Zr_t) is larger than Ztop. To allow comparison between Dr_t and $D_{Ztop,t}$, the depletions are relative and expressed as the fraction of TAW depleted in the root zone (for Dr) or in the top soil (for D_{Ztop}):

– If Dr_t (expressed in fraction of TAW depleted) is smaller than $D_{ZTop,t}$, then the root zone is relative wetter than the top soil, and determines the water stresses. By comparing the soil water content in the root zone (Wr_t) with the threshold soil water contents (Fig. 3.4), the degree of soil water stress affecting leaf expansion, inducing stomatal closure and triggering early senescence is obtained, and the corresponding crop response can be simulated. This is identical with the calculation procedure in the previous versions of AquaCrop.

- IF $Dr_{Ztop,t}$ is smaller than Dr_t, then the top soil is relative wetter than the whole root zone. Consequently, the soil water content in the top soil ($W_{Ztop,t}$) is considered to determine if one or more water stresses occur and how severe they are.

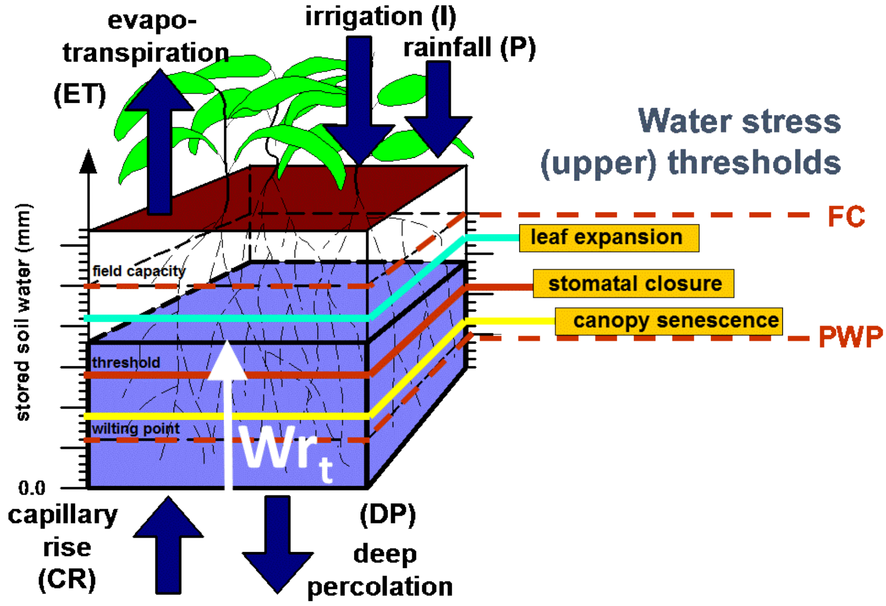


Figure 3.4 – The soil water content in the root zone at time t (Wr_t), and the threshold soil water contents below which leaf expansion slows down, stomatal closure starts to be induced and canopy senescence is triggered.

For germination, which can only occur when the soil water content in the effective root zone (Z_{min}) is above a specific threshold, the soil water content in the root zone at the moment of germination is considered. Hence germination is not controlled by the soil water content in the top soil.

4. Simulation of canopy cover decline

4.1 Canopy decline in the previous versions of AquaCrop

The decline in green crop canopy is described by:

$$CC = CC_x \left[1 - 0.05 \left(e^{\frac{CDC}{CC_x} t} - 1 \right) \right] \qquad \text{(Eq. 4.1)}$$

where CC canopy cover at time t [fraction ground cover];
CC_x maximum canopy cover at the start of senescence (t=0) [fraction ground cover];
CDC canopy decline coefficient [day^{-1} or growing degree day^{-1}];
t time [days or growing degree days].

By adjusting the CDC in Eq. 4.1 to the degree of water stress, the equation is used to describe early canopy senescence under severe water stress conditions. The canopy decline will be very small when water stress is limited, but increases with larger water stresses. This is simulated by adjusting the canopy decline coefficient with the water stress coefficient for senescence (Ks_{sen}). To guarantee a fast enough decline at strong root zone depletion, the 8th power of Ks_{sen} is considered:

$$CDC_{adj} = \left(1 - Ks_{sen}^{8}\right) CDC \qquad \text{(Eq. 4.2)}$$

where CDC is the reference canopy decline coefficient and Ks_{sen} the water stress coefficient for early canopy senescence (Fig. 4.1).

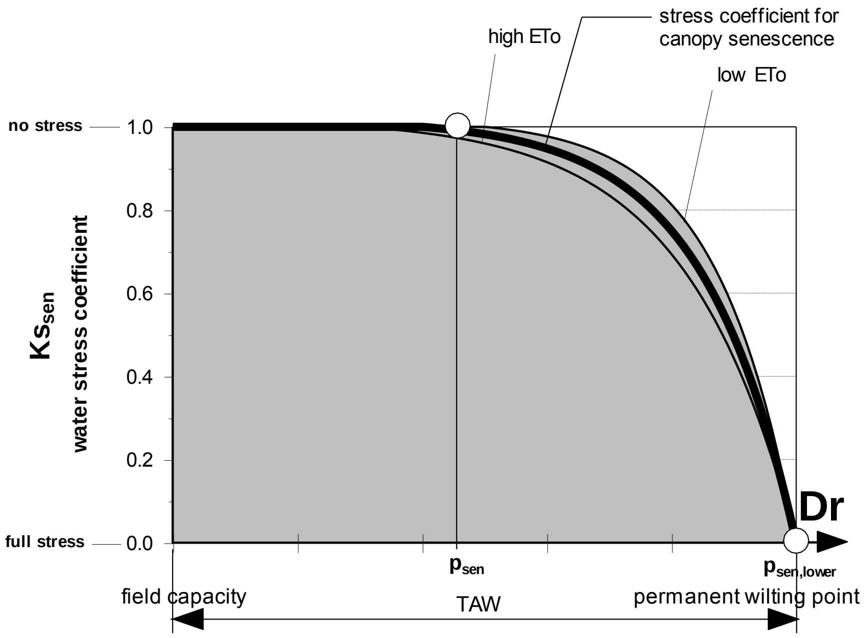


Figure 4.1 – Water stress coefficient for early canopy senescence (Ks_{sen}) for various degrees of root zone depletion (Dr)

4.2 UPDATE in Version 6.0

In Eq. 4.1, CCx is the maximum canopy cover at the start of senescence (t=0). For a crop at seedling stage, CCx will be very small, and the ratio of CDC/CCx (i.e. the power of the exponent) will be many folds larger than the ratio for the nearly full canopy situation (CCx at about 100%), under which the crop calibration was usually carried out. Hence, when the water content of the soil falls below the threshold for senescence, a crop at seedling stage with very low CCx, will last only a few days before its CC is reduced to zero.

Although the senescence of larger plants may take longer because they simply have more leaves to shed, the time to reduce CC to zero for a small crop (low CCx) seems to be far too small when simulated with Eq. 4.1. To make the simulation of senescence duration less divergent for different CCx, the exponent in Eq. 4.1 is modified by adding a constant to CCx (the denominator) and by multiplying the CDC (the numerator) by a factor:

$$CC = CC_x \left[1 - 0.05 \left(e^{\frac{3.33\ CDC}{CC_x + 2.29} t} - 1 \right) \right] \qquad \text{[Eq. 4.3]}$$

With the values of 3.33 in the numerator and 2.29 in the denominator of the exponent, the senescence duration for a crop at seedling stage (CCx about 2 %), will be 70% of the crop with full canopy cover (CCx about 98 %), which is believed to be a good approximation (Fig. 4.2).

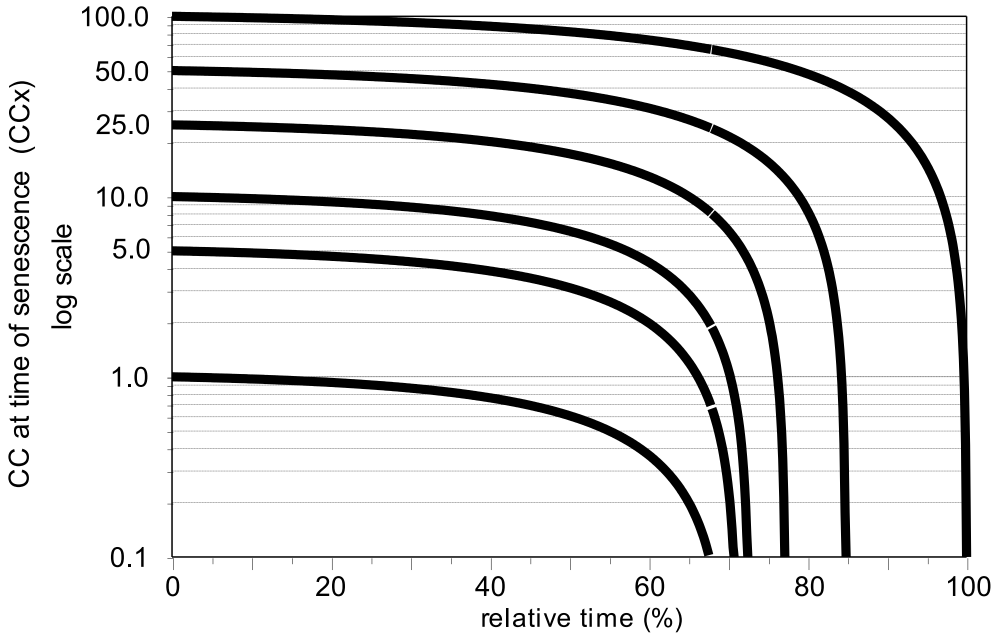


Figure 4.2 – Relative time for the canopy to reach zero %, for various CCx at the start of senescence (for CDC = 0.004 per GDD)

Since the proposed modifications do not result in changes of senescence duration for the full canopy situation, it is believed that there is no need to recalibrate CDC (all the calibrations done so far were for the full canopy situation).

5. Simulation of cold stress

5.1 Previous version: Cold stress correction on biomass production

The effect of cold stress was simulated in previous AquaCrop versions by considering a temperature stress coefficient Ks_b affecting (as target crop parameter) the normalized biomass water productivity (Eq. 5.1). Depending on the number of growing degrees generated on a day, daily biomass production varied between zero, and full production (Fig. 5.1). As discussed by Vanuytrecht (2013), Ks_b integrated the effect of low temperatures, reduced light intensities and shorter day lengths outside the summer season in temperature climates at mid latitudes.

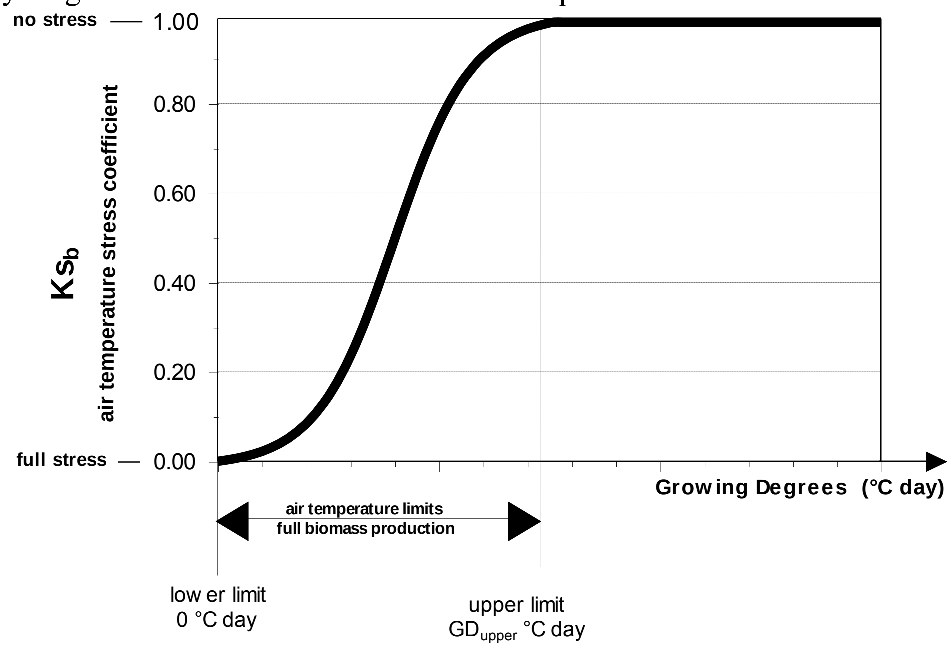


Figure 5.1 – The air temperature stress coefficient for reduction of biomass production (Ks_b) for various levels of growing degrees.

The cumulative aboveground biomass (B) is given by:

$$B = \left(Ks_{b,i}\ WP^*\right) \sum \left(\frac{Tr_i}{ETo_i}\right) \qquad \text{(Eq. 5.1)}$$

where WP* is the normalized biomass water productivity, $Ks_{b,i}$ the cold stress coefficient, and (Tr_i/ETo_i) the ratio of the daily crop transpiration over the reference evapotranspiration for that day. The daily crop transpiration in Eq. 5.1 is given by:

$$Tr_i = Ks_i\ Kc_{Tr,i}\ ETo_i \qquad \text{(Eq. 5.2)}$$

where $Kc_{Tr,i}$ is the crop transpiration coefficient, and Ks_i the water stress coefficient on day i. Ks becomes Ks_{aer} in case of water logging (excess water), and Ks_{sto} when water shortage results in stomata closure.

5.2 Update: Cold stress correction on crop transpiration

The update in Version 6.0 consists in assigning the crop transpiration coefficient (Kc_{Tr}) as the target parameter for the cold stress coefficient (Eq. 5.3). As such, emphasis is given on the reduction in stomatal conductance at low temperature. Daily crop transpiration (Tr) is calculated by multiplying ETo with the crop transpiration coefficient and by considering the effect of water stress (Ks) and cold stress (Ks_{Tr}) on that day:

$$Tr_i = Ks_i \left(Ks_{Tr,i} \; Kc_{Tr,i} \right) ETo_i \qquad \text{(Eq. 5.3)}$$

The cumulative aboveground biomass production is given by:

$$B = WP^* \sum \left(\frac{Tr_i}{ETo_i} \right) \qquad \text{(Eq. 5.4)}$$

The cold stress coefficient for crop transpiration (Ks_{Tr}) keeps the logistic shape. Ks_b, which is removed from the program is replaced by Ks_{Tr} in ***the Crop characteristics*** menu (Fig. 5.2).

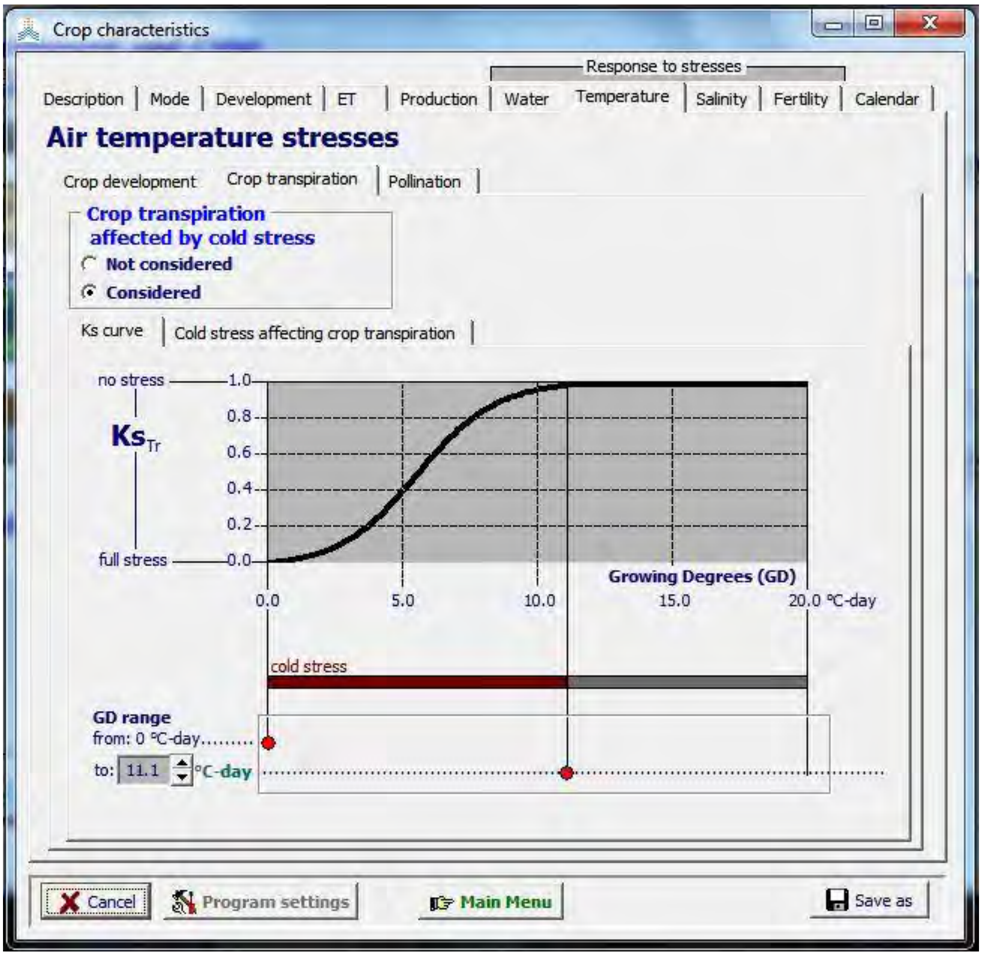


Figure 5.2 – Specification of the cold stress coefficient for crop transpiration (Ks_{Tr}) in the *Crop characteristics* menu.

If the growing degrees generated in a day drops below an upper threshold (GD_{upper}) the crop transpiration is limited by air temperature and Ks_{Tr} is smaller than 1 (Fig. 5.2). In AquaCrop it is assumed that crop transpiration is completely halted when it becomes too cold to generate any growing degrees (Ks_{Tr} = 0 for 0 °C day). Between the lower (0°C day) and upper limit (GD_{upper}) the variation of the stress coefficient is described by a logistic function.

The upper threshold (GD_{upper}) is a conservative crop parameter, and its value can be adjusted between 0.1 and 20 °C day. In Version 6.0, the value for the upper threshold (GD_{upper}) for crop transpiration remains the same as the previous assigned value for biomass production.

5.3 Simulation results

☐ **Reduction of crop transpiration**
In simulations with version 6.0, the crop transpiration during cold periods will be less than in previous AquaCrop versions. The magnitude of the reduction depends on the timing and the severity of the cold stress period. In most cases, cold stress affects the crop when its canopy cover is still small, as for winter wheat or for summer crops which are sown early in the year. As such the reduction of the crop transpiration over the growing cycle is mildly.

☐ **Simulated biomass production remains identical in the absence of water stress**
In the absence of any water stress during the growing cycle, the simulated biomass production and crop yield remain identical between the different versions of AquaCrop. When water stress does not affect crop transpiration, Ks is 1 in Eq. 5.2 and 5.3. Although the simulated crop transpiration in the previous AquaCrop versions is higher than in version 6.0, the simulated reduction in the cumulative biomass production will be identical to the simulated reduction in the cumulative crop transpiration. By comparing the set of equations in both versions of AquaCrop, it is obvious that B obtained with Eq. 5.1 is identical with B simulated with Eq. 5.4 when Ks = 1. As long as water stress is absent, the simulated biomass production and crop yield remain unaltered between the various versions of AquaCrop, even if soil fertility stress and/or salinity stress affects the crop production.

☐ **Slightly higher simulated biomass production in the presence of water stress**
When insufficient rainfall or irrigation limits full crop production, the simulated biomass production and crop yield will generally be slightly higher in Version 6.0 than in the previous AquaCrop versions. Due to the simulated reduction in crop transpiration during the cold period, more water remains available in the root zone. This might reduce the water stress affecting canopy expansion and stomatal closure later in the season when rainfall and/or irrigation is insufficient. The effect on biomass production and crop yield depends on the timing and the severity of the periods of water and cold stress and the storage capacity of the root zone.

☐ **Crop output file**
The structure of the Crop output file, in which daily simulation results are saved, is slightly changed. This was required since cold stress is assumed to affect crop transpiration and no longer (directly) biomass production in Version 6.0 (Table 5.1).

Table 5.1 Output file for crop development and production
Default file name: ProjectCROP.OUT

Nr	Symbol	Description	Unit
1	Day		-
2	Month		-
3	Year		-
4	DAP	Days after planting/sowing	-
5	Stage	Crop growth stage: 0: before or after cropping; 1: between sowing and germination or transplant recovering; 2: vegetative development; 3: flowering; 4: yield formation and ripening -9: no crop as a result of early canopy senescence	-
6	GD	Growing degrees	°C-day
7	Z	Effective rooting depth	m
8	StExp	Percent water stress reducing leaf expansion	%
9	StSto	Percent water stress inducing stomatal closure	%
10	StSen	Percent water stress triggering early canopy senescence	%
11	StSalt	Percent salinity stress	%
12	StWeed	Relative cover of weeds	%
13	CC	Total green Canopy Cover of crop and weeds	%
14	CCw	Crop green Canopy Cover in weed infested field	%
15	***StTr***	***Percent temperature stress affecting crop transpiration***	***%***
16	Kc(Tr)	Crop coefficient for transpiration	-
17	Trx	Maximum crop transpiration of crop and weeds	mm
18	Tr	Total transpiration of crop and weeds	mm
19	TrW	Crop transpiration in weed infested field	mm
20	Tr/Trx	Relative total transpiration of crop and weeds (100 Tr/Trx)	%
21	WP	Crop water productivity adjusted for CO2, soil fertility and products synthesized	g/m^2
~~21~~	~~StBio~~	~~Percent temperature stress affecting biomass production~~	~~%~~
22	Biomass	Cumulative crop biomass	ton/ha
23	HI	Harvest Index adjusted for failure of pollination, inadequate photosynthesis and water stress	%
24	Yield Part	Crop yield (HI x Biomass)	ton/ha
25	Brelative	Relative biomass (Reference: no water, no soil fertility, no soil salinity stress, no weed infestation)	%
26	WPet	ET Water productivity for yield part (kg yield produced per m3 water evapotranspired)	kg/m^3

Reference:

Vanuytrecht, E. 2013. Crop responses to climate change **-** Impact on agricultural production and the soil water balance in the Flemish Region of Belgium. PhD. Manuscript Nr. 1128. KU Leuven, Arenberg Doctoral School, Fac. Of Bioscience Engineering, Leuven Belgium.

6. Calibration and simulation of salinity stress

6.1 Crop parameters (Tabular sheet: Soil salinity stress)

☐ **Crop response to soil salinity stress**

When the crop response to salinity stress is set at 'Not considered' in the ***Crop characteristics*** menu, AquaCrop will still simulate the building up of salts in the soil profile, but will not consider the effect of soil salinity stress on the crop. When 'Considered' is selected, AquaCrop displays the tabular sheets where the salt tolerance and crop response can be specified (Fig. 6.1).

☐ **'Salt tolerance' tabular sheet**

The salt tolerance of the crop determines the maximal biomass production that can be obtained in a salt affected root zone (Fig. 6.1). For the selected tolerance, AquaCrop derives from the 'Biomass – ECe' relationship, the maximal biomass production (expressed as a percentage) that still can be reached if no other stresses affect the production (no soil fertility, water, air temperature and/or weed stresses). The average electrical conductivity of the saturation soil-paste extract (ECe) from the root zone is the indicator for soil salinity. Soil salinity stress varies between 0% (with full biomass production) and 100% (resulting in no biomass production).

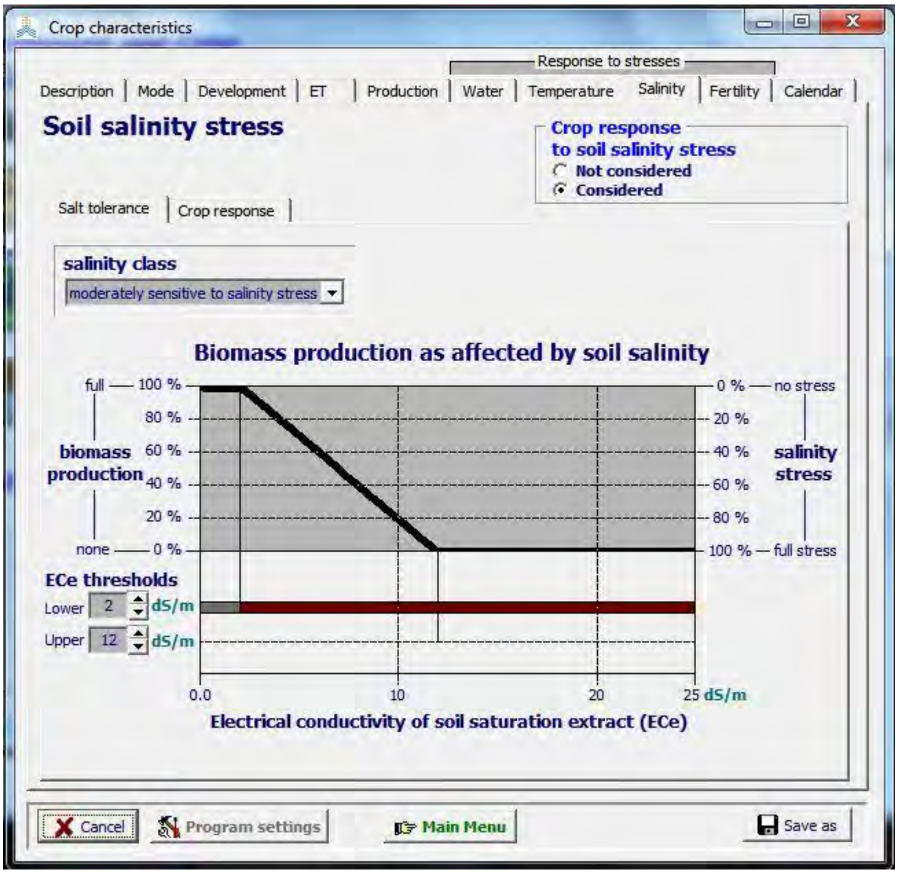


Figure 6.1 – Specification of the upper and lower thresholds of the electrical conductivity of soil saturation extract (ECe) with the corresponding salinity class and 'Biomass – ECe' relationship in the 'Salt tolerance' tab sheet.

The user specifies the effect of soil salinity stress by selecting a sensitivity class (Tab. 6.1) or by specifying values for the lower and upper threshold for soil salinity in the root zone (Fig. 6.1). The thresholds for ECe, which are crop specific and conservative crop parameters, are expressed in deciSiemens per meter (dS/m). Indicative values for various crops, are given in Annex III. Distinction is made between:

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

Table 6.1 – Classes and corresponding default values for the lower (ECe_n) and upper (ECe_x) threshold of soil salinity stress

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

The reduction in biomass production is the result of a less dense crop, a poor development of the canopy cover, and a partial closure of the stomata. These effects of soil salinity stress are displayed in the 'Crop response' tabular sheet. Since the individual effects of salinity stress on crop density, development of the canopy cover and closure of the stomata are not well documented in literature for simulation in AquaCrop, the user can calibrate the crop response to soil salinity stress (Section 2 of this note).

☐ **'Crop response' tabular sheet**

In the 'Canopy Cover' (Fig. 6.2) and 'Stomata closure' (Fig. 6.3) sheets of the 'Crop response' tabular sheet, the canopy cover and stomatal closure are displayed for a selected salinity stress (ECe). By altering the ECe value in the sheets, the crop responses to various soil salinity stresses can be studied. The integrated effect of crop responses results in the biomass production as displayed in the 'Biomass – ECe' relationship (Fig. 6.1 in the 'Salt tolerance' tabular sheet). The biomass production is the maximum that can be obtained when the soil is well-watered.

When the soil is not well-watered, water depletion in the root zone results in an increase of the salt concentration in the remaining soil water. Although root zone depletion does not alter ECe (the indicator for soil salinity), it increases the electrical conductivity of the soil water (ECsw). The stronger the root zone depletion, the larger ECsw, and the more difficult it becomes for the crop to extract water from its root zone. This results in an stronger closure of the stomata when the soil dries out. The stomata closure for various root zone depletions is plotted for the selected salinity stress (ECe) in the 'Stomatal closure' tabular sheet (Fig. 6.3).

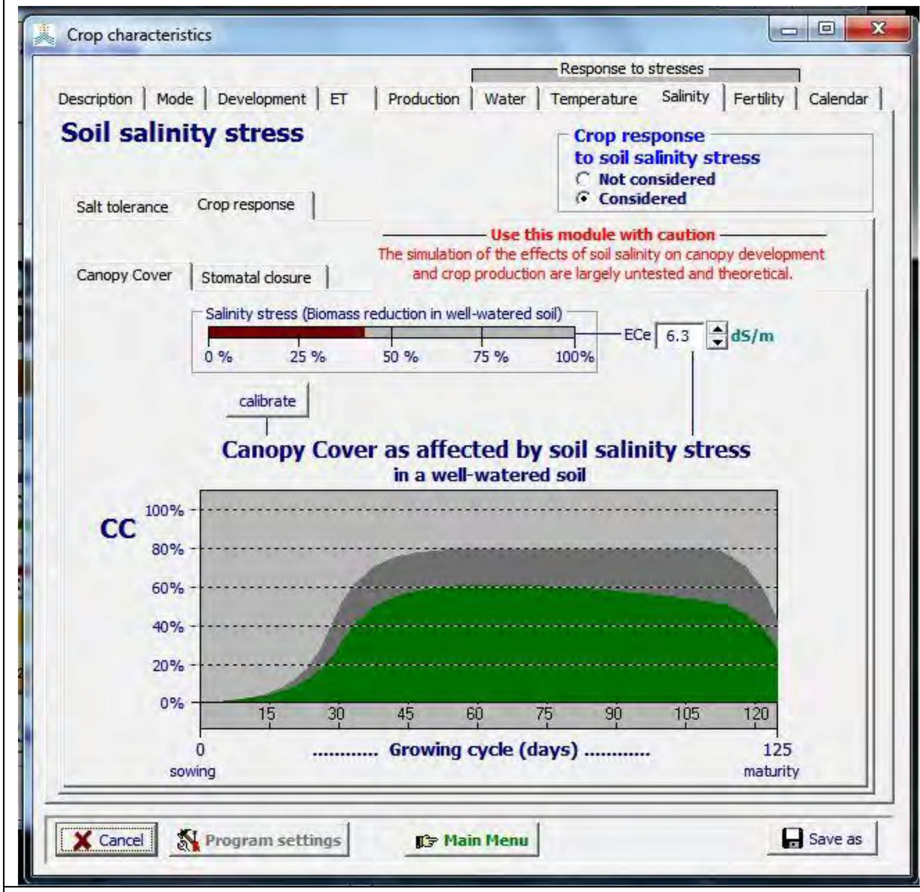


Figure 6.2 – Development of the Canopy Cover (CC) for a selected soil salinity stress of 43% (ECe = 6.3 dS/m), resulting in a 43% reduction of biomass production if no other stresses occur (i.e. in a well-watered soil).

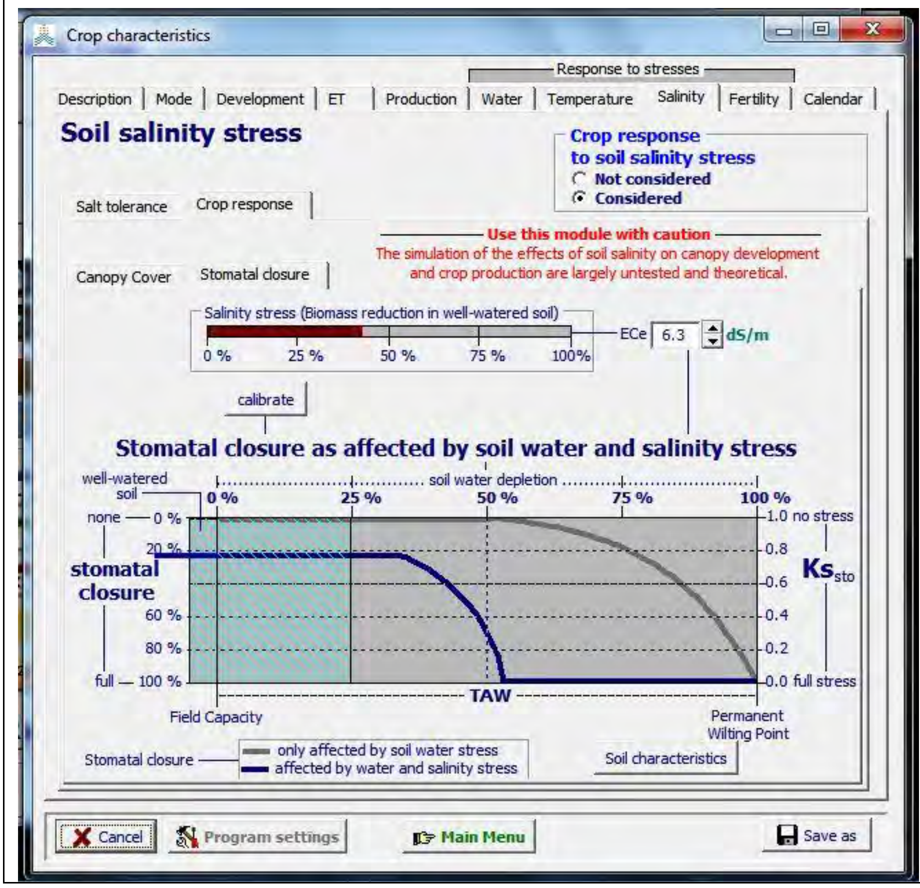


Figure 6.3 – Stomatal closure at a soil salinity stress of 43% (ECe = 6.3 dS/m), resulting in a 43% reduction of biomass production in a well-watered soil (shaded part at the left side of the graph).

The additional stomatal closure for various root zone depletions is plotted as well (right side of the graph).

6.2 Calibration for soil salinity stress

☐ **Biomass - ECe relationship**

Between the lower (ECe_n) and upper (ECe_x) threshold of the saturated soil-paste extracts, the shape of the 'Biomass – ECe' curve determines the effect of soil salinity on the biomass production in a well-watered soil. A linear shape is assumed (Fig. 6.1).

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

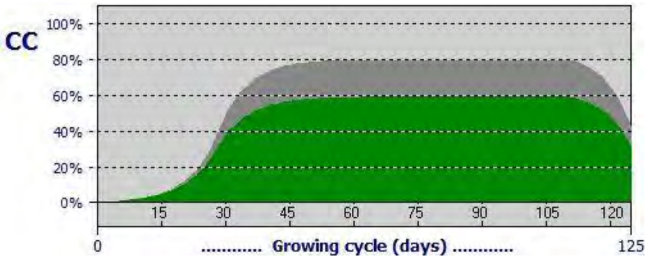
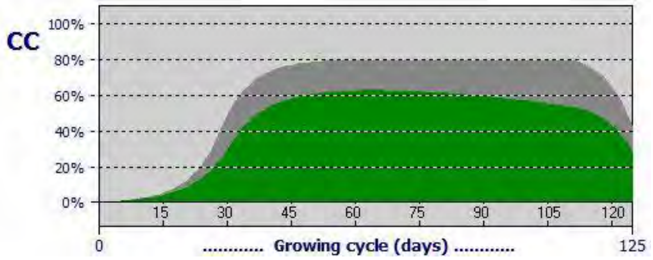
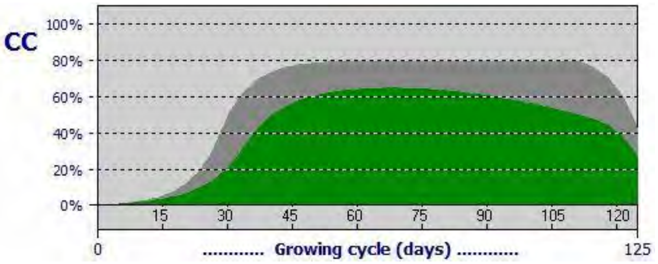
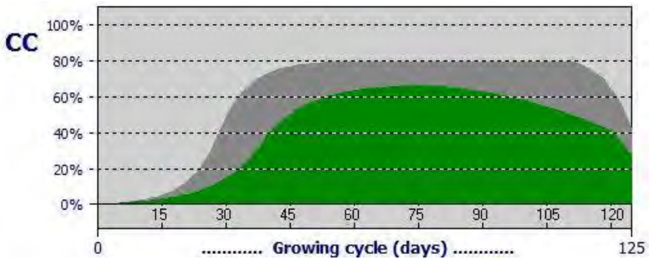
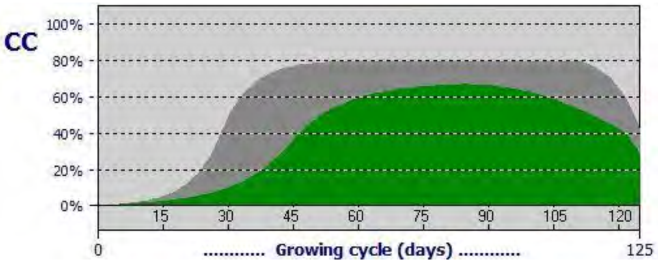
In a well-watered saline soil, and in the absence of any other stresses than salt stress, AquaCrop obtains the relative biomass production from the 'Biomass – ECe' relationship (Fig. 6.1). The reduction in biomass is the result of the integrated effect of four processes: (i) a slow canopy expansion, (ii) a poor canopy cover (less dense crop), (iii) a decline of the canopy cover during the crop cycle, and (iv) a partial closure of the stomata. Although the total reduction in biomass (i.e. the combined effect of the four processes) in a well-watered soil is given by the 'Biomass – ECe' relationship, the individual effects of salinity stress on the four processes are not sufficient documented in literature for simulation in AquaCrop. The same maximal biomass production can be obtained by assigning various combinations of weights to each of the involved 4 processes of crop response. The calibration process consists in selecting a specific combination.

If the development of the canopy cover is observed in the field, the user can calibrate the effect of salinity stress on the development, in the 'Canopy Cover' tabular sheet (Fig. 6.4). This is done by selecting a class or percentage of canopy cover distortion (Tab. 6.2). The canopy distortion is expressed with reference to the development of the canopy cover in the absence of any stress (as calibrated in the 'Development' tabular-sheet of the ***Crop characteristics*** menu). For 'no' distortion, the effect of salinity stress consists mainly of a reduction of CC_x (less dense crop), which results in a canopy cover which is parallel to the reference development in the non-stressed environment. If a distortion is considered, additional effects of salinity stress on (i) the rate of canopy expansion and (ii) the steady decline of the canopy cover in the season are considered. The stronger the distortion, the stronger the additional effects (Tab. 6.2).

In AquaCrop, the percentage of stomata closure in the well-watered-soil is taken as identical to the decline of CCx. Since the maximum biomass production for a particular soil salinity stress should remain identically for any degree of distortion, a stronger canopy distortion with additional effects on Canopy cover, results automatically in a smaller decline of CCx (and a smaller degree of stomata closure). If only the reduction of the maximum canopy cover (CCx) is available from field observations, the plot of the CCx reduction might be helpful for calibration (Fig. 6.5). This plot shows also the percentage of stomatal closure in a well-watered soil.

As long as the soil is well watered (no significant root zone depletion between wetting events) and the ECe (salt stress) remains fairly constant throughout the season, the selection of the distortion of the canopy cover by salinity stress will not have a significant effect on the simulated biomass production (Fig. 6.6).

Table 6.2 – Classes for Canopy Cover distortion due to salinity stress. The corresponding effect on the canopy cover development is displayed for a salinity stress of 41%.

<table>
<tr><th rowspan="2">Class</th><th colspan="2">Canopy Cover distortion (%)</th><th rowspan="2">Development of the canopy cover under salinity stress (green) with reference to its development in a non-stressed environment (grey)</th></tr>
<tr><th>Default</th><th>Range</th></tr>
<tr><td>None</td><td>0</td><td>-</td><td>
</td></tr>
<tr><td>Moderate</td><td>25</td><td>1 – 35</td><td>
</td></tr>
<tr><td>Intermediate</td><td>50</td><td>36 – 60</td><td>
</td></tr>
<tr><td>Strong</td><td>75</td><td>61 – 90</td><td>
</td></tr>
<tr><td>Very strong</td><td>100</td><td>91 – 100</td><td>
</td></tr>
</table>

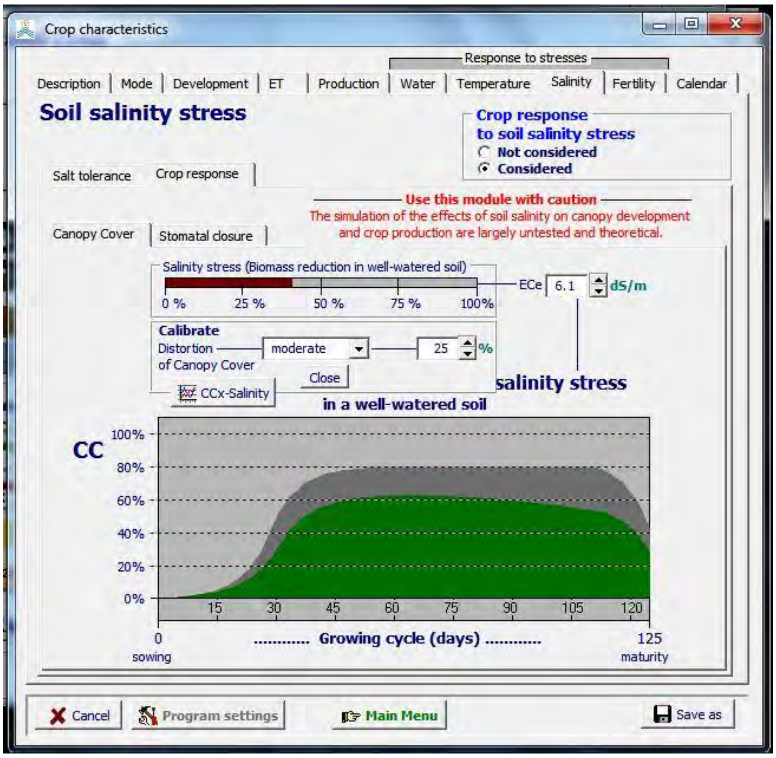


Figure 6.4 –The calibration of the effect of salinity stress on the development of the canopy cover in a well-watered soil, consists in selecting a class of canopy distortion or by specifying the percentage of the distortion in the 'Canopy Cover' tabular sheet.

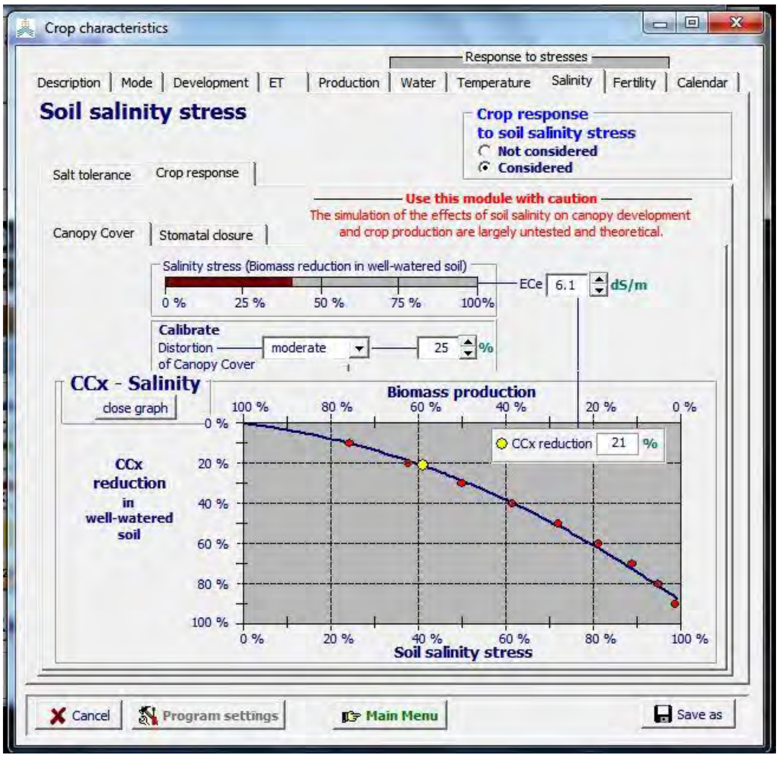


Figure 6.5 – Display of the effect of salinity stress on the reduction of the maximum canopy cover (CCx) in a well-watered soil in the 'Canopy Cover' tabular sheet. The percentage of stomatal closure in a well-watered soil is considered as identical to the percentage of CCx reduction.

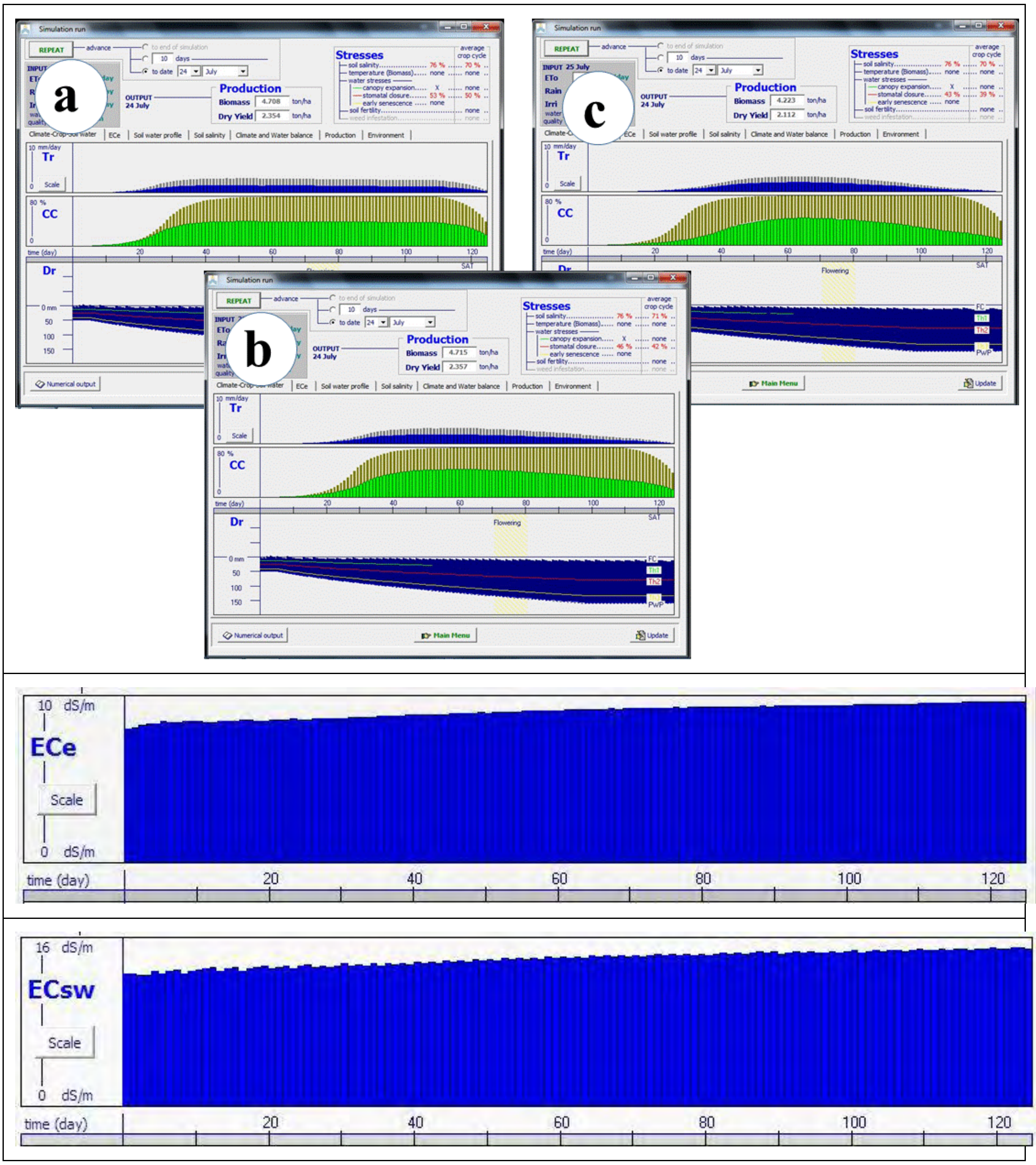


Figure 6.6 – Simulation of canopy development (CC) and biomass production and crop yield in a saline soil for (a) no canopy distortion, (b) an intermediate distortion of 50%, and (c) a very strong distortion of 100 %, and the corresponding Electrical Conductivity of the soil saturation extract (ECe) and soil water (ECsw).

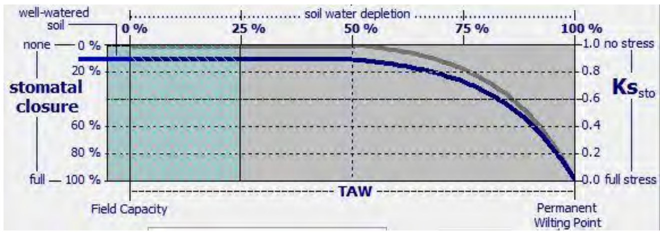
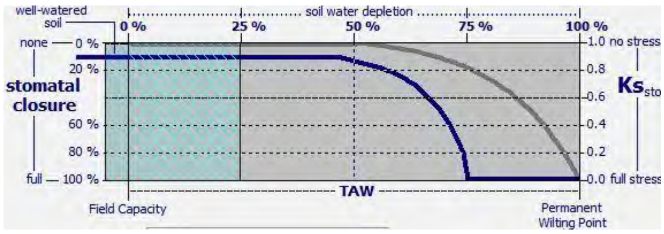
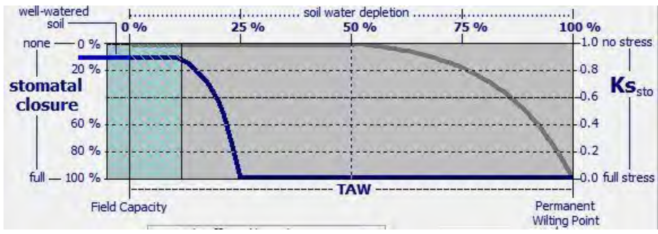
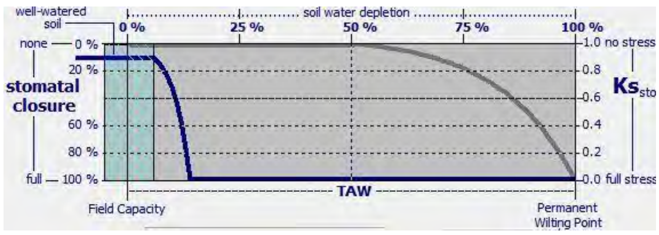
In each of the three simulations presented in Fig. 6.6, the salinity stress throughout the season remained fairly constant (70 %) and the biomass production was very similar (about 30 % of the production in the absence of any stress). In this example the loamy soil was well-watered by a very frequent application of water of 3 dS/m by drip irrigation. The crop, which is moderately sensitive to salinity stress (ECe_n = 2 dS/m and ECe_x = 12 dS/m), received 5 mm of water each time 20% of RAW was depleted. At the start of the simulation process the whole soil profile was at Field Capacity, and the soil salinity in the soil profile was 8 dS/m.

☐ Crop response when root zone depletion increases the salinity stress

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

The effect of ECsw on stomata closure can be calibrated in the 'Stomatal closure' tabular sheet (Fig. 6.7). This is done by selecting a class or percentage for the effect of ECsw on stomatal closure (Tab. 6.3). Since ECsw depends on the physical characteristics of the soil layer, the soil water content at saturation, field capacity and permanent wilting point, can be displayed (Fig. 6.8).

Table 6.3 – Classes for the response of stomatal closure to the Electrical Conductivity of the soil water (ECsw). The various graphs display the stomatal closure for various root zone depletions, for a salinity stress of 25 % and a moderate distortion of the canopy cover (25%).

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

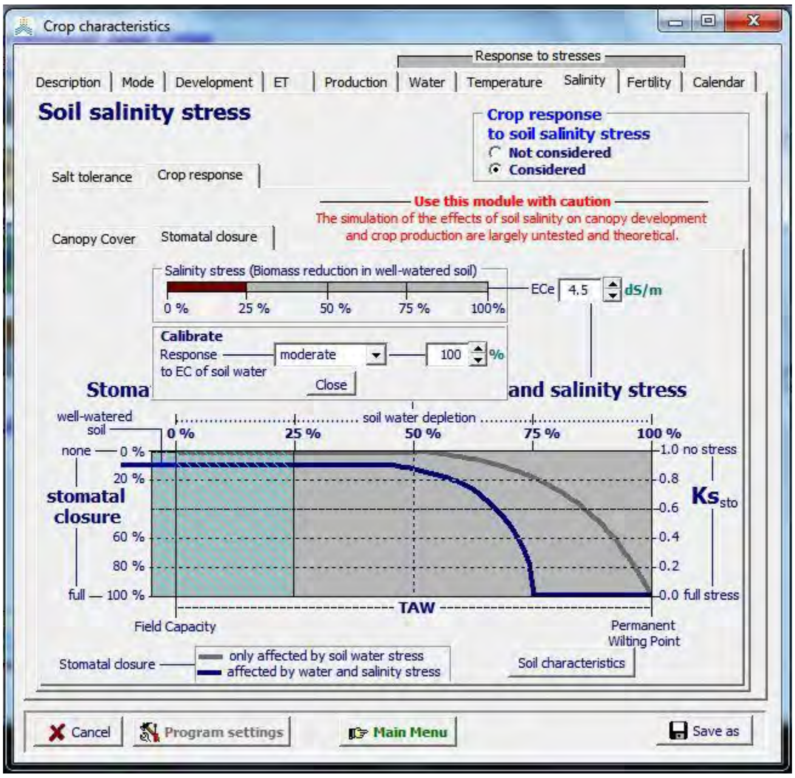


Figure 6.7 –The calibration of the effect on stomatal closure of salt concentration in a depleting root zone, consists in selecting a class of the response to the Electrical Conductivity of the soil water (ECsw) or by specifying the percentage of the response in the 'Stomatal closure' tabular sheet.

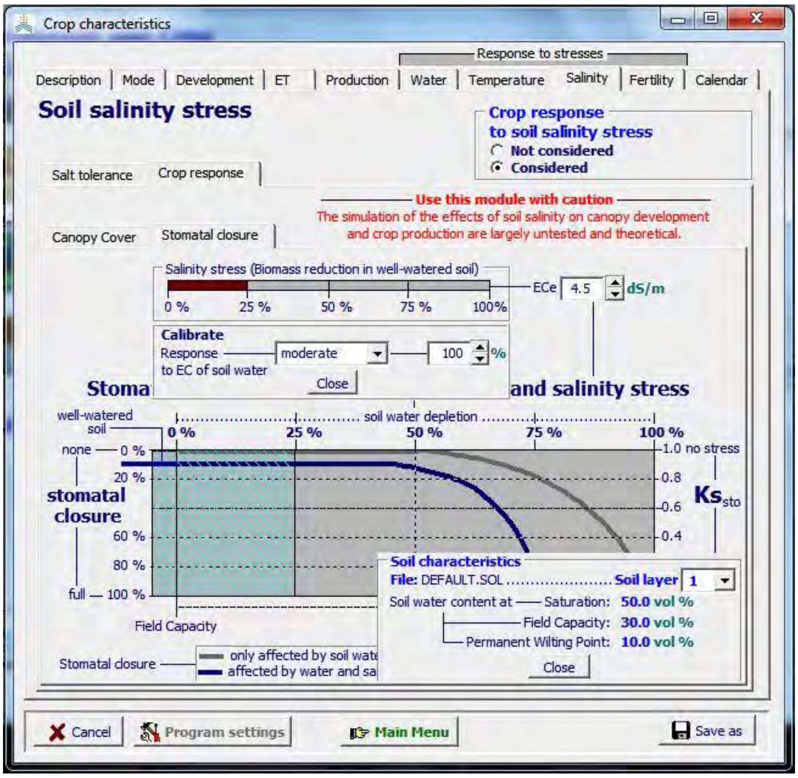


Figure 6.8 – Display of the soil physical characteristics of the soil layer for which the response to ECsw is valid.

For a simulation in which the root zone depletion is important between irrigation events, the canopy development, crop production, and salt concentration in the root zone are plotted in Figure 6.9.

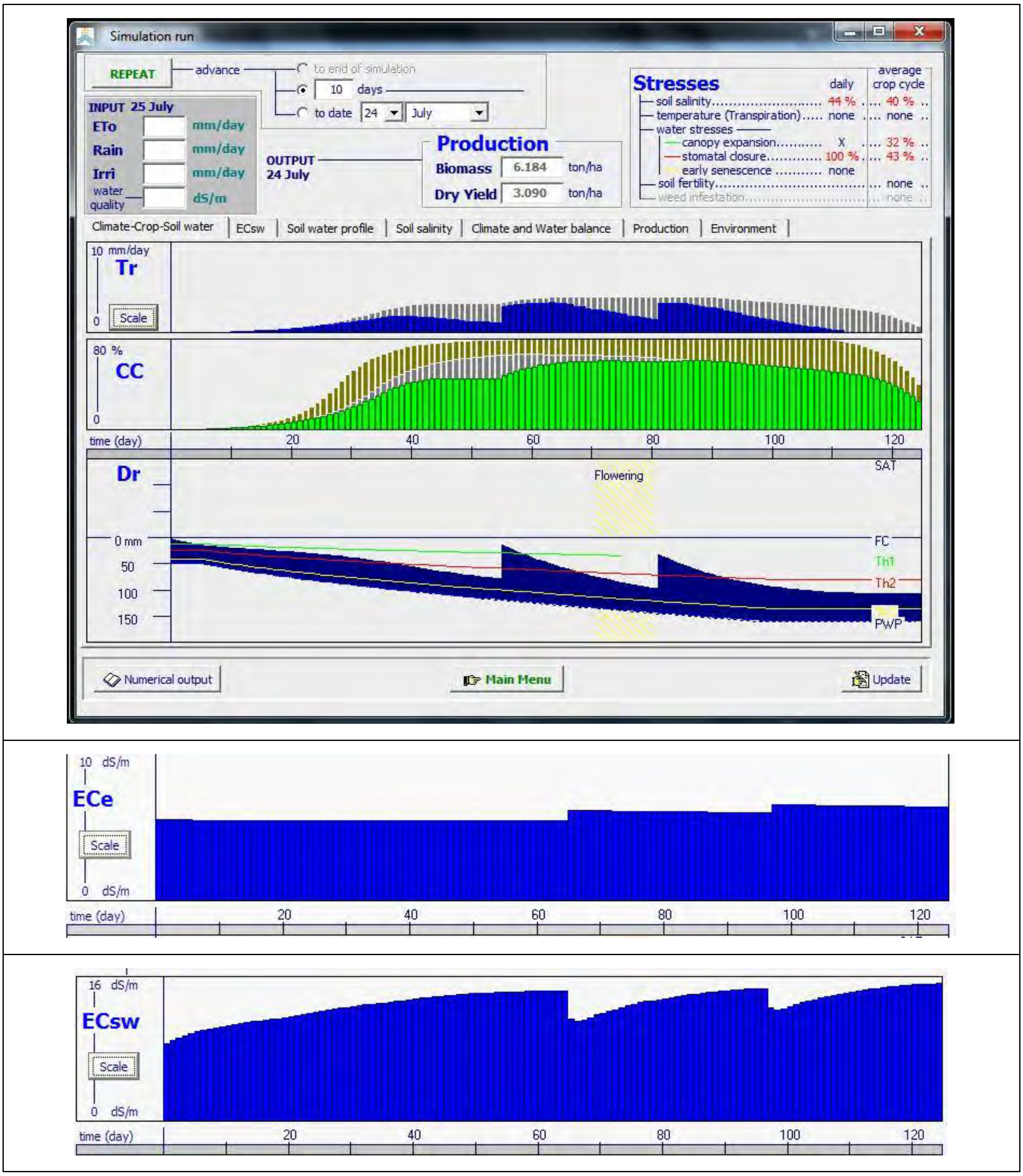


Figure 6.9 – Simulation of crop transpiration (Tr) and Canopy Cover (CC) in a saline soil with strong root zone depletions, and the corresponding simulated Electrical Conductivity of the soil saturation extract (ECe) and of the soil water (ECsw). The Canopy Cover that could have been reached in a well-watered soil is displayed in grey. The Canopy Cover displayed in olive is CC in the absence of any stress.

The simulation displayed in Fig. 6.9, was run for a crop which is moderately sensitive to salinity stress (ECe_n = 2 dS/m and ECe_x = 12 dS/m). The class for the canopy cover distortion was selected as intermediate (50%) and the class for the response of stomatal closure as affected by the Electrical Conductivity of the soil water (ECsw) was selected as moderate (100%). At the start of the simulation process the whole soil profile was at Field Capacity, and the soil salinity in the soil profile (ECe) was 5.5 dS/m. In the simulation run, the loamy soil received two irrigation applications of 65 mm with poor water quality of 4 dS/m by basin irrigation. In the simulation, the average salinity stress was only 40 % (ECe ranging between 5.5 and 6.6 dS/m). For this salinity stress, a biomass production of 60% could have been expected if the soil was well-watered. Nevertheless the biomass production dropped to only 40 % of the reference production due to a strong root zone depletion (up to 140% of RAW) between the two irrigation applications, resulting in serious water and salinity stress affecting the canopy cover development and resulting in a closure of the stomata.

Part 2. Introduction of an extra field management characteristic

7. Possibility to specify the degree of weed management

7.1 List of principal symbols

Symbol	Description	Unit
Canopy Cover (CC)		
CC_{WF}	Green canopy cover of the crop in weed-free conditions	$m^2.m^{-2}$
WC	Green canopy cover of the weeds	$m^2.m^{-2}$
CC_W	Green canopy cover of the crop in weed infested field	$m^2.m^{-2}$
CC_{TOT}	Total green canopy cover of crop and weeds	$m^2.m^{-2}$
Soil evaporation (E)		
E_{TOT}	Soil evaporation in weed infested field	$mm.d^{-1}$
Transpiration (Tr)		
Tr_W	Crop transpiration in weed infested field	$mm.d^{-1}$
Tr_{TOT}	Total transpiration of crop and weeds	$mm.d^{-1}$
Aboveground biomass (B)		
B_W	Dry above ground biomass of crop in weed infested field	$Mg.ha^{-1}$
Yield (Y)		
Y_W	Dry crop yield in weed-infested field	$Mg.ha^{-1}$
Weed infestation		
f_{weed}	Adjustment factor for canopy expansion in weed infested field	-
f_{shape}	Shape factor for f_{weed}	-
RC	Relative cover of weeds	-

Subscript **W** refers to weed infested conditions
Subscript **WF** refers to weed-free conditions.
Subscript **TOT** refers to the combination of crop and weeds in weed infested fields

Crop development and production in weed infested fields was simulated for barley and wheat fields in Ethiopia and Australia (Van Gaelen et al., 2016). The results showed good model performance.

7.2 Relative cover of weeds (RC)

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

$$RC = \frac{WC}{WC + CC_W} = \frac{WC}{CC_{TOT}} \qquad \text{(Eq. 7.1)}$$

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

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

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

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

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

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

Because of the advantages of RC and the use of canopy cover in AquaCrop as the integrator of the combined effects of competition for light, water and nutrients, RC proofed to be well applicable for the simulation of the effect of weed infestation on crop development and production (Van Gaelen et al., 2016).

7.3 Weed management in the *Field management* menu

To simulate the effect of weeds on crop development and production, the user specifies in the ***Field management*** menu (Fig. 7.1):

1. the Relative Cover (RC) of weeds in season, which expresses the weed infestation level as observed in the field. By selecting a class for weed management, default values for RC are assigned (Tab. 7.1);
2. the expansion of CC due to weed infestation, which expresses how the total canopy cover responds to weed infestation under non limiting soil fertility. Since weeds can occupy space that is not used by the crop in weed-free conditions, the total CC might be larger than the crop canopy cover in weed-free conditions.

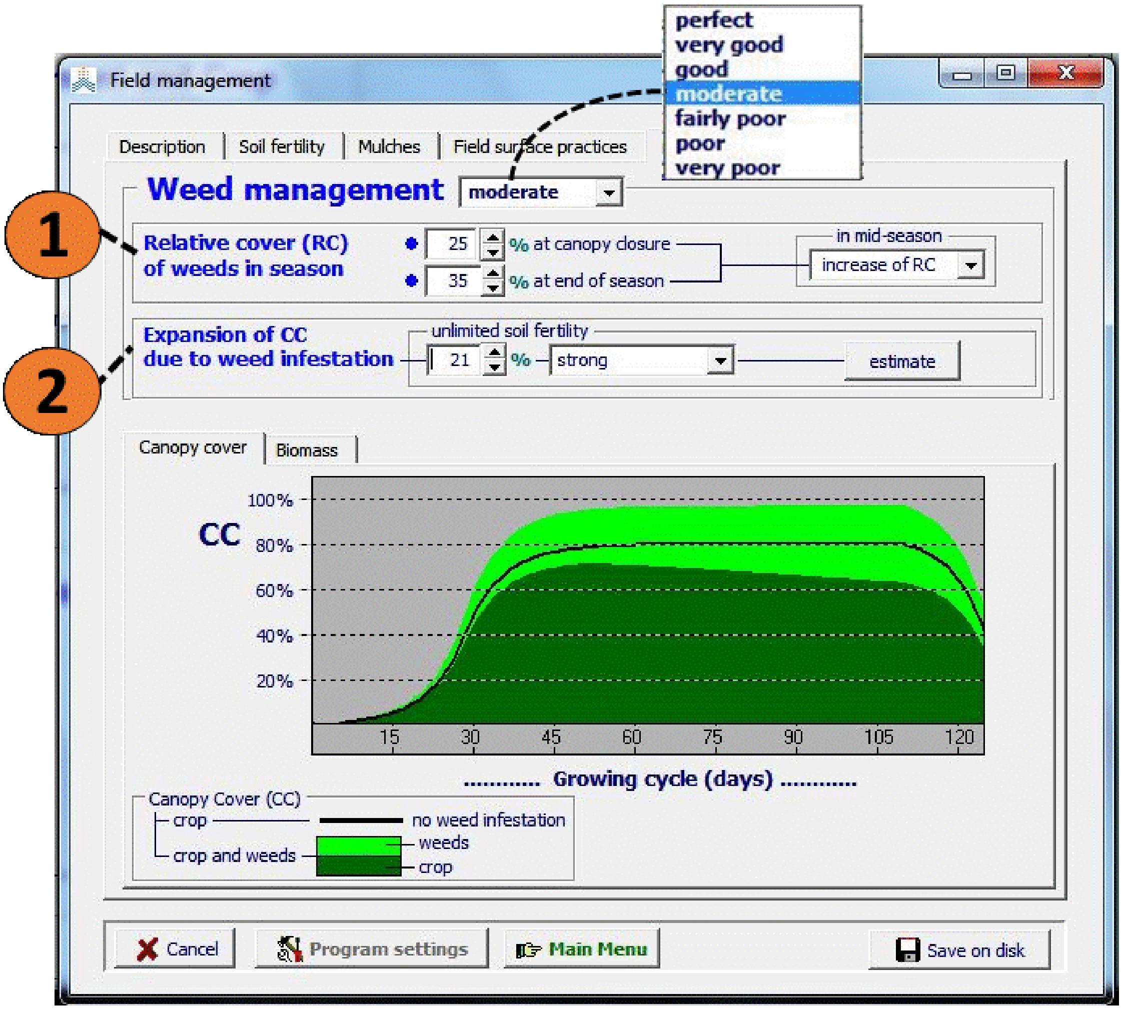


Figure 7.1 – Specification of (1) the Relative cover of weeds (RC) and (2) the expansion of canopy cover (CC) in the 'Weed management' tabular sheet of the *Field management* menu. In the graph the corresponding total canopy cover of crop (dark green) and weeds (light green) in the weed infested field is displayed. The canopy cover for weed-free conditions (black line) is given as a reference.

Weeds can not only occupy space that is not used by the crop, but can also suppress the canopy development of the crop. For that reason, the canopy cover of the crop in weed infested fields (dark green area in Fig. 7.1), will be smaller than the crop canopy cover in weed-free conditions (black reference line in Fig. 7.1).

Table 7.1 – Classes for weed management, and the corresponding default values and ranges for the relative weed cover (RC) at canopy closure.

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

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

Distinction is made between (Fig. 7.1):

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

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

Due to weed infestation and in the presence of unlimited soil fertility, the total canopy cover of crop and weeds (CC_{TOT}) can be larger than the crop canopy cover in weed-free conditions. The expansion of CC is quantified (Fig. 7.2):

1. by specifying the expansion directly as a percentage increase of the crop canopy cover in weed-free conditions;
2. by specifying the total CC of crop and weeds in the mid-season stage;
3. by selecting a class for the canopy expansion (Table 7.2).

By quantifying the expansion of CC and by considering the selected RC at canopy closure, a corresponding shape factor (f_{shape}) for the CC_{TOT} - RC relationship is assigned. By selecting f_{shape} directly (option 4 in Fig. 7.2), the corresponding different ways of expressing the expansion of CC is calculated.

The shape factor (f_{shape}) for the CC_{TOT} - RC relationship (Fig. 7.3), depends on the type of weed and hence might differ for various weed-crop combination:

- a negative f_{shape} value gives a concave relation between CC_{TOT} and RC, indicating that the crop is more competitive than the weed for light and that weeds will first occupy space that under weed-free conditions is not colonized by the crop;

- a positive value gives a convex relation, indicating that the weeds are more competitive than the crop for obtaining light, and will occupy first space that under weed-free conditions would be used by the crop. This results in a stronger suppression of the crop canopy cover than when f_{shape} is negative;
- a value for f_{shape} close to zero, gives an almost linear relationship between CC_{TOT} and RC.

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

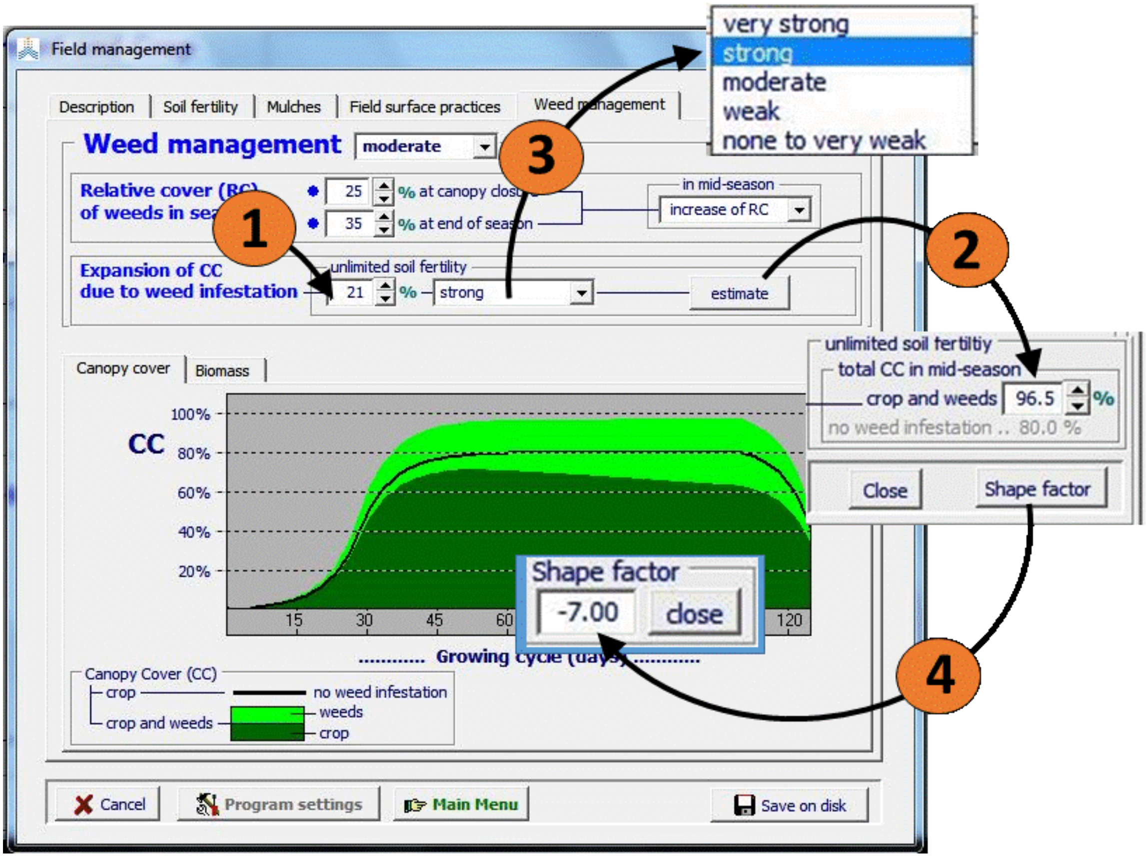


Figure 7.2 – Various ways of specifying the expansion of CC due to weed infestation, (1) by specifying a percent increase, (2) by specifying the total CC at mid-season in a weed infested field, (3) by selecting a class for the expansion of CC, or (4) by specifying a value for the shape factor.

Table 7.2 – Classes for the expansion of CC due to weed infestation and the corresponding default values and ranges for the shape factor (f_{shape}).

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

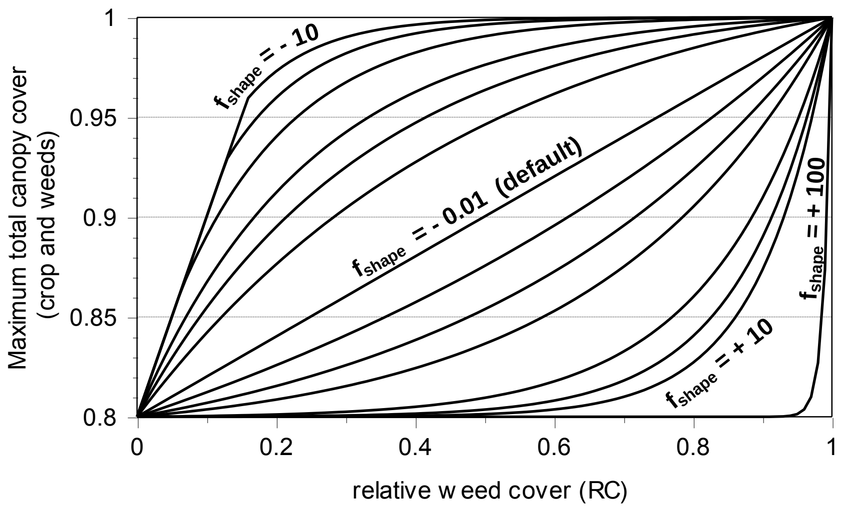


Figure 7.3 – Maximum total canopy cover of weeds and crop at mid-season ($CC_{x,TOT}$) for different relative weed covers (RC) and different shape factors (f_{shape}) for a field that in weed-free conditions would have a CC_x of 0.8.

In case soil fertility limits the biomass production, the selection of the relative biomass production in the soil fertility tabular sheet determines the crop canopy cover that can be reached in weed-free conditions (Fig. 7.4 A). Since the expansion of CC is blocked by soil fertility, the total canopy cover of crop and weeds that can be obtained in the weed infested field is identical to the crop canopy cover that can be reached in weed-free conditions (Fig. 7.4 B).

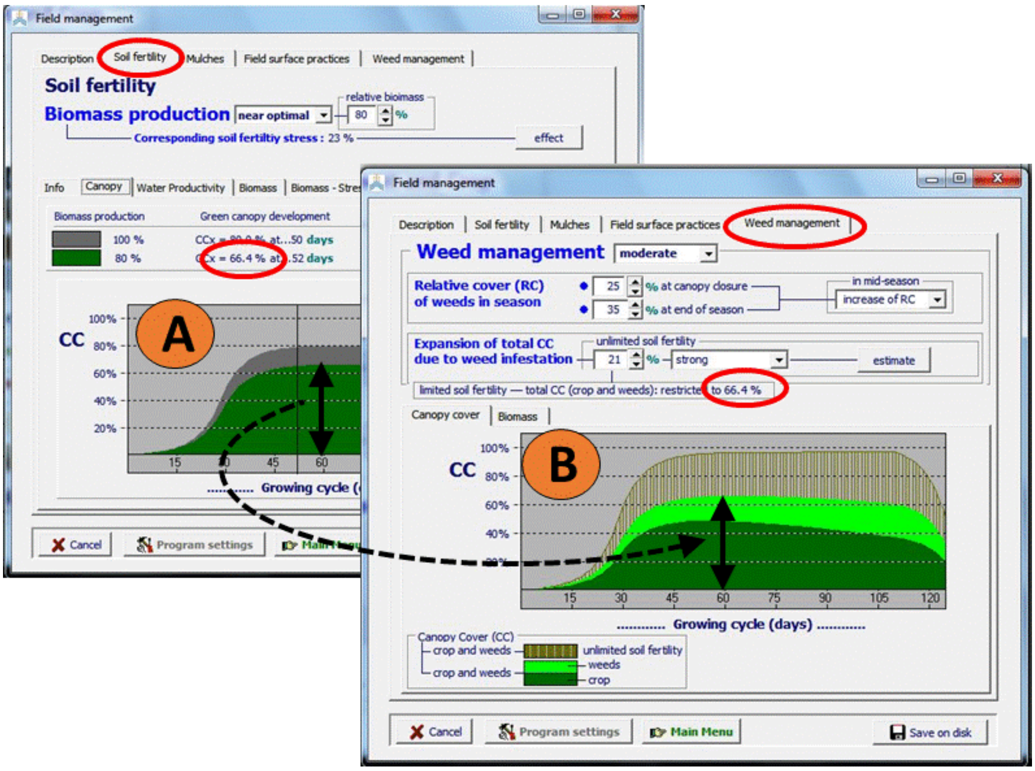


Figure 7.4 – (A) The crop canopy cover that can be reached with limited soil fertility in weed-free conditions and (B) the total canopy cover of crop and weeds that can be reached in a weed infested field with limited soil fertility, as displayed in the *Field management* menu.

☐ **Reduction in biomass production**

In the ‘biomass’ tabular sheet of the weed-management sheet in the ***Field management*** menu, an estimate of the maximum crop biomass production that can be obtained in the weed infested field is displayed (Fig. 7.5).

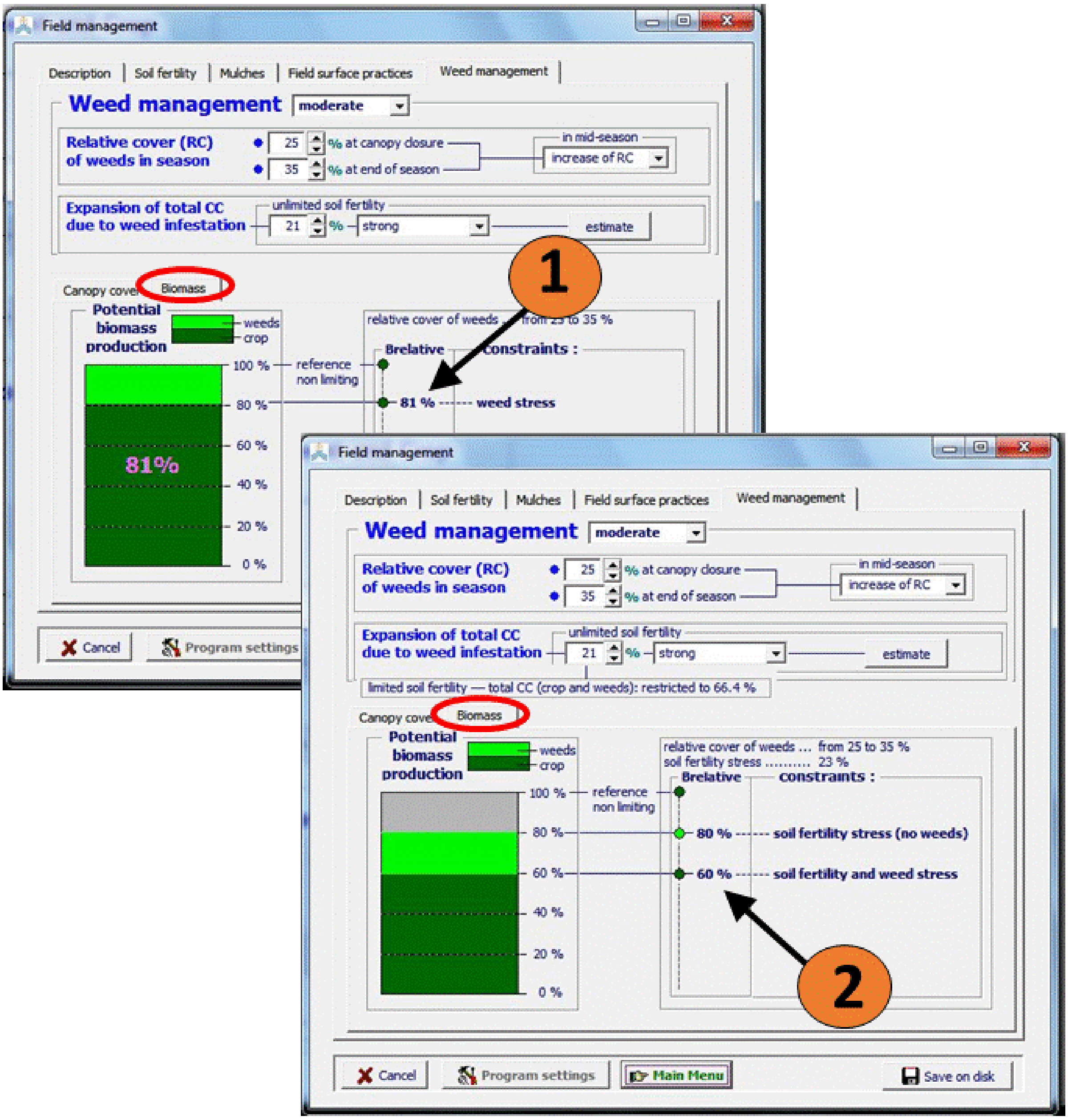


Figure 7.5 – The estimated relative maximum crop biomass production that can be obtained in a weed infested field, (1) without and (2) with soil fertility stress as displayed in the *Field management* menu.

7.4 Simulation of crop development and production in weed infested field

☐ **Assumptions**

Weeds affect crop development and production trough competition for the available resources (water, light, and nutrients). In AquaCrop the competition is expressed by the relative cover of weeds (RC). It is thereby assumed:

- that weeds and crop are equally sensitive to water, temperature, salinity and fertility stress. This might be justified since a difference in sensitivity between weeds and crop will be reflected by a difference in relative cover of weeds (RC). As such, RC also reflects indirectly the differences in sensitivity to stresses of crop and weeds;
- that weeds and crop have the same growth cycle. This might be justified since weeds already in the field at sowing will be most likely removed during land preparation. Weeds germinating much later than the crop will hardly affect RC during the crop cycle and their competition for the resources will be limited;
- that weeds and crop have a similar crop transpiration coefficient. This might be justified since maximum transpiration coefficients ($Kc_{Tr,x}$) for various crop types are similar;
- that weeds and crop have a similar root system and soil water extraction. This might be justified since a difference in root system and water extraction will be reflected by a difference in relative cover of weeds (RC). As such, the RC also reflect indirectly the differences in root system and water extraction of crop and weeds.

☐ **Step 1 – Crop (CC_W) and total canopy cover (CC_{TOT})**

▪ **Unlimited soil fertility**

In the presence of unlimited soil fertility, the total canopy cover of crop and weeds (CC_{TOT}) can be larger than the crop canopy cover in weed free conditions (CC_{WF}) especially when weeds not only suppress the crop but also expand in the free space between the individual plants (Fig. 7.6).

CC_{TOT} is simulated by multiplying the initial (CCo_{WF}) and maximum crop canopy cover (CCx_{WF}) for weed-free conditions, with an adjustment factor f_{weed}:

$$CCo_{TOT} = f_{weed}\ CCo_{WF} \qquad \text{(Eq. 7.2)}$$

$$CCx_{TOT} = f_{weed}\ CCx_{WF} \qquad \text{(Eq. 7.3)}$$

where CCo_{TOT} and CCx_{TOT} are respectively the total initial and total maximum canopy cover of crop and weeds. The adjustment factor for canopy cover in a weed infested field (f_{weed}) is given by:

$$f_{weed} = 1 - \left(1 - \frac{1}{CCx_{WF}}\right)\left(\frac{e^{f_{shape}\ RC} - 1}{e^{f_{shape}} - 1}\right) \quad \le \quad \frac{1}{CCx_{WF}} \qquad \text{(Eq. 7.4)}$$

where CCx_{WF} (fraction) is the maximum crop canopy cover under weed-free conditions, RC the relative cover of weeds (fraction) and f_{shape} a shape factor (Fig. 7.3) expressing the expansion of the canopy cover due to weed infestation. Given that CC_{TOT} cannot exceed 1, the maximum value of f_{weed} is ($1/CCx_{WF}$).

To assure that the length of the crop cycle is not affected, the Canopy Decline Coefficient (CDC) needs to be adjusted as well:

$$CDC_{TOT} = CDC_{WF} \frac{(CCx_{TOT} + 2.29)}{(CCx_{WF} + 2.29)} \qquad \text{(Eq. 7.5)}$$

where CDC_{WF} is the canopy decline coefficient under weed-free conditions.

The crop canopy development in the weed-infested field (CC_W) can be derived from CC_{TOT} by considering the relative cover of weeds (RC):

$$CC_W = CC_{TOT}\ (1 - RC) \qquad \text{(Eq. 7.6)}$$

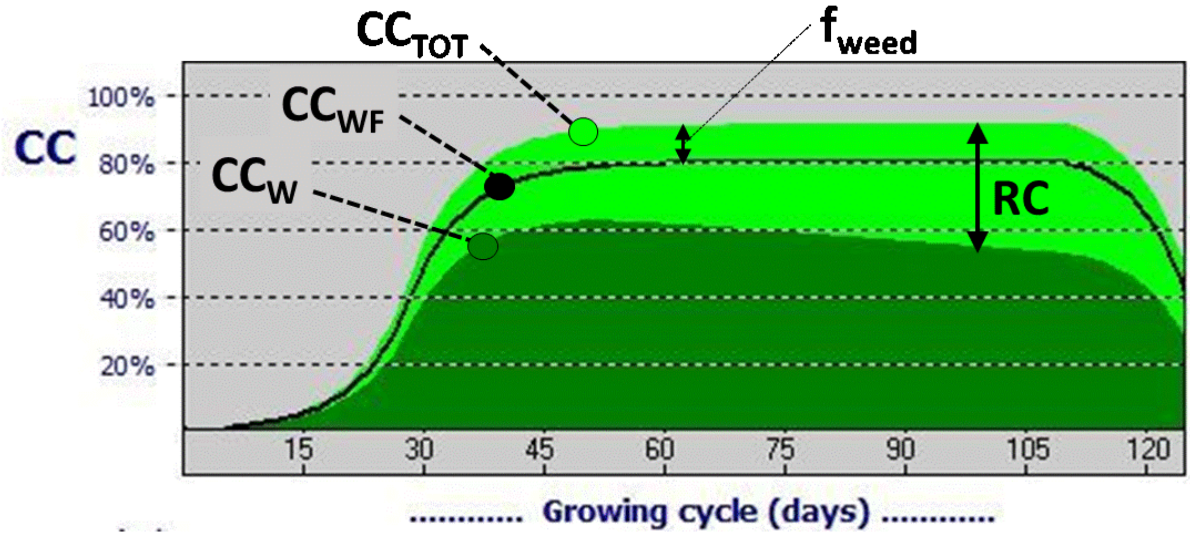


Figure 7.6 – Total canopy cover of crop and weeds (CC_{TOT}), crop canopy cover under weed-free conditions (CC_{WF} – reference) and crop canopy cover in a weed infested field (CC_W), with indication of the adjustment factor for canopy expansion (f_{weed}) and the relative cover of the weeds (RC).

- **Limited soil fertility**

In case of limited soil fertility, CC_{TOT} is entirely determined by the available soil nutrients in the absence of water or salinity stress. As such the expansion of CC for unlimited soil fertility is not considered. Given that weeds and crop are assumed to be equally sensitive to water, temperature, salinity and fertility stress, CC_{TOT}, will be the same as the crop canopy cover under weed-free conditions (CC_{WF}).

☐ Step 2 – Total transpiration (Tr_{TOT}) and soil water balance

As a result of the faster development of CC_{TOT} and the higher canopy cover, the transpiration rate is larger and the soil evaporation lower in a weed infested field than in a weed-free field. This affects the soil water balance, and might affect the timing and magnitude of soil water stresses in the season as well. Hence, the total transpiration of crop and weeds (Tr_{TOT}) and the soil evaporation (E_{TOT}) in the weed-infested field needs to be considered to simulate correctly the soil water balance.

By assuming that weeds and crop have a similar maximum crop transpiration coefficient ($Kc_{Tr,x}$), the total transpiration can be derived from the simulated total canopy cover (CC_{TOT}). When linking total transpiration to the total canopy cover, it is thereby assumed that weeds and crop have the same sensitivity to water and cold stress and similar rooting system. The total transpiration is given by:

$$Tr_{TOT} = Ks \ Ks_{Tr} \ CC^*_{TOT} \ Kc_{Tr,x} \ ET_o \quad \text{(Eq. 7.7)}$$

where Ks is the water stress coefficient, Ks_{Tr} the cold stress coefficient for transpiration, CC^*_{TOT} the total canopy cover adjusted for micro-advective effects, and ETo the reference evapotranspiration.
The soil evaporation in the weed-infested field (E_{TOT}) is given by:

$$E_{TOT} = Kr \left(1 - CC^*_{TOT}\right) Ke_x \ ET_o \quad \text{(Eq. 7.8)}$$

where Kr is the evaporation reduction coefficient and Ke_x the maximum soil evaporation coefficient for fully wet and not shaded soil surface.

☐ **Step 3 – Crop transpiration (Tr_W)**

Crop transpiration in a weed infested field (Tr_W) is proportional to CC_W (Eq. 6). In the calculation of Tr_W, the adjustment for micro-adjustments is based on the total canopy cover CC_{TOT}:

$$Tr_W = Ks \ Ks_{Tr} \left[CC_W + \left(CC^*_{TOT} - CC_{TOT}\right)\right] Kc_{Tr,x} \ ET_o \quad \text{(Eq. 7.9)}$$

☐ **Step 4 – Crop dry above-ground biomass (B_W)**

- **Unlimited soil fertility**

The crop dry above-ground biomass in a weed-infested field (B_W) is given by:

$$B_W = WP^* \sum \frac{Tr_W}{ET_o} \quad \text{(Eq. 7.10)}$$

where WP^* is the normalized biomass water productivity.

- **Limited soil fertility**

When soil fertility limits crop development and production, the crop dry above-ground biomass in the weed-infested field (B_W) is given by:

$$B_W = Ks_{WP,adj} \ WP^* \sum \frac{Tr_W}{ET_o} \quad \text{(Eq. 7.11)}$$

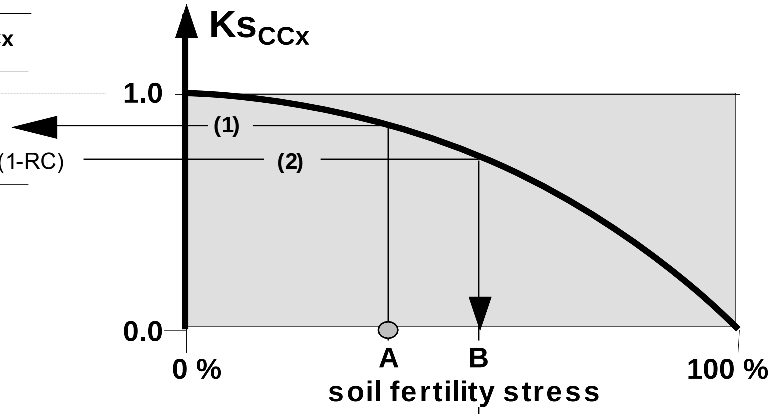
where $Ks_{WP,adj}$ is the adjusted soil fertility stress coefficient for the crop biomass water productivity in a weed-infested field. The adjustment for Ks_{WP} is required since for an identical level of limited soil fertility, the crop biomass production in a weed-infested field will be lower than in a weed free field since weeds compete with the crop for the limited nutrients. The adjustment of Ks_{WP} is given by the decline of the crop canopy cover in a weed infested field (Box 7.1).

Box 7.1 – Adjustment of Ks_{WP} in a weed-infested field with limited soil fertility

When soil fertility is limited and in the absence of weeds (soil fertility level A), the value for the soil fertility stress coefficient for maximum canopy cover (Ks_{CCx}) is determined by the shape of the Ks_{CCx} - stress curve (1). In the presence of weeds, the value for the stress coefficient will drop to Ks_{CCx} (1-RC). This value (2) determines the corresponding soil fertility stress level (B) in the Ks_{CCx} - stress curve. 'B' is the soil fertility stress level for the crop, which development is not only limited by soil fertility stress, but also by the presence of weeds. Once the soil fertility stress level (B) for the crop is obtained, the corresponding value for the soil fertility stress coefficient for biomass production (Ks_{WP}) for that stress level, can be derived from the Ks_{WP} - stress curve (3).

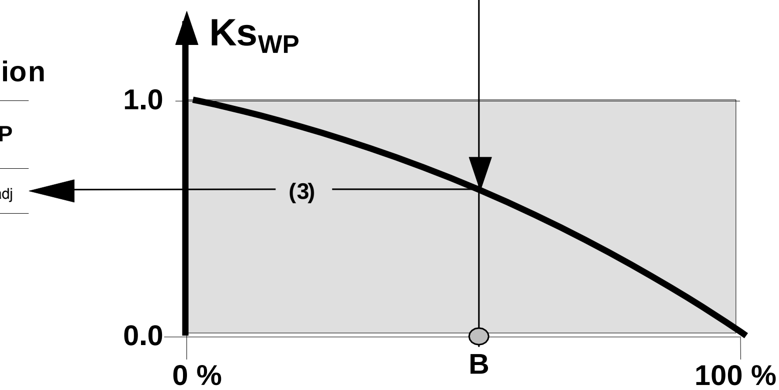
maximum crop canopy cover

Soil fertility	Weeds	Ks for CCx
unlimited	none	1.0
limited	none	Ks_{CCx}
limited	present	Ks_{CCx} (1-RC)



crop biomass production

Soil fertility	Weeds	Ks for WP
limited	present	$Ks_{WP,adj}$



Soil fertility stress:
A: given soil fertility stress for the crop for weed-free conditions
B: derived soil fertility stress for the crop in a weed-infested field

☐ **Step 5 – Crop dry yield (Y_W)**

Once the dry above-ground biomass of the crop (B_W) is determined, crop dry yield in a weed-infested field (Y_W) is obtained by multiplying B_W with the harvest index (HI):

$$Y_W = HI \; B_W \qquad \text{(Eq. 7.12)}$$

HI might be different from the reference harvest index (HIo) if water and/or temperature stress affects yield formation and/or pollination. The adjustment of HI depends on the timing and the magnitude of the stresses.

In the calculation of Y_W a simplification is made since it is assumed that the effect of weeds on the harvest index is negligible. Nevertheless, it is observed in the field that weed infestation affects yield not only through a lower biomass production (B_W) but also trough a lower number of ear bearing tillers, grains per ear and 1000-kernel weight (Wilson and Peters, 1982, Morishita and Thill, 1988). To avoid over-parametrisation this is neglected in AquaCrop, especially since the effect of weed stress on HI might be small compared to the effect of weed stress on biomass production (Van Gaelen, 2011). Further-on, the adjustment of HI might be simulated indirectly in AquaCrop, since the presence of weeds might cause extra water stress for the crop (due to larger total transpiration of crop and weeds). As a consequence the simulated HI might be lower than the simulated HI in weed-free conditions.

☐ **Step 6 – ET water productivity (WP_{ET})**

The ET water productivity in a weed infested field is given by:

$$WP_{ET} = \frac{Y_w}{(E_{TOT} + Tr_{TOT})} \qquad \text{(Eq. 7.13)}$$

WP_{ET} in a weed infested field is most likely lower than in weed free conditions, since crop dry yield (Y_W) might be smaller and total evapotranspiration of crop and weeds (E_{TOT} + Tr_{TOT}) might be larger than under weed-free conditions.

7.5 Simulation run

In the 'Climate-Crop-Soil water' tab-sheet of the ***Simulation run*** menu, the total canopy cover of crop and weeds (CC_{TOT}) and the crop canopy cover (CC_W), and the total transpiration of crop and weeds (Tr_{TOT}) and crop transpiration (Tr_W) are displayed (Fig. 7.7).

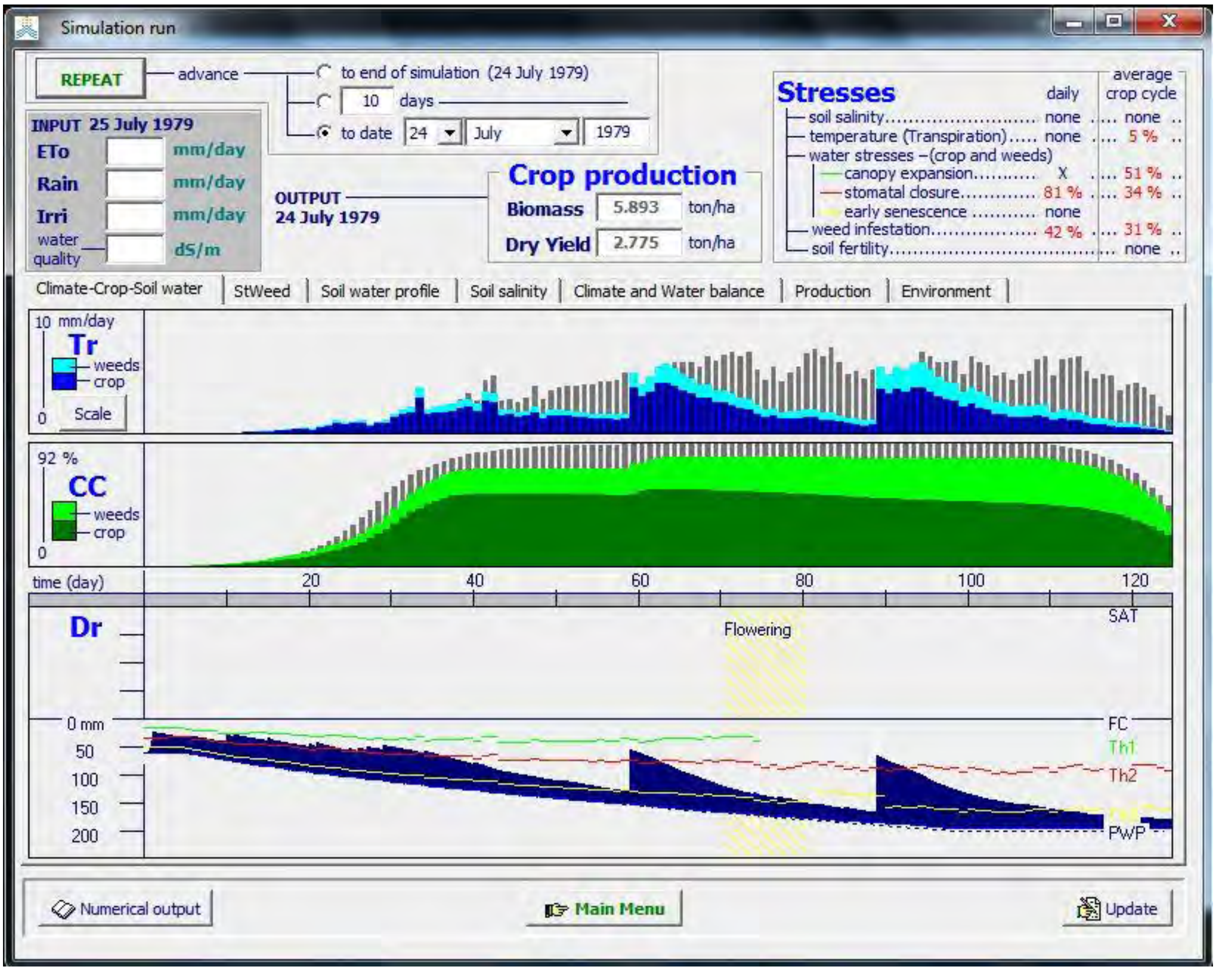


Figure 7.7 – Display in the *Simulation run* menu of the transpiration of crop and weeds (Tr_{TOT}) and of the crop only (Tr_W), the canopy cover of crop and weeds (CC_{TOT}) and of the crop only (CC_W), the crop dry-above biomass (B_W) and crop dry yield (Y_W) in a weed infested field.

In the second sheet of the ***Simulation run*** menu, the user can select a particular parameter (default is 'Rain') for further analysis (Tab. 7.3). Several crop parameters and parameters of the soil water and soil salinity balance, as well as simulated stresses (such as the weed stress) can be selected and the scale for the plot can be adjusted (Fig. 7.8).

Table 7.3 – Parameters and variables of the soil water balance, crop, soil salinity and stresses that can be selected for display in the Simulation run menu

Symbol	Description	Units
Soil water balance		
CR	Capillary rise	mm
Sum(Cr)	Capillary rise (cumulative)	mm
Drain	Deep percolation	mm
Sum(Drain)	Deep percolation (cumulative)	mm
Zgwt	Depth groundwater table	m
ET	Evapotranspiration	mm
Sum(ET)	Evapotranspiration (cumulative)	mm
ETx	Evapotranspiration (maximum)	mm
ET/ETx	Evapotranspiration (relative)	%
Inf	Infiltrated water	mm
Sum(Inf)	Infiltrated water (cumulative)	mm
Irri	Irrigation	mm
Sum(Irri)	Irrigation (cumulative)	mm
Rain	Rainfall	mm
Sum(Rain)	Rainfall (cumulative)	mm
Evap	Soil evaporation	mm
Sum(E)	Soil evaporation (cumulative)	mm
Ex	Soil evaporation (maximum)	mm
E/Ex	Soil evaporation (relative)	%
Runoff	Surface runoff	mm
Sum(RO)	Surface runoff (cumulative)	mm
Crop variables		
Biomass	Biomass produced (cumulative)	ton/ha
B(rel)	Biomass produced (relative)	%
Sum(Tr)	Transpiration (cumulative)	mm
Tr/Trx	Transpiration (relative)	%
GDD	Growing degrees	°C-day
HI	Harvest Index (HI)	%
Z	Rooting depth (effective)	m
WP	Water Productivity (WP)	g/m^2
Yield	Yield	ton/ha
Soil salinity		
SaltIn	Salt infiltrated in the profile	ton/ha
Sum(Sin)	Salt infiltrated in the profile (cumulative)	ton/ha
SaltOut	Salt drained out of the profile	ton/ha
Sum(Sout)	Salt drained out of the profile (cumulative)	ton/ha
SaltUp	Salt moved upward from groundwater table	ton/ha
Sum(Sup)	Salt moved upward (cumulative)	ton/ha
SaltTot	Salt stored in the profile	ton/ha
SaltZ	Salt stored in the root zone	ton/ha

ECe	EC of saturated soil-paste extract from root zone	dS/m
ECsw	EC of soil water in root zone	dS/m
ECgw	EC of groundwater table	dS/m
Stresses		
StExp	Water stress reducing canopy expansion	%
StSto	Water stress inducing stomatal closure	%
StSen	Water stress triggering early canopy senescence	%
StBio	Cold stress affecting crop transpiration	%
StSalt	Salinity stress affecting development and production	%
StWeed	**Weed infestation (relative cover of weeds)**	**%**

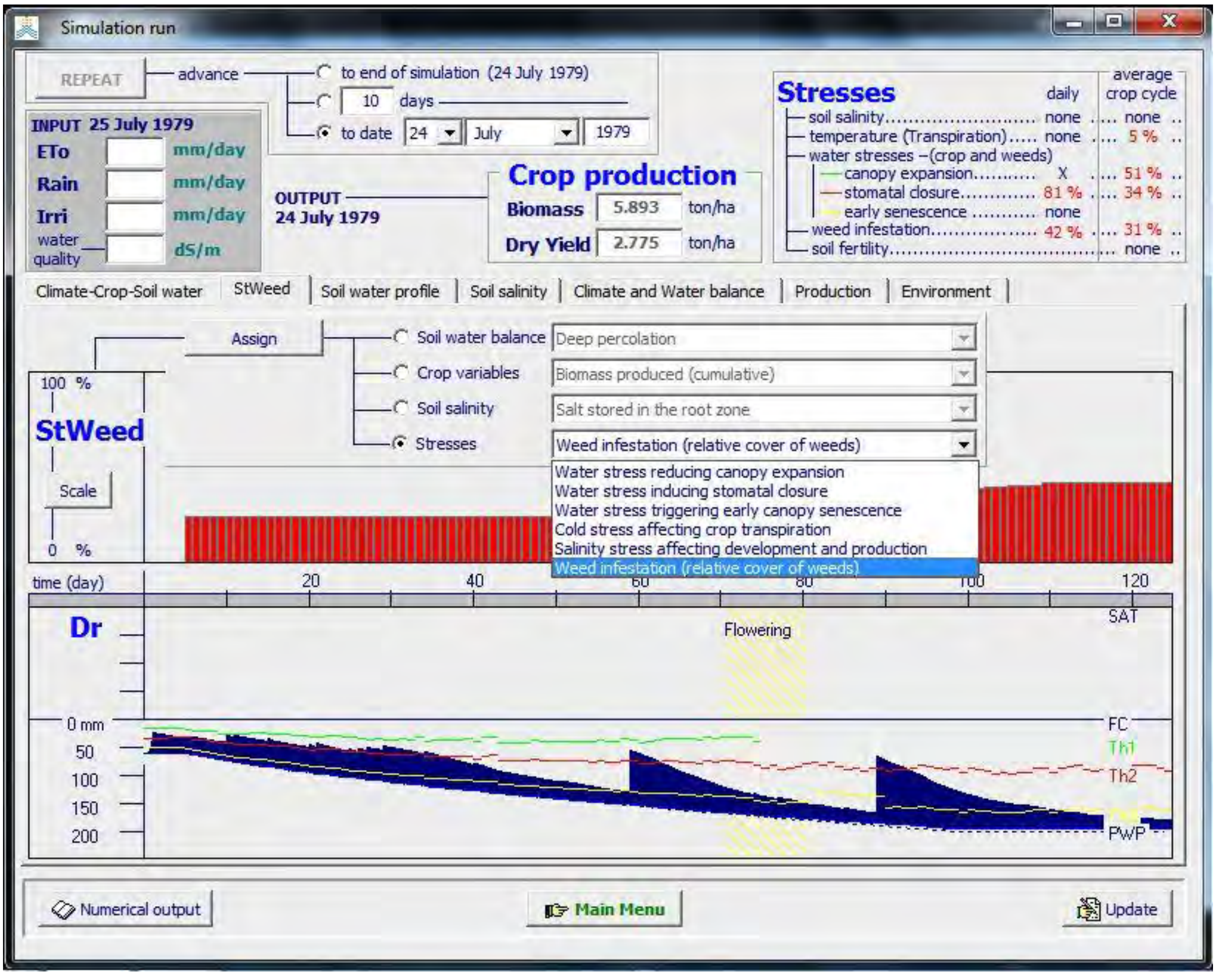


Figure 7.8 - Selection of a parameter for display in the *Simulation run* menu.

In the 'Production' tab-sheet of the ***Simulation run*** menu (Fig. 7.9), the ET water productivity (WP_{ET}) in the weed infested field is displayed, as well as the potential biomass that could have been reached in the absence of any stress, and the details of the calculation of the Harvest Index (HI).

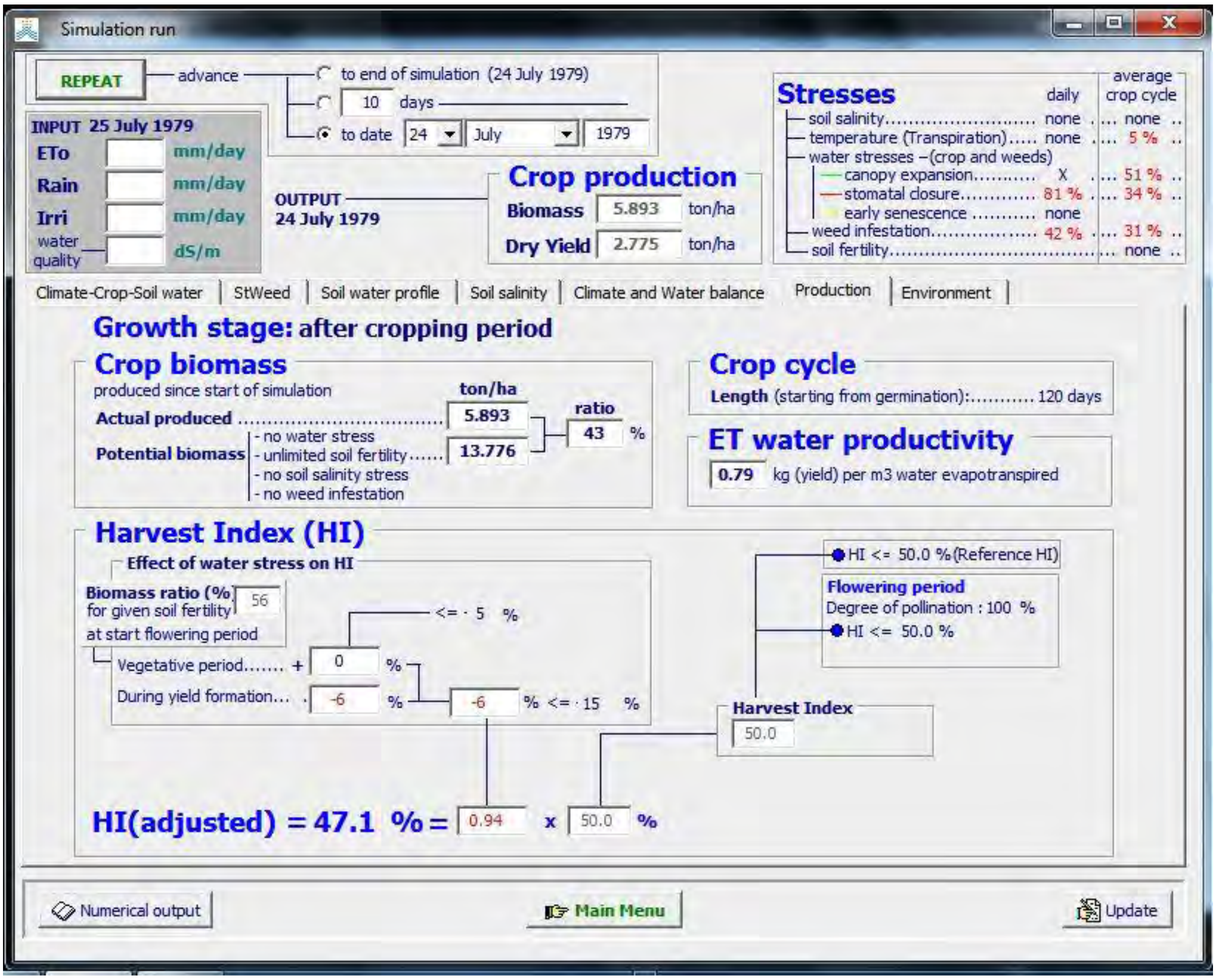


Figure 7.9 – Display in the 'Production' tab-sheet of the *Simulation run* menu, of the ET Water productivity (WP_{ET}) in a weed infested field, the potential biomass that could have been reached in the absence of any stress, and the details of the calculation of the Harvest Index (HI).

The relative cover of the weeds (weed stress), and the total (crop and weeds) and crop transpiration in weed infested fields are additional daily and seasonal output (Tab. 7.4 and 7.5).

Table 7.4 – Output file for crop development and production
Default file name: ProjectCROP.OUT

Nr	Symbol	Description	Unit
1	Day		-
2	Month		-
3	Year		-
4	DAP	Days after planting/sowing	-
5	Stage	Crop growth stage: 0: before or after cropping; 1: between sowing and germination or transplant recovering; 2: vegetative development; 3: flowering; 4: yield formation and ripening -9: no crop as a result of early canopy senescence	-
6	GD	Growing degrees	°C-day
7	Z	Effective rooting depth	m
8	StExp	Percent water stress reducing leaf expansion	%
9	StSto	Percent water stress inducing stomatal closure	%
10	StSen	Percent water stress triggering early canopy senescence	%
11	StSalt	Percent salinity stress	%
12	StWeed	Relative cover of weeds	%
13	**CC**	**Total green Canopy Cover of crop and weeds**	**%**
14	**CCw**	**Crop green Canopy Cover in weed infested field**	**%**
15	StTr	Percent temperature stress affecting crop transpiration	%
16	Kc(Tr)	Crop coefficient for transpiration	-
17	Trx	Maximum crop transpiration of crop and weeds	mm
18	**Tr**	**Total transpiration of crop and weeds**	**mm**
19	**TrW**	**Crop transpiration in weed infested field**	**mm**
20	Tr/Trx	Relative total transpiration of crop and weeds (100 Tr/Trx)	%
21	WP	Crop water productivity adjusted for CO2, soil fertility and products synthesized	g/m^2
22	Biomass	Cumulative crop biomass	ton/ha
23	HI	Harvest Index adjusted for failure of pollination, inadequate photosynthesis and water stress	%
24	Yield Part	Crop yield (HI x Biomass)	ton/ha
25	Brelative	Relative biomass (Reference: no water, no soil fertility, no soil salinity stress, no weed infestation)	%
26	WPet	ET Water productivity for yield part (kg yield produced per m3 water evapotranspired)	kg/m^3

Table 5. – Seasonal output.
Default file name: ProjectRun.OUT

Nr	Symbol	Description	Unit
1	RunNr	Number simulation run	-
2	Day1	Start day of simulation run	-
3	Month1	Start month of simulation run	-
4	Year1	Start year of simulation run	-
5	Rain	Rainfall	mm
6	ETo	Reference evapotranspiration	mm
7	GD	Growing degrees	°C.day
8	CO2	Atmospheric CO2 concentration	ppm
9	Irri	Water applied by irrigation OR net irrigation requirement	mm
10	Infilt	Infiltrated water in soil profile	mm
11	Runoff	Water lost by surface runoff	mm
12	Drain	Water drained out of the soil profile	mm
13	Upflow	Water moved upward by capillary rise	mm
14	E	Soil evaporation	mm
15	E/Ex	Relative soil evaporation (100 E/Ex)	%
16	**Tr**	**Total transpiration of crop and weeds**	**mm**
17	**Trw**	**Crop transpiration in weed infested field**	**mm**
18	Tr/Trx	Relative total transpiration (100 Tr/Trx)	%
19	SaltIn	Salt infiltrated in the soil profile	ton/ha
20	SaltOut	Salt drained out of the soil profile	ton/ha
21	SaltUp	Salt moved upward by capillary rise from groundwater table	ton/ha
22	SaltProf	Salt stored in the soil profile	ton/ha
23	Cycle	Length of crop cycle: from germination to maturity (or early senescence)	days
24	SaltStr	Average soil salinity stress	%
25	FertStr	Average soil fertility stress	%
26	**WeedStr**	**Average relative cover of weeds**	**%**
27	TempStr	Average temperature stress (affecting crop transpiration)	%
28	ExpStr	Average leaf expansion stress	%
29	StoStr	Average stomatal stress	%
30	Biomass	Cumulative biomass produced	ton/ha
31	Brelative	Relative biomass (Reference: no water, no soil fertility, no soil salinity stress)	%
32	HI	Harvest Index adjusted for failure of pollination, inadequate photosynthesis and water stress	%
33	Yield	Yield (HI x Biomass)	ton/ha
34	WPet	ET Water Productivity for yield part (kg yield produced per m3 water evapotranspired)	kg/m^3
35	DayN	End day of simulation run	-
36	MonthN	End month of simulation run	-
37	YearN	End year of simulation run	-

7.6 References

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Kropff, M.J. and Spitters, C.J.T. 1991. A simple model of crop loss by weed competition from early observations on relative leaf area of the weeds. Weed Research 31: 97-105.

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Sattin, M. and Berti, A. 2003. Parameters for weed-free competition [on line]. FAO Plant production and Protection Papers No. 120. Addendum 1: Weed management for developing countries. http://www.fao.org/docrep/006/y5031e/y5031e04.htm

Van Gaelen, H., Delbecque, N., Abrha, B., Tsegay, A., Raes, D. 2016. Simulation of crop water productivity in weed-infested fields for data-scarce regions. Journal of Agricultural Science, 154 (6):1026–1039

Wilson, B.J. & Peters, N.C.B. (1982). Some studies of competition between *Avena fatua* L. and spring barley, I: the influence of *A.fatua* on yield of barley. Weed Research, 22: 143-148.

Part 3. Introduction of extra soil characteristics

8. Possibility to specify the penetrability of a soil horizon

The presence of a restrictive soil layer in the soil profile is a soil characteristic. By specifying the presence as a distinct soil horizon, the depth and thickness of the restrictive layer can be specified (Fig. 8.1). Its penetrability describes the effect on the expansion rate of the root zone. The presence of a restrictive soil layer might affect the maximum rooting depth that can be reached. The limiting effect on root zone expansion can be plotted in the menu (Fig. 8.1).

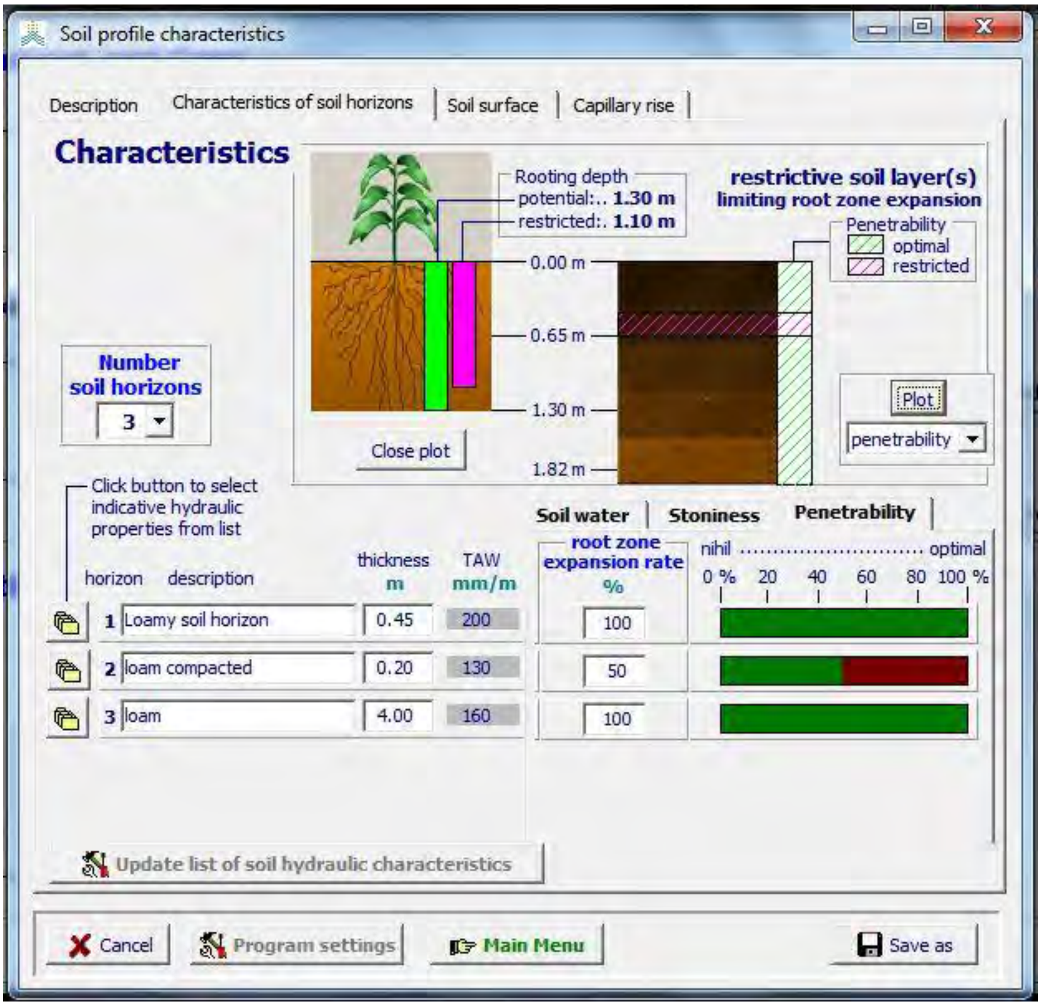

Figure 8.1 – Specification of the depth and thickness of the restrictive soil layer (soil horizon 2: 0.45 – 0.65 meter) and its effect on the expansion rate of the root zone (50% penetrability) in the *Soil profile characteristics* menu. The corresponding development of the effective rooting depth is given in the *Crop characteristics* menu.

9. Possibility to specify gravel in a soil horizon

In Version 6.0 of AquaCrop a soil horizon can contain gravel. Gravel reduces the volume of the fine soil fraction in the soil profile (Fig. 9.1). This affects the soil physical characteristics, has its effect on the simulation of the soil water and salt balance, and might affect crop development and production. In general, under similar environmental conditions:

– water stresses will develop quicker in a soil profile containing gravel (since less water can be stored in the reduced pore volume);
– since the presence of gravel in a soil horizon reduces the volume of its fine soil fraction, less salts (ton per ha) can diffuse in the matrix of such a soil horizon. Nevertheless the salinity stress in a profile with gravel is likely to be larger than in a profile without gravel, since less water can be stored in the profile, and water and salinity stresses develops more easily.

This will reduce crop transpiration, biomass production, crop yield and ET water productivity.

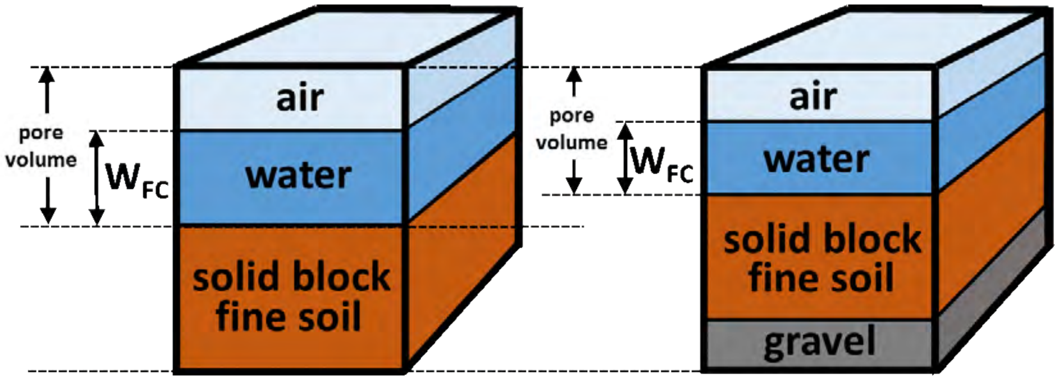

Figure 9.1 – The components of a soil horizon without and with gravel with indication of the pore volume and the soil water content at Field Capacity (WFC).

9.1 The fine soil and gravel fraction of a soil horizon

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

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

$$Mass\ \%_{gravel} = 100\ \frac{m_{gravel}}{m_{gravel} + m_{fine\ soil}} \qquad \text{[Eq. 9.1]}$$

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

9.2 Specifying the soil physical characteristics

Soil characteristics refers to physical parameters required to simulate the retention and movement of water and salt in the soil profile. In AquaCrop, the soil profile can be composed of up to five different horizons, each with their own physical characteristics.

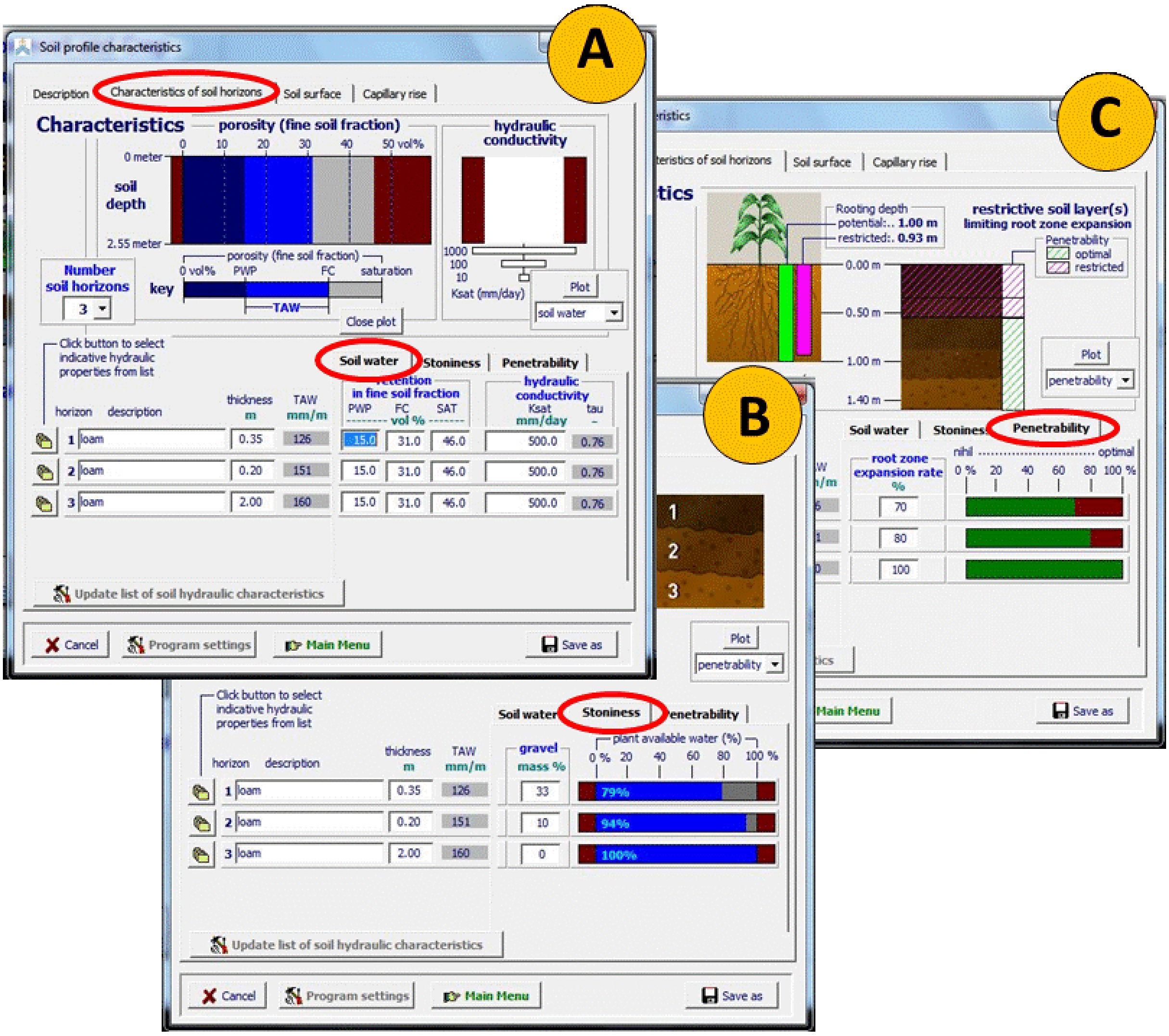

Figure 9.2 - Specification of physcial characteristics of the various soil horizons in the (A) 'Soil water', (B) 'Stoniness' and (C) 'Penetrability' tab-sheet in the *Soil profile characteristics* menu.

In the 'Characteristics of soil horizons' tab-sheet of the ***Soil profile characteristics*** menu the number and thickness of the horizons are specified. The physical characteristics of the horizons and of their fine soil and mass fractions are specified in (Fig. 9.2):

– the '**Soil water'** tab-sheet (Fig. 9.2A)**:** In this tab sheet (i) the water retention in the fine soil fraction at permanent wilting point (PWP), field capacity (FC) and saturation (SAT), and (ii) the hydraulic conductivity (Ksat) of the soil horizon, are specified. Default values for the 12 textural classes are available in AquaCrop's data base and can be selected. AquaCrop displays the corresponding total available soil water (TAW) and drainage characteristic (tau) of the soil horizon;

– the '**Stoniness**' tab-sheet (Fig. 9.2B)**:** In this tab sheet the mass percentage of the gravel (Eq. 1) for the distinctive soil horizons is specified. By considering the corresponding volume percentage of the gravel fraction (Eq. 9.3), AquaCrop calculates the reduction of the volume of the fine soil fraction in which water can be stored, and plots the corresponding relative amount of available water for the plant in the horizon. The presence of gravel will reduce the total available soil water (TAW) of the soil horizon (Eq. 9.2). Aquacrop displays the adjusted TAW for the soil horizon;
– the '**Penetrability**' tab-sheet (Fig. 9.2C)**:** In this tab sheet the root zone expansion rate in the various soil horizons are specified. This might affect the maximum rooting depth that can be reached. The limiting effect on root zone expansion can be plotted in the menu.

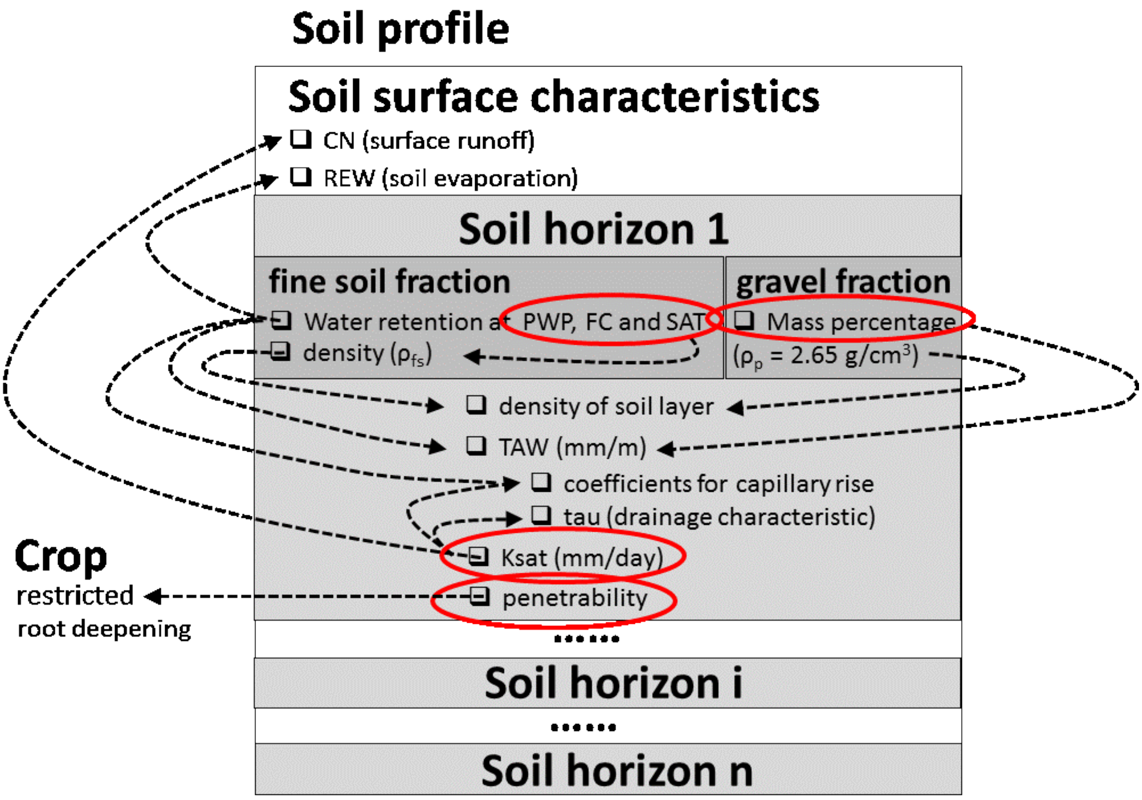

Figure 9.3 – Specified (red circled) soil physical characteristics of the soil horizon and of its fine soil and mass fractions, and the derived characteristics (dotted arrows) for the soil surface, soil horizon and crop.

From the specified soil physical characteristics of the soil horizon, AquaCrop derives (Fig. 9.3):
– from the Ksat of the top soil horizon, a default value for the curve number (CN) of the soil. CN is required for the simulation of the amount of rainfall lost by surface runoff. In the 'Soil surface' tab-sheet of the ***Soil profile characteristics*** menu the value for CN can be adjusted if required;
– from the soil water retention characteristics of the fine soil fraction of the top horizon, a default value for the readily evaporable water (REW) of the soil. REW expresses the maximum amount of water that can be extracted from the top soil in stage I of the evaporation process. In the 'Soil surface' tab-sheet of the ***Soil profile characteristics*** menu the value for REW can be adjusted if required;

– from the densities and percentages of the fine soil and gravel fractions, the density of the soil horizon (Eq. 9.4);
– from the soil water retention characteristics of the fine soil fraction and the percentage of gravel, the total available soil water (TAW) of the soil horizon (Eq. 9.2);
– from the soil water retention characteristics of the fine soil fraction and Ksat, default values for the coefficients for capillary rise of the soil horizon. In the 'Capillary rise' tab-sheet of the ***Soil profile characteristics*** menu, the values for the coefficients can be adjusted if rrequired;
– from Ksat, the drainage coefficient (tau) of the soil horizon.

The adjustment of TAW of the soil horizon to the presence of gravel is obtained by considering the volume percentage of the gravel fraction ($Vol\%_{gravel}$):

$$TAW = 1000 \; (\theta_{FC} - \theta_{PWP}) \, \Delta z \left(1 - \frac{Vol\,\%_{gravel}}{100} \right) \qquad \text{(Eq. 9.2)}$$

where TAW is the total available soil water in mm(water) per meter(depth of the soil horizon), θ_{FC} and θ_{PWP} the soil water content at field capacity and at permanent wilting point in m^3(water) per m^3(fine soil fraction), and Δz the thickness of the soil horizon in meter.

The volume percentage of the gravel fraction is derived from its mass percentage ($Mass\%_{gravel}$) by considering the densities (gram/cm^3) of the soil horizon ($\rho_{soil\ horizon}$) and mineral particles ($\rho_{particles} = 2.65$ g/cm^3):

$$Vol\,\%_{gravel} = \frac{\rho_{soil\ horizon}}{\rho_{particles}} \, Mass\,\%_{gravel} \qquad \text{(Eq. 9.3)}$$

The densities (gram/cm^3) of the soil horizon ($\rho_{soil\ horizon}$) and of the fine soil (ρ_{fs}) are given by:

$$\rho_{soil\ horizon} = \frac{100}{\left[\dfrac{Mass\,\%_{gravel}}{\rho_{particles}} + \dfrac{(100 - Mass\,\%_{gravel})}{\rho_{fs}} \right]} \qquad \text{(Eq. 9.4)}$$

$$\rho_{fs} = \rho_p \, (1 - \theta_{sat}) \qquad \text{(Eq. 9.5)}$$

Aquacrop adjusts only the TAW value of the soil horizons containing gravel. In the absence of wide-ranging and well described responses to the presence of gravel, other characteristics of the soil profile, soil horizons, and of the crop are not adjusted. If effects of gravel on those characteristics are known, the user can adjust:
– the CN and REW of the soil surface, and the Ksat, penetrability and capillary rise of the soil horizon, in the corresponding tab-sheets of the ***Soil profile characteristics*** menu;
– the water extraction pattern and maximum root extraction in the 'ET' tab sheet of the ***Crop characteristics*** menu;

9.3 Simulating the effect of gravel on the soil water balance

To describe accurately the water extraction by plant roots, and the retention and movement of water and salts in the soil profile, AquaCrop divides the profile in a number of soil compartments (12 by defaults). The soil physical characteristics of each compartment are those of the soil horizon to which it belongs.

By considering the amount of water which infiltrates in the compartment, drains out of the compartment, moves upwards from the groundwater table to the compartment, and is extracted by soil evaporation and crop transpiration from the compartment, the soil water content (θ) of the compartments are continuously updated (Fig. 9.4).

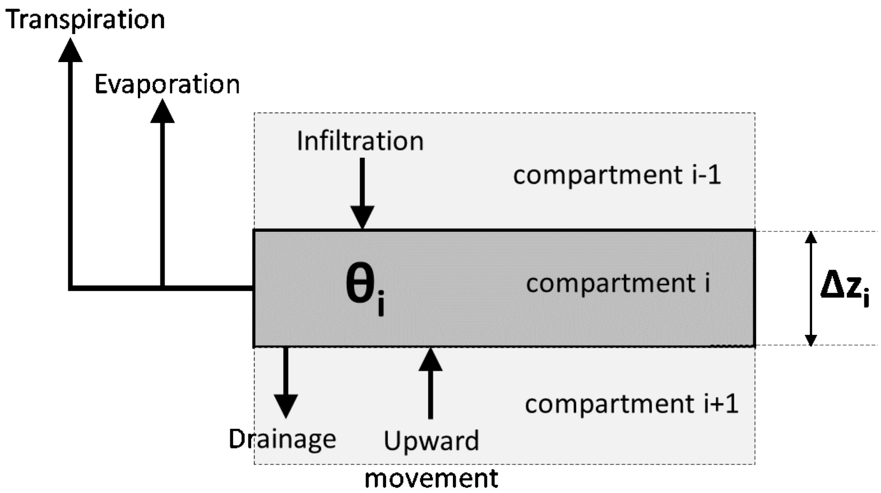

Figure 9.4 – Soil water movement in and out of a compartment and water extraction from that compartment.

The presence of gravel reduces the volume of the fine soil fraction. Consequently, the amount of water that is retained in a soil compartment is given by:

$$W_i = 1000\ \theta_i\ \Delta z_i \left(1 - \frac{Vol\ \%_{gravel}}{100}\right) \qquad \text{(Eq. 9.6)}$$

where W_i is the soil water content in mm(water) in compartment i, θ_i its soil water content expressed in m^3(water) per m^3(fine soil), Δz_i its thickness in meter, and $Vol\%_{gravel}$ the volume percentage of the gravel in the soil horizon to which the compartment belongs. The soil water content in the soil profile (W) is given by the sum of the water contents (expressed in mm) of the individual compartments:

$$W = \sum_{i=1}^{n} W_i \qquad \text{(Eq. 9.7)}$$

The change of the water content in the soil profile is obtained by the soil water balance equation:

$$W_{t+\Delta t} = W_t + (P - RO) + I + CR - E - Tr - Dr \qquad \text{(Eq. 9.8)}$$

where W_t and $W_{t+\Delta t}$ are the soil water content at that start and end of time step Δt, P the rainfall, RO the surface run-off, I the irrigation, CR the capillary rise, E the soil evaporation, Tr the crop transpiration, and Dr the drainage during the time step Δt. All terms in Eq. 9.8 are expressed in mm(water). Although Eq. 9.8 remains valid for soil profiles with or without gravel, the water content in a soil profile with gravel is likely to be different form a profile without gravel since the presence of gravel might affect one or more terms of the equation:

- For an identical soil water content in the top soil (θ_{top}), the amount of rainfall (P) lost by surface run-off (RO) will be identical in a soil profile with or without gravel (unless the user adjusted Ksat of the top horizon or altered directly the Curve Number (CN) of the soil profile);
- Since only θ and tau (the drainage coefficient derived from Ksat) are required to compute drainage, also the drainage rate will not be affected by gravel (unless the user adjusted Ksat of the soil horizon). But the amount of water that will drain out (Dr) of the soil profile with gravel, is less than from a profile without gravel (which has a larger volume of fine soil);
- Similarly the rate of water movement from the groundwater table to the soil profile will not be affected by gravel (unless the user adjusted Ksat and/or the water retention characteristics of the fine soil fraction). But the amount of water that will move upward (CR) to the soil profile with gravel, is less than towards a profile without gravel (which has a larger volume of fine soil);
- Less rainfall (P) and/or irrigation water (I) is required to bring the soil water content of a dry soil profile to field capacity, if the soil profile contains gravel (and as such can store less water). This also means than under excessive rainfall and/or irrigation, a larger fraction of the infiltrated water will be lost by deep percolation (Dr);
- Unless the user adjusted the maximum root extraction, it is assumed that the total root mass is concentrated in the reduced fine soil fraction of the horizon with gravel. Hence, the transpiration rate from a well-watered soil is not affected by gravel. But since a soil profile with gravel can store less water, water stresses will develop quicker in those profiles in the absence of rain and/or irrigation. Long or severe water stresses will more swiftly affect the canopy development, trigger stomata closure and can even induce early senescence, which will affect directly and indirectly crop transpiration (Tr);
- Unless the user adjusted the REW of the soil surface, the soil evaporation rate from a wetted soil surface is not affected by gravel in the soil profile. But since a soil profile with gravel can store less water, the total amount of water lost by soil evaporation (E) will be less;
- Although about the same amount of irrigation water (I) is required throughout the growing cycle in a dry environment, a soil profile with gravel will need to be irrigated more frequently (although with smaller irrigation amounts) than a profile without gravel. The more frequently wetting of the soil surface will affect soil evaporation (E).

In general, water stresses will develop quicker in a soil profile containing gravel, if it is not so well watered throughout the season. This will reduce crop transpiration, biomass production, crop yield and ET water productivity.

9.4 Simulating the effect of gravel on the salt balance

☐ **Salt balance**

Salts enter the soil profile as solutes with the irrigation water or through capillary rise from a shallow groundwater table. Salts are transported out of the soil profile (leached) by means of the drainage water. The drainage function, the process of capillary rise and soil evaporation describes the downward and upward movement of water and salts (convection) in the soil profile. Salts move horizontally in the soil matrix (diffusion) as a result of a salt concentration gradient that builds up between the water solution in the macro and micro pores. As a result of the salt concentration gradient at various soil depths in the soil profile, a vertical salt diffusion also takes place.

To simulate the convection and diffusion of salts, a soil compartment is divided into a number of cells where salts can be stored (Fig. 9.5). A cell is in fact a representation of a volume of pores with a particular mean diameter. Cells with a low number refer to micro pores which have small diameters, while cells with a high number refer to macro pores with large diameters.

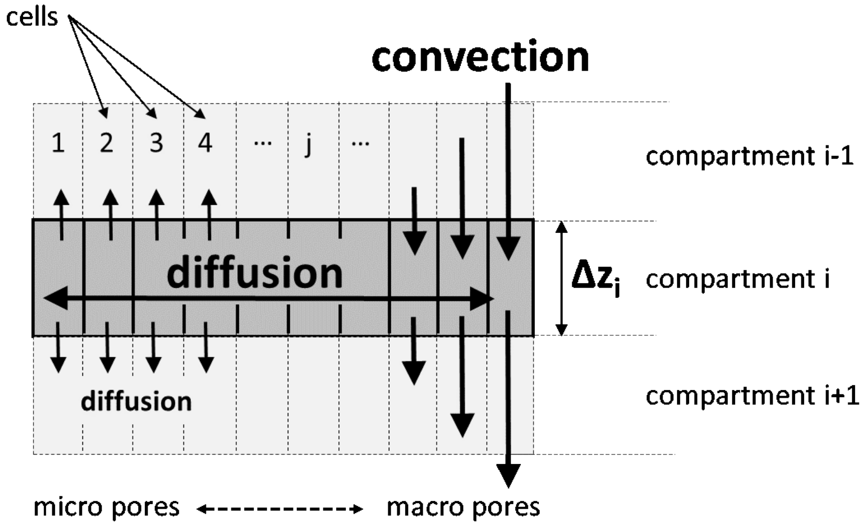

Figure 9.5 – Convection and diffusion of salts in the cells of a soil compartment.

The presence of gravel in the soil horizon reduces the volume of its fine soil fraction. Consequently, the volume of a cell (which is a fraction of the total pore volume), is also reduced by the fraction of the gravel:

$$W_{cell,j} = 1000 \, \frac{\theta_{sat,i}}{n} \, \Delta z_i \left(1 - \frac{Vol\,\%_{gravel}}{100} \right) \qquad \text{(Eq. 9.9)}$$

where $W_{cell,j}$ is the volume in mm(water) of the j[th] cell of compartment i, $\theta_{sat,i}$ the soil water content at saturation (m^3/m^3) of the soil horizon, n the number of cells in the compartment, Δz_i the thickness of the soil compartment (m), and $Vol\%_{gravel}$ the volume percentage of the gravel of the soil layer.

The salt diffusion between two adjacent cells (cell j and cell j+1) is given by the differences in their salt concentration which is expressed by the electrical conductivity (EC) of their soil water. At the end of the time step t+Δt the EC of the soil water in cell j is:

$$EC_{j,t+\Delta t} = EC_{j,t} + f_{diff} \left(\frac{EC_{j,t}\, W_{cell,j} + EC_{j+1,t}\, W_{cell,j+1}}{W_{cell,j} + W_{cell,j+1}} - EC_{j,t} \right) \qquad \text{(Eq. 9.10)}$$

where EC is the electrical conductivity of the soil water in the cell (dS/m), W_{cell} the volume of the cell (mm), and f_{diff} a salt diffusion coefficient.

The salt content of a cell is given by:

$$Salt_{cell,j} = 0.64\ W_{cell,j}\ EC_{cell,j} \qquad \text{(Eq. 9.11)}$$

where $Salt_{cell,j}$ is the salt content of the j^{th} cell expressed in grams salts per m^2 soil surface, $W_{cell,j}$ (Eq. 9.9) its volume expressed in liter per m^2 (1 mm = 1 l/m^2), $EC_{cell,j}$ (Eq. 9.10) it electrical conductivity in dS/m, and 0.64 a global conversion factor used in AquaCrop to convert deciSiemens per meter in gram salts per liter (1 dS/m = 0.64 g/l).

The electrical conductivity of the soil water (EC_{sw}) and of the saturated soil-paste extract (ECe) at a particular soil depth (soil compartment) is:

$$EC_{sw,i} = \frac{\sum_{j=1}^{n} Salt_{cell,j}}{0.64\ (1000\ \theta_i\ \Delta z_i)\left(1 - \frac{Vol\ \%_{gravel}}{100}\right)} \qquad \text{(Eq. 9.12)}$$

$$ECe_i = \frac{\sum_{j=1}^{n} Salt_{cell,j}}{0.64\ (1000\ \theta_{sat,i}\ \Delta z_i)\left(1 - \frac{Vol\ \%_{gravel}}{100}\right)} \qquad \text{(Eq. 9.13)}$$

where n is the number of salt cells of the soil compartment, θ_i the soil water content (m^3/m^3), $\theta_{sat,i}$ the soil water content (m^3/m^3) at saturation, and Δz_i (m) the thickness of the compartment.

☐ **Salinity stress**

The average electrical conductivity of the saturation soil-paste extract (ECe) from the root zone is the indicator for soil salinity. If ECe exceeds a threshold, a reduction of the biomass production is simulated. Additional effects will occur when the water content in the root zone drops. Although the depletion does not alter ECe, the depletion results in an increase of the electrical conductivity of the soil water (ECsw), which induces stronger osmotic forces and a closure of the stomata. This will further reduce the crop development and production. This effect can be calibrated in the ***Crop characteristics*** menu.

Since the presence of gravel in a soil horizon reduces the volume of its fine soil fraction and consequently also of its cells (soil pores), less salts (ton per ha) can diffuse in the matrix of a soil horizon containing gravel. Nevertheless the salinity stress in a profile with gravel is generally larger than in a profile without gravel, since less water can be stored in the profile, and water and salinity stresses develops more easily. This will reduce crop transpiration, biomass production, crop yield and ET water productivity.

Part 4. Updated crop parameters

10. Update of soil water thresholds for soybean, sorghum, potato and cotton

Values more in line with those reported in the literature, were introduced in the revised database of AquaCrop Version 6.0 (Tab. 10).

Table 10. – Updated (upper) threshold for soil water depletion ($p_{sto,upper}$) at which the stomata starts to close, and the shape factor (f_{shape}) for the stress-depletion relationship.

Crop	Version 5.0 and before		Version 6.0	
	$p_{sto,upper}$	f_{shape}	$p_{sto,upper}$	f_{shape}
Wheat	0.65	2.5	0.65	2.5
Tomato	0.50	3.0	0.50	3.0
Sunflower	0.60	2.5	0.60	2.5
Sugar cane	0.50	3.0	0.50	3.0
Sugar beet	0.65	3.0	0.65	3.0
Soybean	0.50	3.0	***0.60***	3.0
Sorghum	0.70	6.0	***0.75***	***3.0***
Quinoa	0.60	4.0	0.60	4.0
Potato	0.55	3.0	***0.60***	3.0
Rice (paddy)	0.50	3.0	0.50	3.0
Maize	0.69	6.0	0.69	6.0
Cotton	0.65	2.5	***0.75***	2.5
Barley	0.60	3.0	0.60	3.0
Dry beans	-	-	***0.60***	***2.5***

11. Update of soil water extraction

The range and default values for the maximum root extraction at the top (Sx(top ¼)) and bottom (Sx(bottom ¼)) quarter of the root zone for various maximum rooting depths (Zr_x) were updated in Version 6.0 of AquaCrop (Tab. 11a). This result in Sx values which are more in line with those reported in the literature (Tab. 11b). The update might alter the simulated soil water profile, but hardly affects the simulated crop development, transpiration and production.

The maximum sink term (Sx) specifies the maximum amount of water that can be extracted by the crop root in the time step of 1 day. It is expressed in m^3(water) per m^3(soil) per day. In AquaCrop distinction is made between the:

- maximum root extraction in the top quarter of the root zone (Sx(top ¼)));
- maximum root extraction in the bottom quarter of the root zone (Sx(bottom ¼)),

which are both non-conservative crop parameters, and can be altered by the user.

The two crop parameters determine

- the maximum root extraction, Ext_{Zx}, in mm/day, which is the maximum amount of water that all the roots together would be able to extract, when the maximum rooting depth (Zr_x) is reached;
- the water extraction pattern throughout the effective root zone, which is expressed by the percentages for the upper (P1), second (P2), third (P3) and bottom (P4) quarter of the root zone.

The default setting of the maximum root extractions in the top and bottom quarter of the root zone, results in an extraction rate (root distribution) of 40, 30, 20, 10% (where the values refer to the upper, second, third and bottom quarter of the root zone as in Fig. 11).

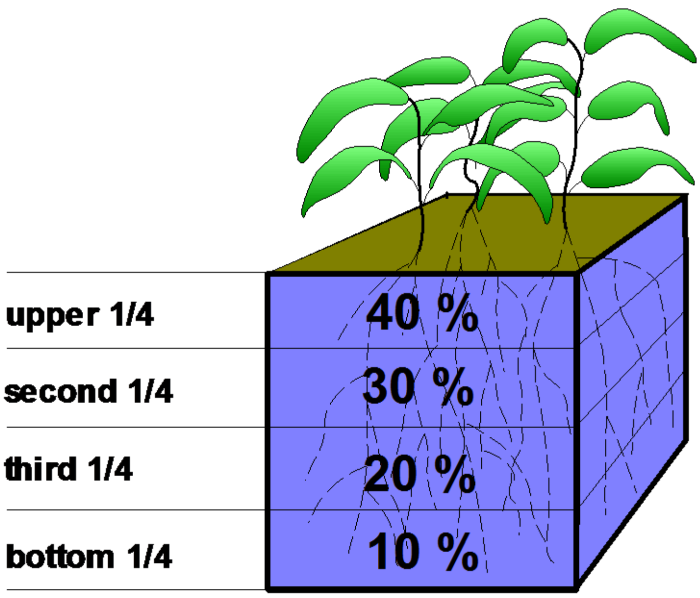

Figure 11. – Default extraction pattern in the root zone

Table 11a. – The range and default values for the maximum root extraction at the top (Sx(top ¼)) and bottom (Sx(bottom ¼)) quarter of the root zone for various maximum rooting depths (Zx), in Version 6.0 of AquaCrop

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

Table 11b. – Updated root extractions at the top and bottom quarter of the root zone for various crops, with indication of the maximum effective rooting depth (Zr_x) and the maximum root extraction (Ext_{Zrx}) that all the roots together would be able to extract when Zr_x is reached.

Crop	Zr_x	Version 5.0 and before			Version 6.0		
		maximum root extraction (Sx)		total maximal root extraction (Ext_{Zrx})	maximum root extraction (Sx)		total maximal root extraction (Ext_{Zrx})
		top ¼	bottom ¼		top ¼	bottom ¼	
	meter	m^3/m^3.day	m^3/m^3.day	mm/day	m^3/m^3.day	m^3/m^3.day	mm/day
Wheat	1.5	0.0280	0.0080	27	0.0480	0.0120	45
Tomato	1.0	0.0240	0.0060	15	0.0480	0.0120	30
Tef	0.6	0.0230	0.0080	9.3	0.0480	0.0120	18
Sunflower	2.0	0.0500	0.0150	65	0.0480	0.0120	60
Sugar cane	1.8	0.0130	0.0030	14.4	0.0480	0.0120	54
Sugar beet	1.0	0.0250	0.0060	15.5	0.0480	0.0120	30
Soybean	2.0	0.0120	0.0030	15	0.0480	0.0120	60
Sorghum	1.8	0.0160	0.0040	18	0.0480	0.0120	54
Quinoa	1.0	0.0240	0.0060	15	0.0480	0.0120	30
Potato	1.5	0.0160	0.0040	15	0.0480	0.0120	45
Rice (paddy)	0.5	0.0480	0.0120	15	0.0480	0.0120	15
Maize	2.3	0.0100	0.0030	15	0.0453	0.0113	65.1
Cotton	2.0	0.0520	0.0150	67	0.0480	0.0120	60
Barley	1.3	0.0190	0.0060	16.3	0.0480	0.0120	39
Dry beans					0.0480	0.0120	

Part 5. Calibration of AquaCrop for new crops

12. Calibration of AquaCrop for dry beans

Table 11. – Calibration values for selected parameters of the Crop Data file

Description	Value	Unit
☐ **Temperature**		
Base temperature (T_{base})	9	ºC
Cut-off temperature (T_{upper})	30	ºC
☐ **Canopy development**		
Canopy cover per seedling at 90% emergence (cc_o)	10	cm^2/plant
Canopy growth coefficient (CGC)	11.8	%/day
Maximum canopy cover (CC_x)	99	%
Crop coefficient for transpiration ($Kc_{Tr,x}$)	1.05	
Canopy decline coefficient (CDC)	0.881	%/GDD
Time from DAP [1] to emergence	59	GDD
Time from DAP to maximum Canopy	752	GDD
Time from DAP to senescence	903	GDD
Time from DAP to maturity	1298	GDD
☐ **Flowering**		
Duration of flowering	233	GDD
Time from DAP to flowering	556	GDD
Length building up Harvest Index	668	GDD
☐ **Root development**		
Maximum rooting depth (Zr_x)	1.7	m
Time from DAP to maximum rooting depth	888	GDD

☐ **Water stress response**		
Canopy expansion p(upper)	0.15	%TAW
Canopy expansion p(lower)	0.65	%TAW
Canopy expansion shape factor	2.5	
Stomatal closure p(upper)	0.6	%TAW
Stomatal closure shape factor	2.5	
Early canopy senescence p(upper)	0.7	%TAW
Early canopy senescence shape factor	2.5	
Maximum positive effect on HI	10%	
Before flowering (+)	small	
During flowering (-)	moderate	
During yield formation (+)	none	
During yield formation (-)	very strong	
☐ **Production**		
Reference harvest index (HI)	40	%
Normalized water productivity (WP*)	15	g/m2
Adjustment for yield formation	90	%

[1] DAP: day after planting

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