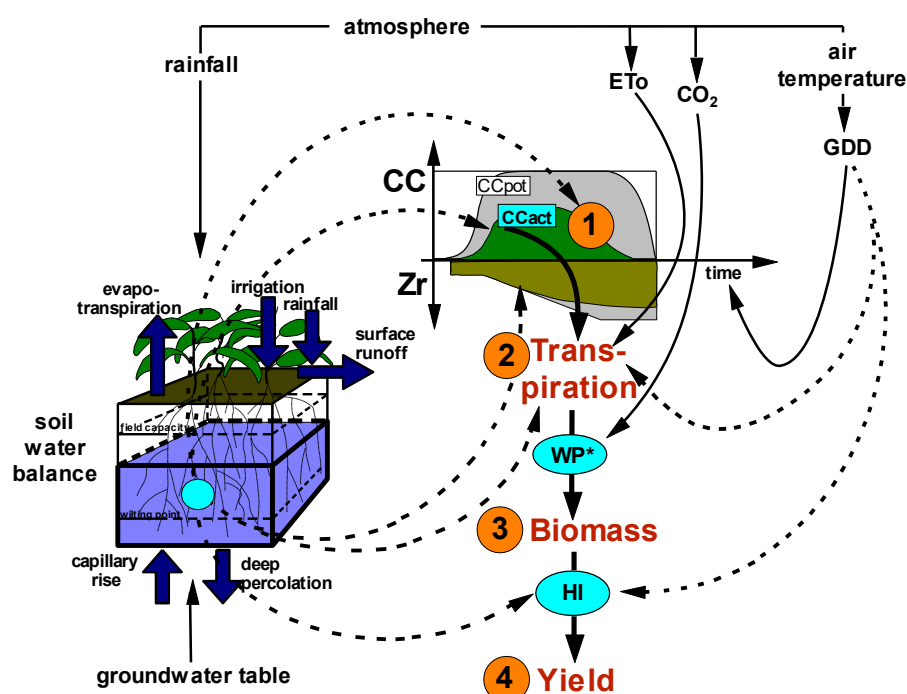




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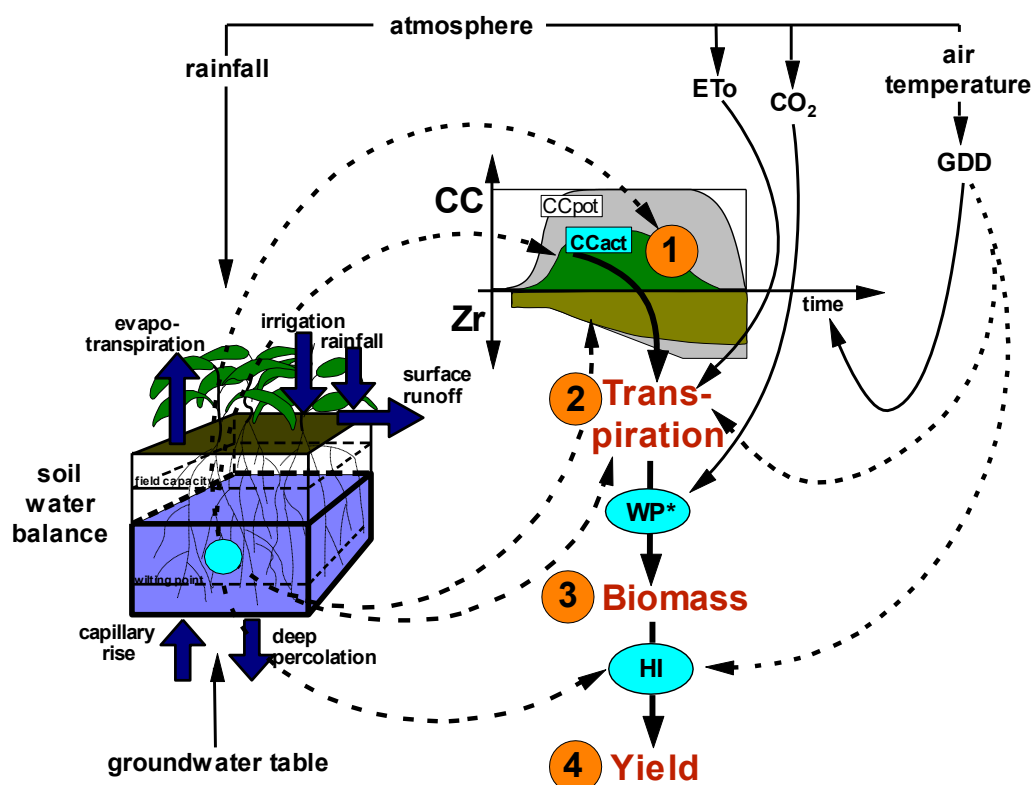
AquaCrop training handbooks



Book I. Understanding AquaCrop

July 2026

AquaCrop training handbooks



Book I Understanding AquaCrop

Food and Agriculture Organization of the United Nations
Rome, 2026

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AquaCrop training handbook I. Understanding AquaCrop July 2026

Prepared by Dirk Raes

The handbook outlines the content of training modules (presented as a set of videos), listed in Annex I.

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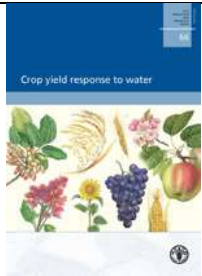
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AquaCrop reference documentation

- ❑ **AquaCrop Software:** After registering as a user, the installation disk and installation guidelines can be downloaded from the FAO website:

Website: <http://www.fao.org/land-water/databases-and-software/aquacrop/en/>

- ❑ **Handbook**

	Steduto, P., Hsiao, T.C., Fereres, E., and Raes, D. 2012. Crop yield response to water. FAO Irrigation and Drainage Paper Nr. 66. Rome, Italy. Download from website: In English: http://www.fao.org/docrep/016/i2800e/i2800e00.htm In Spanish : http://www.fao.org/3/a-i2800s.pdf
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- ❑ **Core reference papers for AquaCrop: 3 Papers in Agronomy Journal**

- Steduto, P., Hsiao, T.C., Raes, D., Fereres, D. 2009. AquaCrop - The FAO Crop Model to Simulate Yield Response to Water: I. Concepts and Underlying Principles. *Agronomy Journal* 101 (3): 426–37. doi:10.2134/agronj2008.0139s.
- Raes, D., Steduto, P., Hsiao, T.E., Fereres, E. 2009. AquaCrop - The FAO Crop Model to Simulate Yield Response to Water: II. Main Algorithms and Software Description. *Agronomy Journal* 101 (3): 438–47. doi:10.2134/agronj2008.0140s.
- Hsiao, T. C., Heng, L., Steduto, P., Rojas-Lara, B., Raes, D., Fereres, E. 2009. AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: III. Parameterization and Testing for Maize. *Agronomy Journal* 101 (3): 448–59. doi:10.2134/agronj2008.0218s.

- ❑ **Reference manual**

Raes, D., Steduto, P., Hsiao, T.C., and Fereres, E. 2026. AquaCrop Reference manual (Version 7.3). <http://www.fao.org/land-water/databases-and-software/aquacrop/en/>

- Chapter 1. AquaCrop – FAO crop-water productivity model to simulate yield response to water
- Chapter 2. Users guide
- Chapter 3. Calculation procedures
- Chapter 4. Calibration guidelines
- Chapter 5. Training videos
- Annex I. Crop parameters
- Annex II. Indicative values for lengths of crop development stages
- Annex III. Indicative values for soil salinity tolerance for some agriculture crops
- Annex IV. ETo calculation procedure

- ❑ **Training videos:** consult AquaCrop webpage for Youtube playlist of videos

- ❑ **Contact e-mail address:** AquaCrop@fao.org

Chapter 1. Introduction



1. Introduction to AquaCrop

Corresponding Training video: Nr. 1 'Introduction to AquaCrop'.

1.1 The AquaCrop model

AquaCrop is a crop simulation model which describes the interactions between the plant and the soil (Fig. 1.1). From the root zone, the plant extracts water and nutrients. Field management (e.g. soil fertility) and irrigation management are considered since it affects the interaction. The described system is linked to the atmosphere through the upper boundary which determines the evaporative demand (ET_o) and supplies CO₂ and energy for crop growth. Water drains from the system to the subsoil and the ground water table through the lower boundary. If the groundwater table is shallow water can move upward to the system by capillary rise.

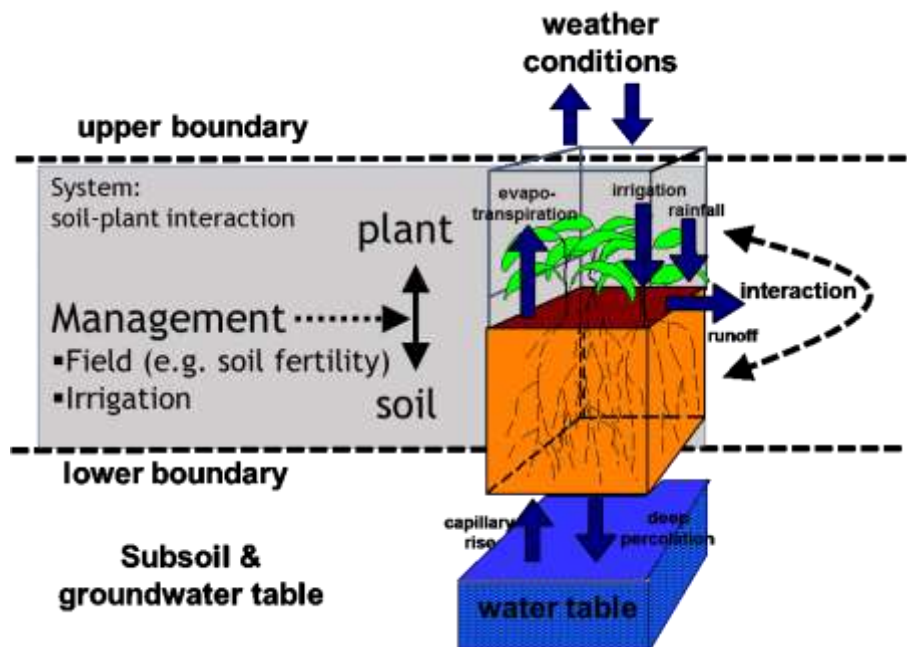


Figure 1.1 – The part of the reality that is described by AquaCrop

FAO developed AquaCrop to address food security and to assess the effect of environment and management on crop production. When designing the model, an optimum balance between simplicity, accuracy and robustness was pursued. To be widely applicable AquaCrop uses only a relatively small number of explicit parameters and mostly-intuitive input-variables that can be determined by simple methods. On the other hand, the calculation procedures is grounded on basic and often complex biophysical processes to guarantee an accurate simulation of the crop response in the plant-soil system.

1.2 Practical applications

AquaCrop can be used as a planning tool or to assist in management decisions for both irrigated and rainfed agriculture. AquaCrop is particularly useful (Fig. 1.2):

- to understand the crop response to environmental changes (educational tool);
- to compare attainable and actual yields in a field, farm, or a region;
- to identify constraints limiting crop production and water productivity (benchmarking tool);
- to estimate net irrigation water requirement and to design irrigation schedules;
- to develop strategies under water deficit conditions to maximise water productivity through;
 - irrigation strategies: e.g. deficit irrigation;
 - crop and management practices: e.g. adjusting planting date, cultivar selection, fertilization management, use of mulches, rain water harvesting;
- to study the effect of climate change on food production, by running AquaCrop with both historical and future weather conditions;
- for planning purposes, by analyzing scenarios useful for water administrators and managers, economists, policy analysts and scientists.

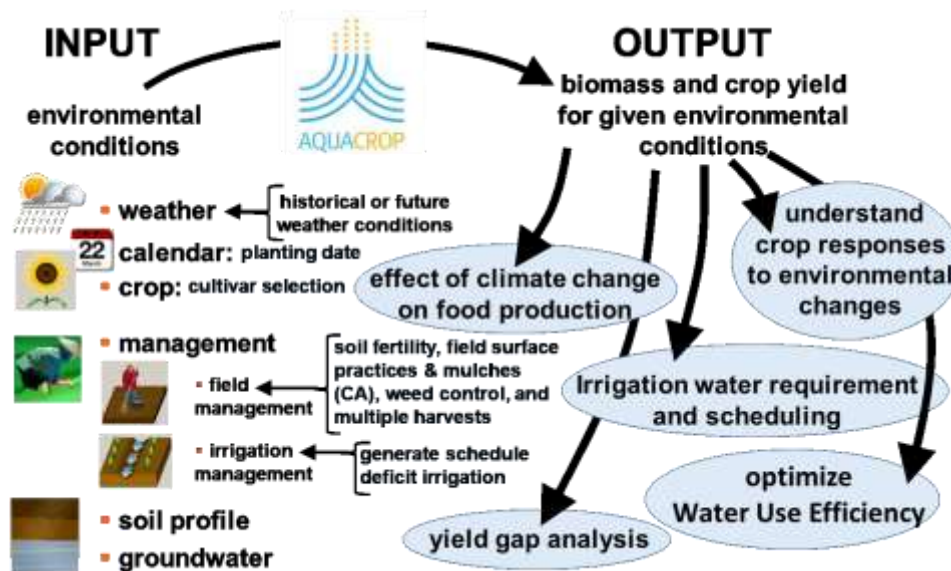


Figure 1.2 – Practical applications

1.3 The calculation scheme of AquaCrop

AquaCrop simulates final crop yield in four steps that are easy to understand, and which makes the modeling approach transparent. The four steps (which run in series at each daily time step) consist in the simulation of:

1. **Development of green canopy cover (CC):** In AquaCrop foliage development is expressed through green canopy cover (CC) and not via Leaf Area Index (LAI). The green canopy cover (CC) is the fraction of the soil surface covered by the canopy. It ranges from zero at sowing (0 % of the soil surface covered by the canopy) to a maximum value at mid-season which can be 1 when a full canopy cover is reached (100 % of the soil surface covered by the canopy). By adjusting daily the soil water content in the soil profile, AquaCrop keeps track of the stresses which might develop in the root zone. Soil water stress might affect the leaf and hence canopy expansion and if severe might trigger early canopy senescence;

2. **Crop transpiration (Tr):** For well-watered conditions, Tr is calculated by multiplying the reference evapotranspiration (E_{To}) with a crop coefficient (K_{cTr}). The crop coefficient is proportional to CC and hence varies throughout the life cycle of the crop in correspondence with the simulated canopy cover. Water stress does not only affect canopy development but might also induce stomata closure and hence affect, also directly, crop transpiration;
3. **Above-ground biomass (B):** The above ground biomass produced is proportional to the cumulative amount of crop transpiration (ΣTr). The proportional factor is the biomass water productivity (WP). In AquaCrop WP is normalized for the effect of the climatic conditions which makes the normalized biomass water productivity (WP^*) valid for diverse locations, seasons, and CO_2 concentrations;
4. **Crop yield (Y):** The simulated above ground biomass (B) integrates all photosynthetic products assimilated by the crop during the season. By using a Harvest Index (HI), which is the fraction of B that is the harvestable product, crop yield (Y) is obtained from B. The actual HI is obtained by adjusting, during simulation, the reference Harvest Index (HI_o) with an adjustment factor for stress effects.

Temperature and water stresses directly affect one or more of the above processes (Fig. 1.3). AquaCrop considers also the effect of weed infestation, soil fertility and soil salinity stress on canopy development crop transpiration and biomass production.

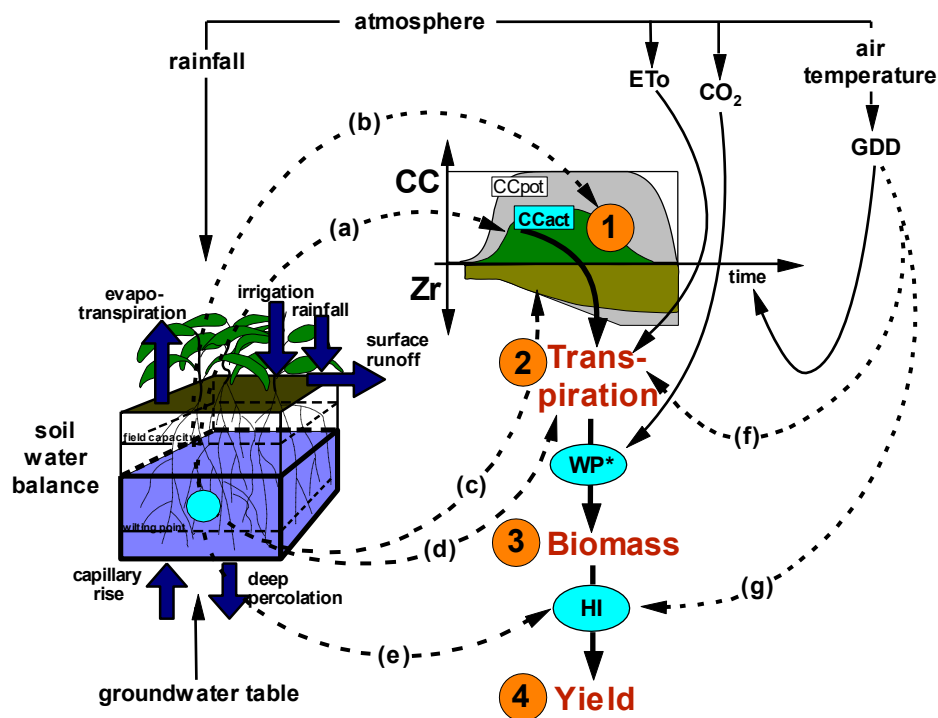


Figure 1.3 – Calculation scheme of AquaCrop with indication of the 4 steps, and the processes (dotted arrows) affected by water stress (a to e) and temperature stress (f to g). CC is green canopy cover; Z_r , rooting depth; E_{To} , reference evapotranspiration; WP^* , normalized biomass water productivity; HI, harvest index; and GDD, growing degree day. Water stress: (a) slows canopy expansion, (b) accelerates canopy senescence, (c) decreases root deepening but only if severe, (d) reduces stomatal opening and transpiration, and (e) affects harvest index. Cold temperature stress (f) reduces crop transpiration. Hot or cold temperature stress (g) inhibits pollination and reduces HI.

1.4 Input requirement

AquaCrop uses a relatively small number of explicit parameters and largely intuitive input variables. Those are either widely available or require just simple methods for their determination. Input consists of weather data, crop and soil characteristics, and management practices that define the environment in which the crop will develop. Soil characteristics are divided into soil profile and groundwater characteristics and Management practices into field management and irrigation management practices (Fig.1.4).

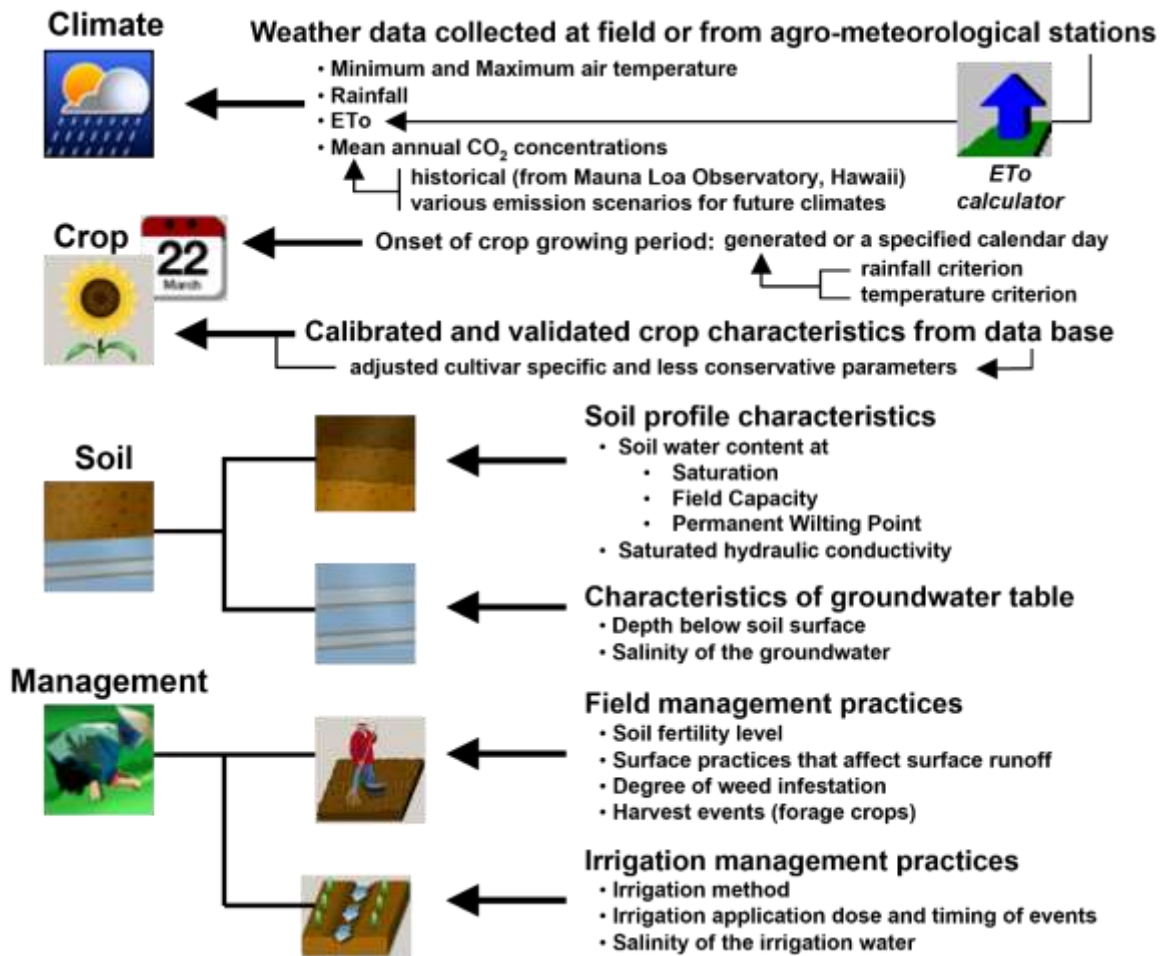


Figure 1.4 – Required input data for AquaCrop

1.5 Limitations

- AquaCrop is designed to predict crop yield at the single field scale (point simulations). The field is assumed to be uniform without spatial differences in crop development, transpiration, soil characteristics, and management;
- Only vertical incoming (rainfall, irrigation and capillary rise) and outgoing (evaporation, transpiration, and deep percolation) water fluxes are considered.

Chapter 2. Climate



2.1 Required weather data to run AquaCrop

Corresponding Training video Nr. 2.1 ‘Required weather data’.

For each day of the simulation period, AquaCrop requires:

- **reference evapotranspiration (ET_o):** ET_o is a measure of evaporative demand of the atmosphere, and determines the rate of the crop transpiration and soil evaporation;
- **minimum (T_n) and maximum (T_x) air temperature:** Temperatures are required (i) to calculate growing degree days which determine crop development and phenology, (ii) for making adjustments in crop transpiration during cold periods, and (iii) for calculating heat and cold stresses affecting pollination;
- **rainfall data:** Rainfall is required to update the soil water balance and to calculate soil water stresses affecting crop growth and production processes.

Input of ET_o, T_x and T_n can be daily, 10-daily or monthly. In the absence of daily data AquaCrop invokes built-in procedures to estimate the required daily data (time step of the simulation) based on the 10-day or monthly means. The larger the time aggregation the less reliable is the model outcome.

Also rainfall input can be daily, 10-daily or monthly. However, the use of 10-daily or monthly rainfall should be avoided since rainfall is extremely heterogeneous distributed over time. The dynamic nature of crop response to water will be lost by using 10-daily or monthly totals.

For the adjustment of crop transpiration and biomass water productivity, AquaCrop requires also the mean annual **atmospheric CO₂ concentration ([CO₂])**. The ‘MaunaLoa.CO2’ file contains observed mean annual [CO₂] for the period 1902 till today. By using other CO₂ files with projected atmospheric composition for the future, one can test the crop response for climate change scenarios.

2.2 Reference evapotranspiration (ET_o)

Corresponding Training video Nr. 2.2 ‘Reference evapotranspiration’.

2.2.1 Concept of reference evapotranspiration (ET_o)

Reference evapotranspiration (ET_o) is the evapotranspiration from a well-defined reference (vegetated) surface for standard conditions. The standard conditions are non-limiting conditions that achieve full production of a reference vegetated surface under the given climatic conditions. The concept of ET_o was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development, management practices and environmental (other than weather conditions) aspects. The only factors affecting ET_o are weather parameters. Consequently, ET_o is a climatic parameter and can be computed from weather data.

2.2.2 FAO Penman-Monteith method

To meet the need for a standardized method to compute ETo from meteorological data, FAO developed the FAO Penman-Monteith method. This method overcomes the shortcoming of the Penman method and the need for local calibration of resistance factors when using the Penman-Monteith equation. FAO worked out the Penman-Monteith equation for one particular evaporating surface: i.e. for a grass reference surface. To avoid difficulties with a living grass reference, a hypothetical grass reference has been selected. The reference surface closely resembles an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water supply.

2.2.3 Evaporating power of the atmosphere

A map of the average total annual ETo (evaporating power of the atmosphere) is presented in Fig. 2.1, in which ETo is computed from mean monthly climatic data for the period 1961 – 1990 with the FAO Penman-Monteith. The mean annual ETo ranges from less than 1 mm/day in the high latitudes of the Northern hemisphere, up to 8 mm/day and more in the desert regions in the sub tropics.

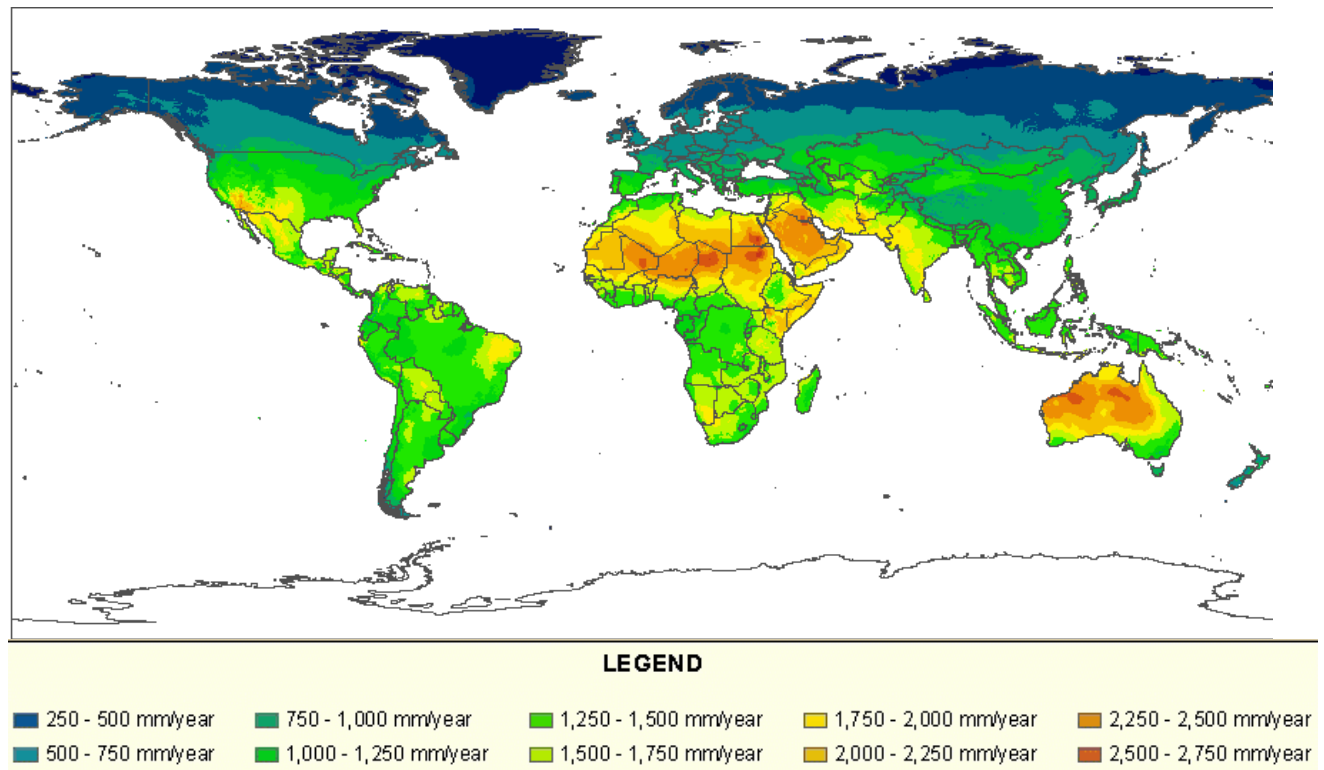


Figure 2.1 – Global map of average annual reference evapotranspiration (ETo)

2.3 Determination of reference evapotranspiration

Corresponding Training video Nr. 2.3 ‘Determination of reference evapotranspiration (ETo)’.

2.3.1 ETo calculator embedded in AquaCrop

An ETo calculator embedded in AquaCrop, is available to calculate reference evapotranspiration (ETo) from meteorological data by means of the FAO Penman-Monteith equation (Allen et al., 1998). The program can handle daily, ten-daily and monthly climatic data. The data can be given in a wide variety of units and climatic parameters.

2.3.2 Required data to calculate ETo

- **Air temperature:** The sensible heat of the surrounding air transfers energy to the crop and exerts as such a controlling influence on the rate of evapotranspiration. The maximum (T_x) and minimum (T_n) air temperature are measured with thermometers, thermistors or thermocouples mounted in a thermometer shelter at 2 meter above the soil surface;
- **Air humidity:** The difference between the saturation (e_s) and actual (e_a) vapour pressure, called the vapour pressure deficit or saturation deficit, is an accurate indicator of the actual evaporative capacity of the air. The higher the air temperature, the higher the storage capacity, and the higher e_s . It is not possible to directly measure e_a . It is commonly derived from dewpoint temperature (T_{dew}) or relative humidity. Where humidity data are lacking or are of questionable quality, an estimate of e_a can be obtained by assuming that T_{dew} is near the daily minimum temperature (T_n):

$$T_{dew} \approx T_n - a$$

with ‘a’ equal to 0°C in humid regions, and 1 to 2 °C in arid regions.

- **Radiation data:** The evapotranspiration process is determined by the amount of energy available to vaporize water. Solar radiation can be measured with pyranometers, radiometers or solarimeters. It can also be estimated from the actual duration of sunshine which is measured with a Campbell-Stokes sunshine recorder. In absence of any measurement, solar radiation (R_s) can be estimated from the air temperature difference ($T_x - T_n$). It requires the maximum (T_x) and minimum (T_n) air temperature, and the extraterrestrial radiation (R_a) for the given location and time of the year:

$$R_s \approx k_{Rs} \sqrt{(T_x - T_n)} R_a$$

Indicative default values for k_{Rs} are 0.16 for interior locations and 0.19 for coastal locations.

- **Wind speed:** The process of vapour removal depends on wind and air turbulence which transfers large quantities of air over the evaporating surface. Wind speed is measured with anemometers at a reference height of 2 m above the surface. Wind speed measured at different heights needs to be converted to the reference height of 2 meter. Where no wind data are available, one of the available general classes of monthly wind speed data, can be selected;
- **Station location:** Latitude (North or South) is required for computation of the extra-terrestrial radiation (R_a) and the maximum hours of bright sunshine (day length). Altitude in meters above sea level is required to compute the psychrometric constant (γ).

2.4 Import climatic data

Corresponding Training video Nr. 2.4 ‘Import climatic data’.

2.4.1 Prepare text file with climatic data

From a spreadsheet containing climatic data (columns) for a number of data records (rows), the numerical values are copied and pasted in a text file, which is stored in the IMPORT directory.

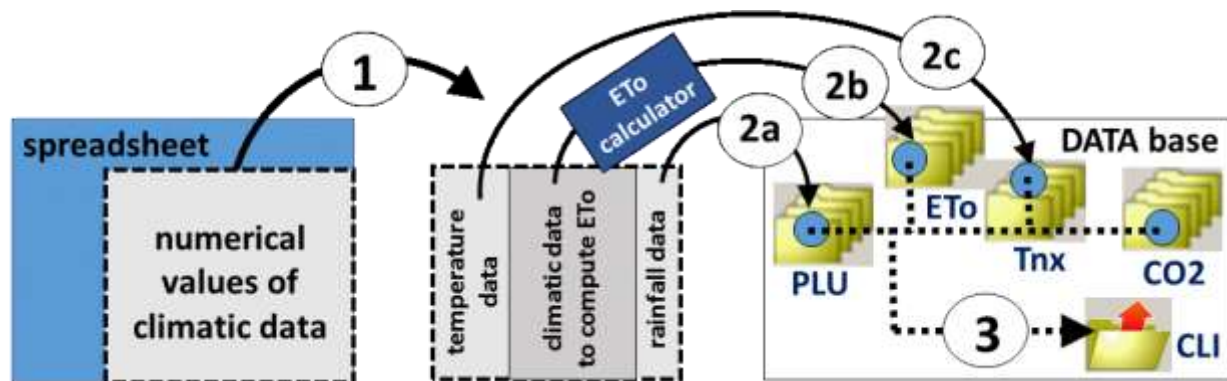


Figure 2.2 – (1) Copy the text file with the numerical values of climatic data in the IMPORT directory of AquaCrop; (2) Import the climatic data in a (a) PLU, (b) ETo, and (c) Tnx file of the DATA base of AquaCrop; and (3) Create the enveloping climate file (CLI)

2.4.2 Import the climatic data from the text file in AquaCrop’s data base

For the text file with climatic data:

1. Specify the type of data (daily, 10-day or monthly) and the time range (from date - to date);
2. Specify the climatic parameter and its unit, for each of the columns of the text file;
3. Run a range check by adjusting the data range assigned by the program for each parameter;
4. Specify the characteristics of the meteorological station for the determination of ETo;
5. Import the climatic data in the data base, by specifying the path (default is the DATA directory of AquaCrop), and the names and descriptions of the PLU, Tnx, and ETo files. Rainfall data are stored in PLU files, and minimum and maximum air temperature in Tnx files. After the computation of ETo, with the help of the ETo calculator, ETo data are stored in ETo files.

2.4.3 Create a climate file

Next to imported PLU, ETo and Tnx files, the data base of AquaCrop also contains CO2 files. For running simulations with historical climatic data, the ‘MaunaLoa.CO2’ file can be selected. For crop yield estimates for future years, CO2 files with estimates from IPCC are available.

To create a climate file, the PLU, ETo and Tnx file containing the climatic data of the meteorological station, and a CO2 file are selected. The enveloping climate file (CLI file) contains only the names of the selected rainfall, ETo, air temperature, and CO₂ file (Fig. 2.2).

Chapter 3. Soil



3.1 Soil water retention and soil water movement

Corresponding Training video Nr. 3.1 'Water retention and movement'.

3.1.1 Soil water balance

□ Soil physical characteristics:

- Soil texture: The relative proportion of the mass of sand, silt and clay fractions defines the textural class of the soil or of a specific soil layer;
- Bulk density of a soil (ρ_b): The bulk density specifies the amount of dry mass a unit volume of soil contains in its natural field condition;
- Total porosity or total pore volume: It is the ratio of the volume of pores to the bulk volume of the soil. It corresponds with the volumetric soil water content at soil saturation (θ_{SAT});
- Gravel fraction (soil particles larger than 2 mm);
- Penetrability of the soil horizon by crop roots.

Indicative values for soil physical and soil water retention characteristics are given in Table 3.1 for the twelve soil textural classes distinguished in AquaCrop.

Table 3.1 – Default soil characteristics for the twelve distinguished soil textural classes.

Soil textural class	Bulk density (ρ_b)	soil water content (θ)			TAW	Ksat
		SAT	FC	PWP		
	Mg/m ³	vol %	vol %	vol %	mm/m	mm/day
Sand	1.71	36	13	6	70	3,000
Loamy sand	1.63	38	16	8	80	2,200
Sandy loam	1.56	41	22	10	120	1,200
Loam	1.42	46	31	15	160	500
Silt loam	1.42	46	33	13	200	575
Silt	1.52	43	33	9	240	500
Sandy clay loam	1.40	47	32	20	120	225
Clay loam	1.32	50	39	23	160	125
Silty clay loam	1.27	52	44	23	210	150
Sandy clay	1.32	50	39	27	120	35
Silty clay	1.21	54	50	32	180	100
Clay	1.19	55	54	39	150	35

For a given soil texture class bulk density and pore space (θ_{SAT}) vary mainly with soil management practices.

A typical Ksat value does not really exist. Even in a single field, it is not uncommon to measure rather important variations for Ksat in space and time as a result of variations in soil structure, bulk density, biological activity and soil management.

□ **Soil water content:**

The soil water content can be expressed on a mass basis (kg of water), a volume basis (m³ of water), or as an equivalent water depth (millimetre of water). Examples are given in Table 3.2.

- The soil water content expressed on a mass basis (kg water per kg dry soil) is called mass water content (θ_m). It is the mass of soil water with reference to the mass of dry soil:

$$\theta_m = \frac{\text{mass soil water}}{\text{mass dry soil}} \quad (\text{Eq. 3.1})$$

- The soil water content expressed on a volume basis (m³ water per m³ soil volume) is called volumetric water content (θ). It is the volume of soil water with reference to the bulk volume of the soil:

$$\theta = \frac{\text{volume soil water}}{\text{bulk volume soil}} = \frac{\rho_b}{\rho_{\text{water}}} \theta_m \quad (\text{Eq. 3.2})$$

- The equivalent depth of liquid water (mm of water per meter of soil depth) expresses the soil water content in millimetre of water per meter of soil depth:

$$\text{Equivalent depth} = 1000 \theta \quad (\text{Eq. 3.3})$$

In water balance studies it is common to express the amount of water retained in the root zone (W_r) as an equivalent depth of soil water (mm of water). By multiplying the average soil water content in the root zone expressed as an equivalent depth per unit soil depth (1000 θ), by the thickness (Z_r in meter) of the root zone, W_r is obtained:

$$W_r = 1000 \theta Z_r \quad (\text{Eq. 3.4})$$

It is the thickness of the water layer that will be obtained by extracting all the water out of the root zone and distributing it uniformly over the entire soil surface.

Table 3.2 – Calculation of soil water retained in the root zone

How much water (W_r) is retained in the root zone with an effective depth of 0.7 m (Z_r). The soil has a bulk density of 1.3 Mg/m³. The mass of a representative soil sample (not including any tare mass) before and after drying is 254 g and 200 g respectively.

- The mass water content (θ_m) of the sample (Eq. 3.1) is $((254-200)/200 =) 0.27$ g/g. Or 27 % of the dry mass of the collected soil sample is associated with water;
- The volumetric water content (θ) of the sample (Eq. 3.2) is $((1.3/1.0) \times 0.27 =) 0.35$ m³/m³. This means that 35 % of the volume of the sample in its natural state was water;
- The soil water content of the sample expressed as an equivalent depth (Eq. 3.3) is $(1000 \times 0.35 =) 350$ mm (water) per meter soil depth.
- The amount of water W_r retained in the root zone (Eq. 3.4) is $(1000 \times 0.35 \times 0.7 =) 245$ mm.

□ **Soil water retention:**

- **Field Capacity (FC):** Water is stored in the soil between soil aggregates in pore spaces. When the soil is saturated, the water is not strongly retained and will drain downward due to gravitation. Field capacity is reached when the forces that retain water in the soil are in equilibrium with the gravitational forces that pull water downward. Field capacity is an important concept when calculating soil water balances as it determines the amount of water that the root zone retains when the soil has drained after being thoroughly wetted by rainfall or irrigation;

- **Permanent wilting point (PWP):** As more water is removed out of the root zone, the remaining water is stronger retained by the soil matrix and more difficult to extract by the plant roots. Permanent wilting point (PWP) is reached when the soil is so dry that roots are no longer able to extract any water;
- **Total Amount of Water (TAW):** Since field capacity and permanent wilting point are respectively the upper and lower limits of the plant extractable water, they determine the Total Amount of Water (TAW) that can be utilized by the crop. Indicative values for TAW and the soil water content at FC and PWP for various soil textural classes are presented in Table 3.1. Although the presence of gravel in a soil layer does not affect Field Capacity or Permanent Wilting Point, it will lower the value for TAW (by the volume percentage of the gravel fraction).

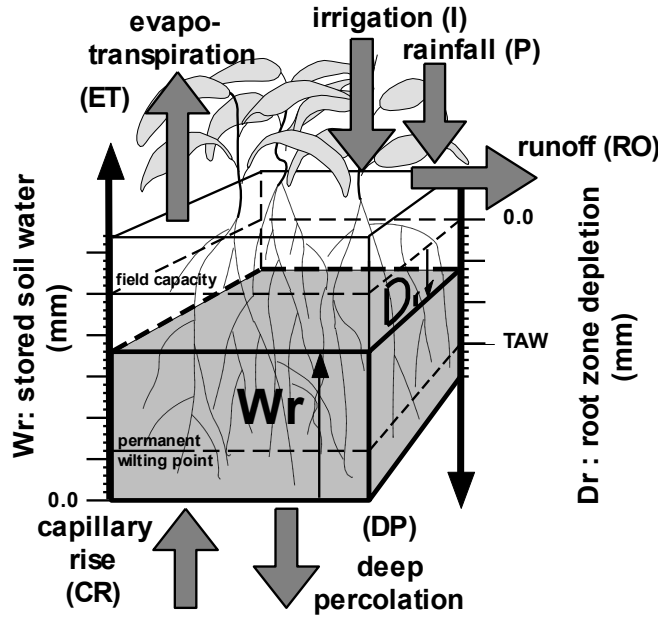


Figure 3.1 – The root zone depicted as a reservoir

□ Calculation of the soil water balance:

To keep track of the soil water content in the root zone (W_r) and the corresponding soil water stress, AquaCrop updates the soil water balance at each daily time step. In soil water balance studies the root zone is often depicted as a reservoir (Fig. 3.1). The change of W_r is monitored by keeping track of the incoming and outgoing water fluxes at its boundaries. Water is added to the soil by rainfall (P) and irrigation (I). Part of P might be lost by surface runoff (RO). Water can also be transported to the root zone by capillary rise (CR) from a shallow groundwater table. Processes such as soil evaporation (E), crop transpiration (Tr), and deep percolation losses (DP) remove water from the soil reservoir:

$$W_{r,t+1} = W_{r,t} + (P - RO) + I + CR - E - Tr - DP \quad (\text{Eq. 3.5})$$

where $W_{r,t}$ and $W_{r,t+1}$ are the water contents in the root zone at time t , and $t+1$. Deep percolation losses (DP) will occur, if after significant rainfall or excessive irrigation, W_r exceeds Field Capacity (i.e. the amount of water that can be retained in the root zone: $W_{r,FC} = 1000 \theta_{FC} Z_r$):

$$DP = W_{r,FC} - W_r \quad (\text{Eq. 3.6})$$

Root zone depletion (Dr) expresses the amount of soil water retained in the root zone as a shortage versus field capacity (Fig. 3.1). Field capacity is selected as the reference ($Dr = 0$) since it expresses the amount of water that remains in a thoroughly wetted root zone after it has drained:

$$Dr = W_{r,FC} - W_r \quad (\text{Eq. 3.7})$$

Table 3.3 – Calculation of the soil water balance and root zone depletion

Given the amount of water retained in the root zone (W_{r1}) of 245 mm, and a mean crop evapotranspiration during a 5-day period of 3 mm/day. The amount of water retained in the root zone after 5-days (Eq. 3.5) will be $W_{r+5} = (245 - 5 \times 3) = 230$ mm.

Given the volumetric soil water content at field capacity (θ_{FC}) of $0.39 \text{ m}^3/\text{m}^3$, the thickness of the root zone (Z_r) of 0.7m, and the soil water content in the root zone (W_r) of 230 mm. The soil water retained in the root zone at FC (Eq. 3.4) is $W_{r,FC} = (1000 \times 0.39 \times 0.7) = 273$ mm, and the root zone depletion (Eq. 3.7) is $Dr = (273 - 230) = 43$ mm. This means that a net irrigation depth of 43 mm is required to bring the root zone back to field capacity.

3.1.2 Soil water movement

□ **Drainage** AquaCrop makes use of a drainage function (i) to simulate the drainage inside and the percolation out of a soil layer, and (ii) to simulate the infiltration of rainfall and/or irrigation. The drainage function requires a drainage characteristic, τ (tau), which is proportional to the saturated hydraulic conductivity (K_{sat}) of the soil layer. The drainage characteristic (tau) expresses the decline in soil water content of a soil layer, originally at saturation, at the end of the first day of free drainage (Fig. 3.2). The decline is expressed as a fraction of the total drainable amount of water, which is the water content between saturation and field capacity.

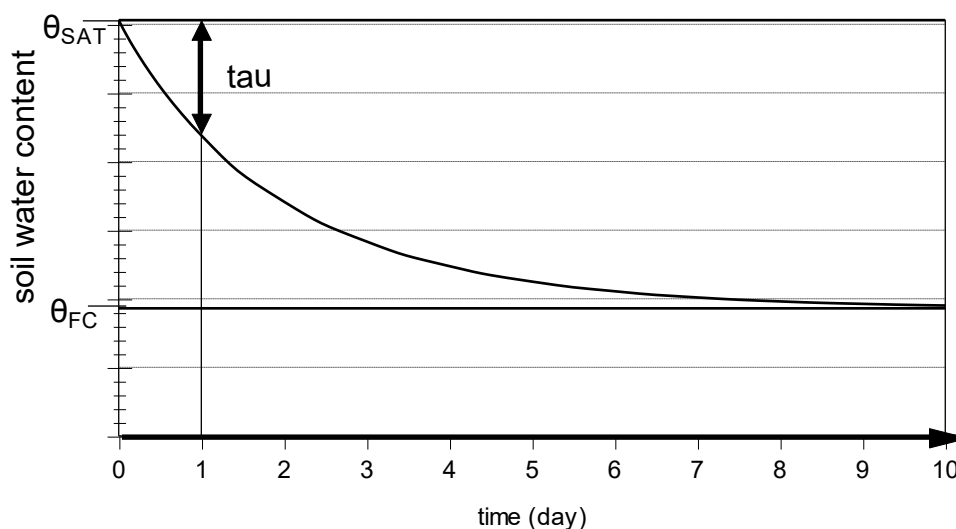


Figure 3.2 – Drainage function describing the decline in soil water content between saturation (θ_{SAT}) and field capacity (θ_{FC}) for a tau of 0.4.

□ **Capillary rise (CR) from a shallow groundwater table:** In AquaCrop the potential CR is computed by considering the soil class and saturated hydraulic conductivity (K_{sat}) of the soil layers through which the water moves upward. To compute the real magnitude of CR, AquaCrop considers the soil water content at the bottom of the root zone, since this determines the driving force (Fig. 3.3);

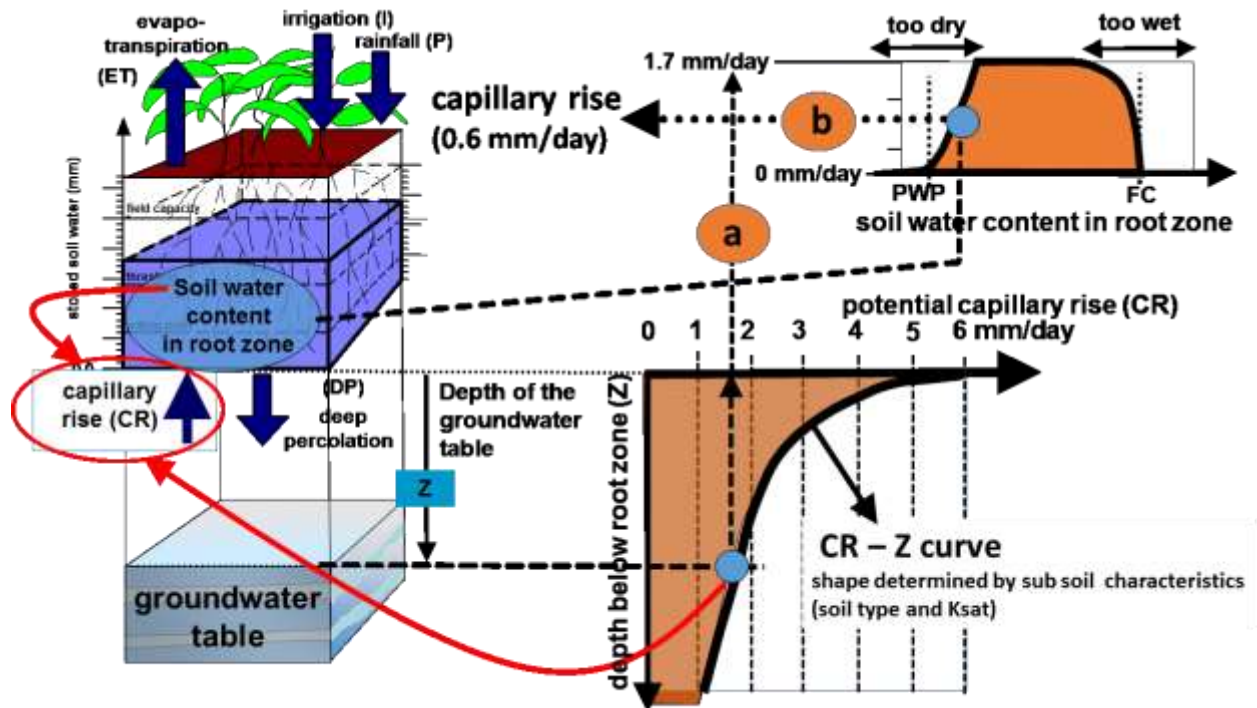


Figure 3.3 – (a) By considering the depth of the groundwater table, the potential capillary rise is obtained from the CR – Z curve, which shape is determined by the characteristics of the subsoil. (b) By considering the soil water content at the bottom of the root zone, the real magnitude of the capillary rise is obtained.

□ **Surface runoff (RO):** The amount of water lost by RO is determined by the Curve Number method which requires a Curve Number (CN) for its simulation:

- The default CN value, which is a soil profile characteristic, is derived from the K_{sat} of the top horizon. At run time, CN will be adjusted to the soil water content of the top soil (Fig. 3.4);
- The CN value will have to be adjusted to the slope, contouring, terracing, type of planting, soil cover and practices affecting infiltration. These are considered as field management characteristics, and quantified when specifying the management (Chapter 5);
- AquaCrop will not simulate surface runoff when water is applied by irrigation since it can be assumed that irrigation is fully controlled by the farmer. Moreover, irrigation events are specified by their net irrigation amount, and water lost by surface runoff should not have been added.

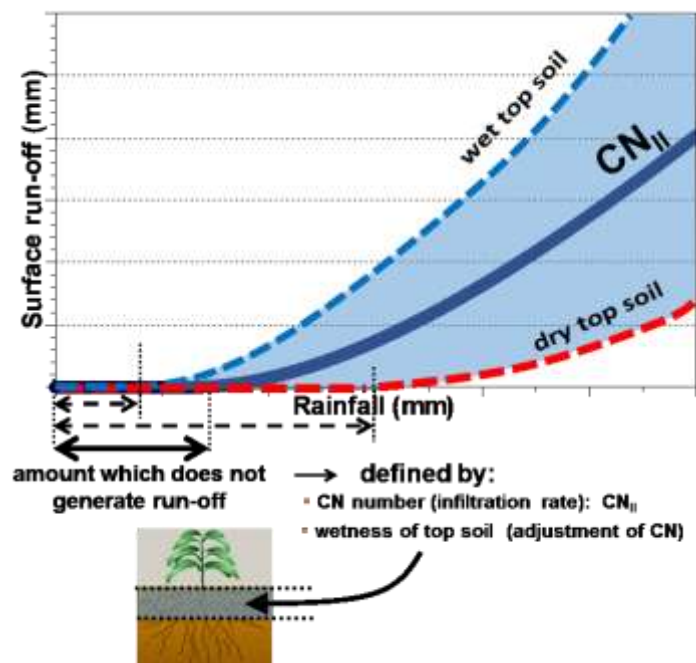


Figure 3.4 – The surface runoff – rainfall relationship, for various wetness of the top soil.

3.2 Soil profile characteristics

Corresponding Training video Nr. 3.2 ‘Soil profile characteristics’.

The soil profile characteristics consist of soil physical parameters required to simulate the retention of water in the root zone and soil water movement. In AquaCrop the soil profile can be composed of up to five different horizons, each with their own physical characteristics. The required soil data for a layered soil profile consist of the volumetric water content at saturation (SAT), field capacity (FC), and permanent wilting point (PWP), the hydraulic conductivity at soil saturation (Ksat), the mass percentage of gravel (if present) and the percentage of root penetrability (if restrictive) for each of the different soil horizons. From the specified data, AquaCrop determines (Fig. 3.5):

- TAW: the total available soil water for the soil water balance calculations;
- REW: the Readily Evaporable Water for the simulation of soil evaporation;
- Soil textural class: for the determination of the capillary rise;
- The capillary rise function (CR_{max}) by considering Ksat and the soil textural class;
- The drainage characteristic (τ) by considering Ksat;
- The default curve number (CN) by considering Ksat.

In the absence of locally measured soil characteristics, the user can make use of indicative values provided by AquaCrop for various soil textural classes (Table 3.1), or indicative values derived with the help of pedo-transfer functions (Tab. 3.4).

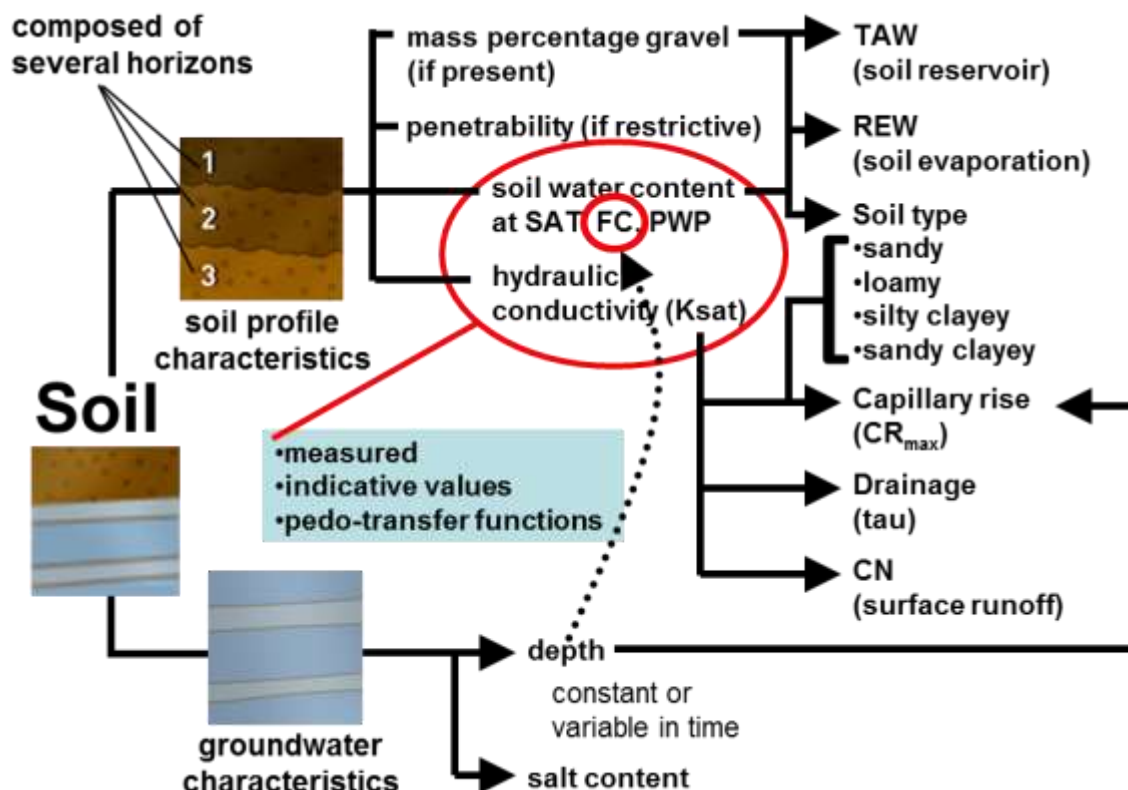


Figure 3.5 – Soil physical and groundwater table characteristics

Table 3.4 – Hydraulic Properties Calculator incorporated in AquaCrop

Soil texture triangle diagram showing the relationship between Sand % Wt, Clay % Wt, and Silt % Wt. The diagram is divided into regions for different soil types: C (Clay), L (Loam), Sa (Sand), Si (Silt), and combinations like SaL, SaCL, SaLC, CL, SiL, SiCL, SiLC.	Calculator developed by the USDA Agricultural Research Service in cooperation with the Washington State University (Keith E. Saxton) incorporated in AquaCrop. From the hydraulic properties calculator, good indicative values for the soil physical characteristics required by AquaCrop can be derived from soil texture, organic matter, and soil compaction (θ_{SAT}, θ_{FC}, θ_{PWP} and K_{sat}).
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3.3 Depth and quality of the groundwater table

Corresponding Training video Nr. 3.3 ‘Depth and quality of the groundwater table’.

The required characteristics for the groundwater table, consist of its depth in meter below the soil surface and of its salinity, expressed in deci Siemens per meter (dS/m). They can be constant or variable in time.

Chapter 4. Crop



4.1 Crop parameters

Corresponding Training video Nr. 4.1 Crop parameters

4.1.1 Type of crop parameters

The data base of AquaCrop contains crop files in which the calibrated and fully validated crop parameters are stored. A distinction is made between:

- **Conservative crop parameters** which do not change substantially with time, management practices, geographic location or climate. They are also assumed not to change with cultivars unless shown otherwise. Examples are the thresholds for stresses and the normalized biomass water productivity (WP*);
- **Cultivar specific and non- conservative parameters** which might require an adjustment when selecting a cultivar or environmental conditions different than the ones assumed at calibration. Examples are the length of the growing cycle and plant density.

4.1.2 Tuning of crop parameters

When running a simulation for a specific cultivar and in a specific environment (as described by the selected climate, crop, field management conditions) the conservative crop parameters do not require adjustment. The cultivar specific and non- conservative crop parameters might require an adjustment since they vary with the selected cultivar and might be affected by field management, conditions in the soil profile, or the climate (Fig. 4.1). Following parameters might need tuning:

☐ Parameters affected by planting and management:

- Planting method (direct sowing or transplanting);
- Plant density, which will determine the initial (CC_0) and maximum (CC_x) canopy cover; and
- Time to reach 90% seedling emergence (affected by field preparation and soil temperature).

☐ Cultivar specific crop parameters (phenology):

- Time to reach maximum canopy cover (CC_x);
- Time to beginning of canopy senescence;
- Time to physiological maturity;
- Time to start of flowering (or the start of yield formation); and
- Duration of flowering.

☐ Parameters affected by conditions in the soil profile:

- The maximum effective rooting depth (Z_x); and
- The roots deepening rate (or the time to reach Z_x)

which are affected by soil **physical** characteristics (temperature, mechanical impedance, aeration) and soil **chemical** characteristics (pH, salinity, high levels of aluminum or manganese).

☐ **Calibration of crop response to soil fertility:** see 5.3 ‘Calibration for soil fertility’.

☐ **Calibration of crop response to soil salinity:** see 6.3 ‘Soil salinity’.

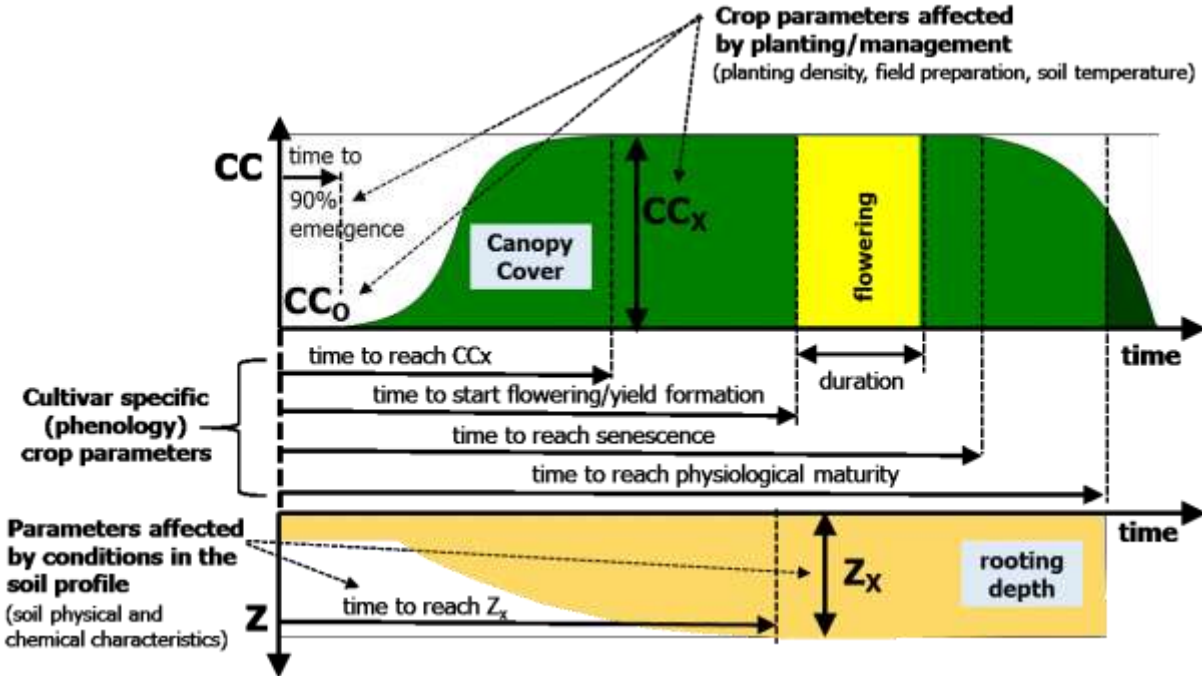


Figure 4.1 – Crop parameters to be tuned to the selected cultivar and the environmental conditions

4.1.3 Crop development adjustment to temperature regime

□ Growing degree days:

The development of the green canopy cover and the deepening of the root system is simulated as a function of time in AquaCrop. The user has the option to simulate crop development in calendar days or growing degree days (GDD).

The heat units ($^{\circ}\text{C}$) accumulated during a day (which are the GDD expressed in $^{\circ}\text{C}$ day), are calculated by subtracting the base temperature from the average air temperature (T_{avg}):

$$0 \leq GDD = T_{\text{avg}} - T_{\text{base}} \quad (\text{Eq. 4.1})$$

The base temperature (T_{base}), which is crop specific conservative parameter, is the temperature below which crop development does not progress. If the average air temperature is below T_{base} no heat units can be accumulated during that day and GDD is zero (Fig. 4.2).

□ Converting calendar into thermal time:

When tuning crop parameters, the time to reach a particular stage is usually expressed in calendar days. By converting the calendar time into thermal time, the length and duration of the crop development stages will be adjusted to the temperature regimes of the distinctive years.

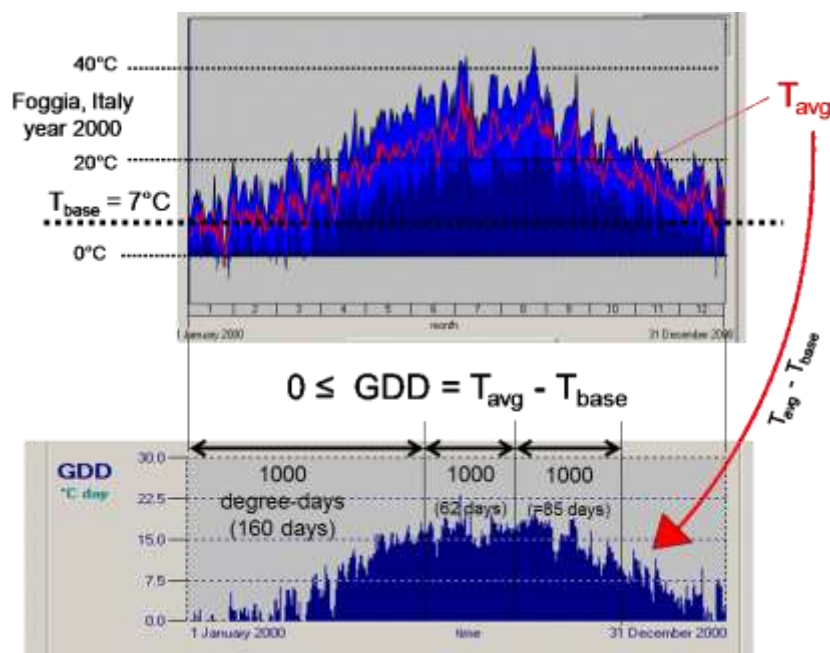


Figure 4.2 – Calculation of GDD for Foggia (Italy) with a base temperature of 7 °C.

4.2 Stress coefficients (Ks)

Corresponding Training video Nr. 4.2 ‘Stress coefficients’.

The effect of any kind of environmental stress on the crop development and production is simulated in AquaCrop by stress coefficients (Ks). In essence, Ks is a modifier of its target model parameter, and vary in value from one (no stress) to zero (full stress) as function of a stress indicator (Fig. 4.3)

Stress indicators:

- **Water shortage stress:** The stress indicator is the relative root zone depletion ($Dr_{relative}$), and varies between zero at field capacity (0% depletion) and one (100% depletion) at permanent wilting point (PWP);
- **Water logging stress:** The stress indicator is the degree of excess water, defined as the amount of water between soil saturation and the anaerobic point, at which deficient aeration conditions start to occur in the root zone;
- **Air temperature stress:** The stress indicators are growing degree days, GDD, (for inhibition of crop transpiration at low temperatures), or the daily minimum (T_n) and maximum (T_x) air temperature (for inhibition of pollination by extreme cold and heat respectively);
- **Soil salinity stress:** The stress indicator is the average electrical conductivity of saturation soil-paste extract (ECe) from the root zone.

Thresholds and shape of the Ks curve: The relation between the stress indicator and Ks is defined by 3 conservative crop parameters: (i) an upper and (ii) lower threshold of the stress indicator and (iii) a curve shape. Above the upper threshold, stress is non-existent and Ks is one. At and below the lower threshold, the stress effect is maximum and Ks is zero. The shape of the

Ks curve between the two thresholds can be linear or convex. Thresholds are crop specific and considered as a non-conservative parameter.

Simulation:

The Ks coefficients, which modify the rate of all kind of processes, are adjusted daily at the end of each time step, by checking how far the values of the stress indicators ($D_{r_{relative}}$, T_n , T_x , GDD, and ECe) are below or above their thresholds on that day.

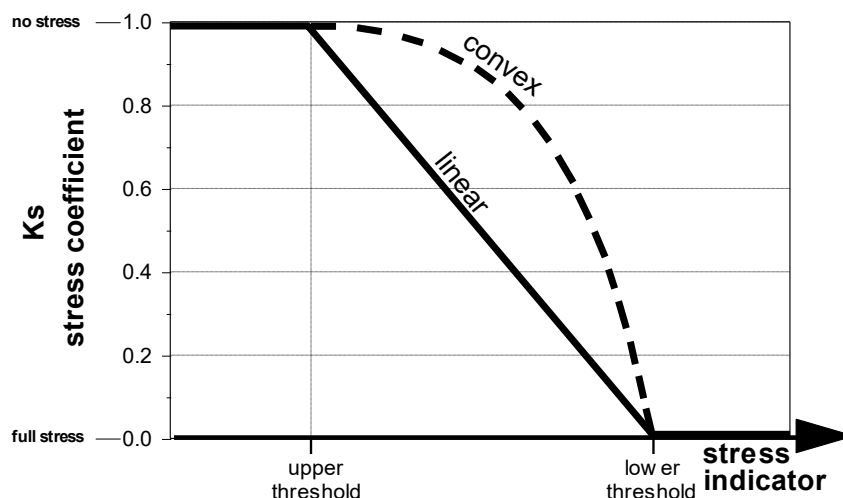


Figure 4.3 – Stress coefficient (Ks)

4.3 Crop development (Step 1)

Corresponding Training video Nr. 4.3 ‘Crop development’.

4.3.1 Green canopy cover (CC)

In AquaCrop, foliage development is expressed through green canopy cover (CC) and not via Leaf Area Index (LAI). The green canopy cover (CC) is the fraction of the soil surface covered by the canopy:

$$CC = \frac{\text{soil surface covered by the green canopy}}{\text{unit ground surface area}} \quad (\text{Eq. 4.2})$$

CC ranges from zero at sowing (0 % of the soil surface covered by the canopy) to a maximum value at mid-season which can be 1 when a full canopy cover is reached and 100 % of the soil surface is covered by the canopy. The shadow on the soil surface of the canopy cover when the sun is right overhead is the canopy cover.

4.3.2 Canopy development

The canopy cover at germination (CC_0) is very small (generally around 1%). During the expansion stage, CC increases. This is described by means of a Canopy Growth Coefficient (CGC). The maximum canopy cover (CC_x) that will be reached at mid-season, varies with crop type and planting density (generally around 75 % up to 100 %). In the late season, the green canopy cover declines due to senescence. This is described by a Canopy Decline Coefficient (CDC). The canopy development for non-limiting conditions is given in Fig. 4.4.

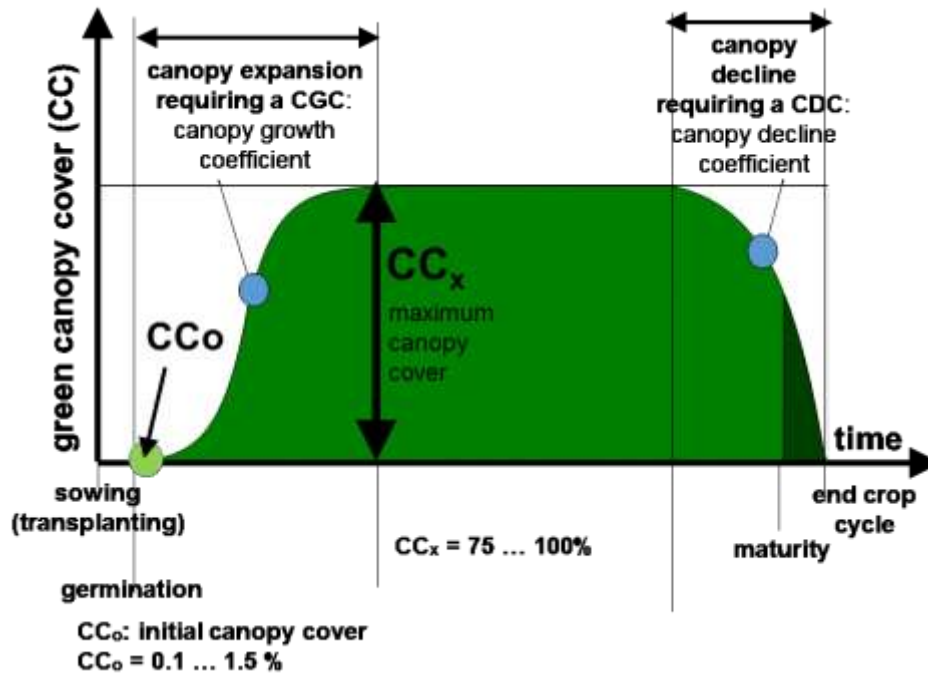


Figure 4.4 – Canopy development for non-limiting conditions

When running a simulation the canopy development might be quite different from the development under non-limiting conditions. Water stress might affect leaf expansion and even result in early canopy senescence. The effect of water stress on CC is described by two water stress coefficients (K_s). There is a K_s for leaf expansion ($K_{s_{exp,w}}$) with CGC as target crop parameter, and a K_s for early canopy decline ($K_{s_{sen}}$) with CDC as target crop parameter. When the water content in the root zone (W_r) drops below the threshold for leaf expansion, $K_{s_{exp,w}}$ becomes smaller than 1 and canopy expansion declines. When the water content in the root zone drops below the threshold for early canopy decline, $K_{s_{sen}}$ becomes smaller than 1 and canopy decline is triggered (Fig 4.5).

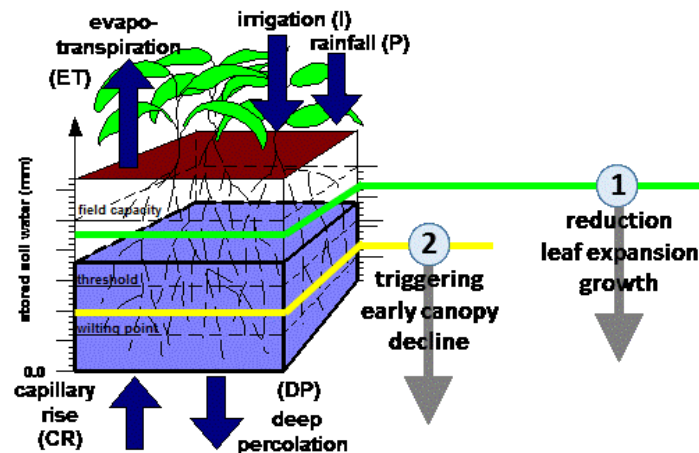


Figure 4.5 – Thresholds for (1) leaf expansion growth and (2) early canopy decline

In Fig. 4.6, the canopy development is plotted for conditions where water stress affected leaf expansion and resulted in early canopy senescence. About 1 month after sowing, soil water stress started to limit canopy development. Due to the absence of any rainfall, the canopy expansion was completely halted, and around 50 DAS early senescence was triggered. The rate of green canopy decline increased gradually and reached its maximum when the root zone depletion reached permanent wilting point. The severe water stress strongly reduced the length of the crop cycle.

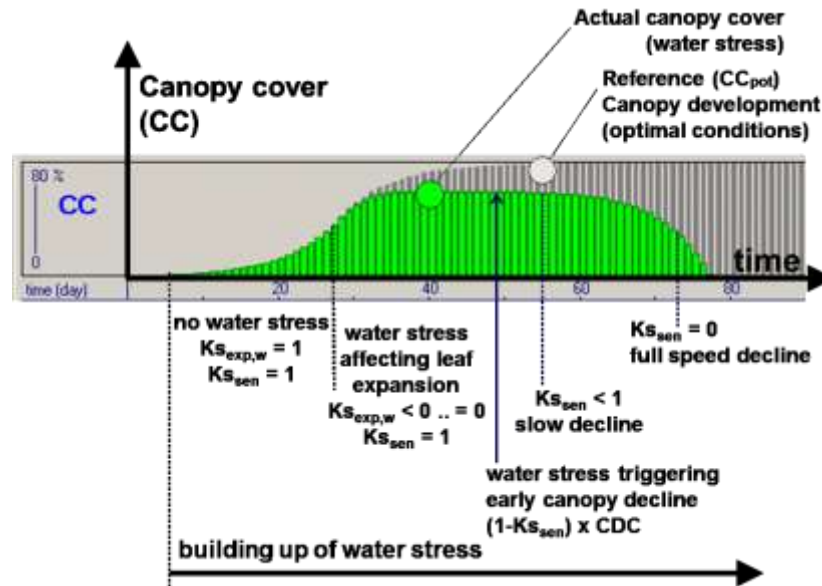


Figure 4.6 – Canopy development affected by water stress

In Figure 4.7 an overview is given of all factors affecting the simulation of the green canopy cover development. The effect of soil salinity and fertility stress on canopy development is discussed in sections 5.2 (Field management), 5.3 (Calibration for soil fertility) and 6.3 (Soil salinity).

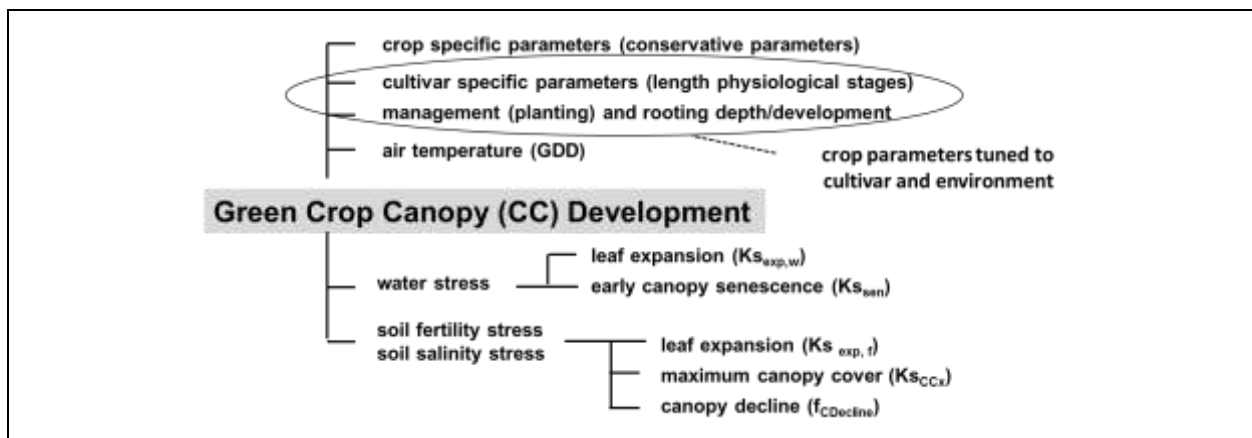


Figure 4.7 – Overview of factors affecting the simulation of the green crop canopy (CC) development

4.3.3 Expansion of the root zone

At sowing/planting the effective rooting depth is at its minimum (Z_n). In a well-watered soil the root zone will expand till the maximum effective rooting depth (Z_x) is reached (Fig 4.8). The root zone expansion curve describes the rate of root deepening ($\Delta Z/\Delta t$).

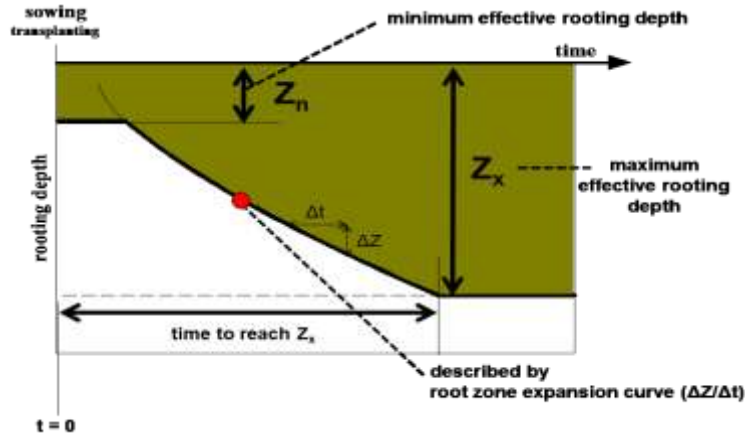


Figure 4.8 – Expansion of the root zone in a well-watered soil

Conditions affecting root deepening:

- When the root zone depletion exceeds the threshold for stomatal closure the incremental daily root deepening $\Delta Z/\Delta t$ under optimal conditions is adjusted by multiplying the expansion rate with the water stress coefficient for stomatal closure ($K_{s_{sto}}$). The water stress alters the shoot/root ratio, since water stress affecting canopy expansion occurs earlier than water stress affecting stomatal closure (which affects the expansion of the root zone);
- If the sub-soil at the front of root zone expansion is too dry, the root deepening will slow down and can even stop if the soil water content at the front is at permanent wilting point;
- Root deepening is slow in soil layers with low penetrability (expressed as a percentage between 100 and 0 %). Below the restrictive layer, the root zone expansion is normal again.

4.4 Crop transpiration (Step 2)

Corresponding Training video Nr. 4.4 ‘Crop transpiration’.

Crop transpiration is calculated by multiplying the reference evapotranspiration (ET_o) with the crop transpiration coefficient ($K_{c_{Tr}}$) and by considering a water stress (K_s) and cold stress ($K_{s_{Tr}}$) coefficient, which are 1 when stress does not induce stomatal closure:

$$Tr = (K_s K_{s_{Tr}}) K_{c_{Tr}} ET_o \quad (\text{Eq. 4.3})$$

The crop transpiration coefficient ($K_{c_{Tr}}$) is proportional to the green canopy cover (CC):

$$K_{c_{Tr}} = K_{c_{Tr,x}} CC^* \quad (\text{Eq. 4.4})$$

where $K_{c_{Tr,x}}$ is the crop coefficient for maximum crop transpiration (determined by the characteristics that distinguish the crop with a complete canopy cover from the reference grass), and CC^* the canopy cover adjusted for micro-advective effects. For most crops $K_{c_{Tr,x}}$ is in the range of 1.05 up to 1.20. $K_{c_{Tr,x}}$ is adjusted downwards for ageing throughout the crop cycle and severely once senescence is triggered.

The effect of water stress on crop transpiration is simulated by means of a water stress coefficient (K_s) with $K_{c_{Tr,x}}$ as target crop parameter. If the stress is due to a shortage of water a soil water stress coefficient for stomatal closure ($K_{s_{sto}}$) is considered. If the stress is due to an excess of water, a soil water stress coefficient for water logging or deficient aeration ($K_{s_{aer}}$) is considered. When the water content in the root zone drops below the threshold for $K_{s_{sto}}$, or is above the threshold for $K_{s_{aer}}$, the stress coefficient becomes smaller than 1 and crop transpiration declines (Fig 4.9a).

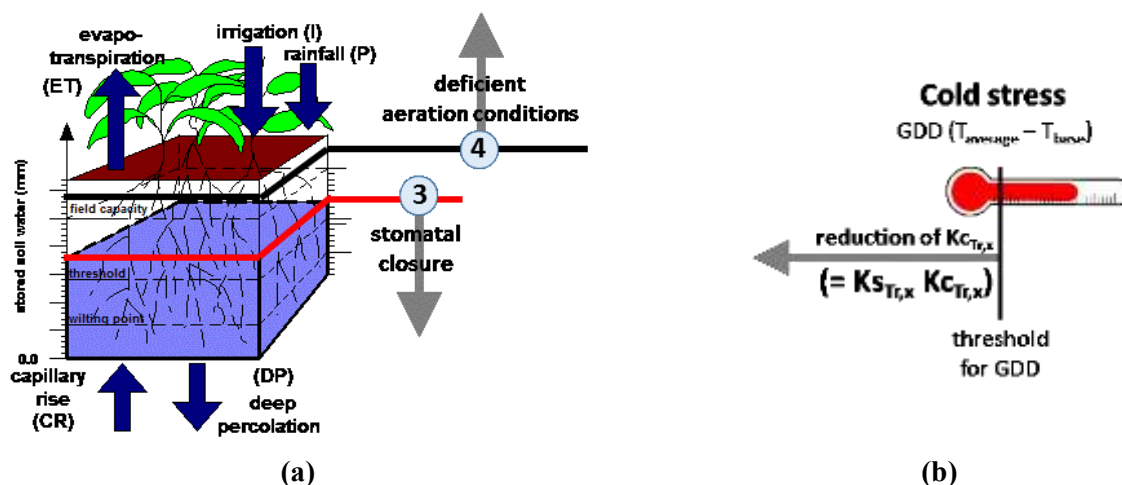


Figure 4.9 – (a) Thresholds for (3) stomatal closure and (4) deficient aeration conditions affecting crop transpiration, and (b) the effect of cold stress on transpiration

To simulate the effect of cold stress, a temperature stress coefficient for crop transpiration ($K_{s_{Tr}}$) is considered. Its target model parameter is $K_{c_{Tr,x}}$. The growing degree days (GDD) which can be generated in a day is used as the stress indicator to describe cold stress on crop transpiration.

Figure 4.10 gives an overview of all factors affecting simulation of crop transpiration. Crop canopy (CC) development was discussed above in section 4.3 and the effect of soil salinity stress will be discussed below in section 6.3 (Soil salinity).

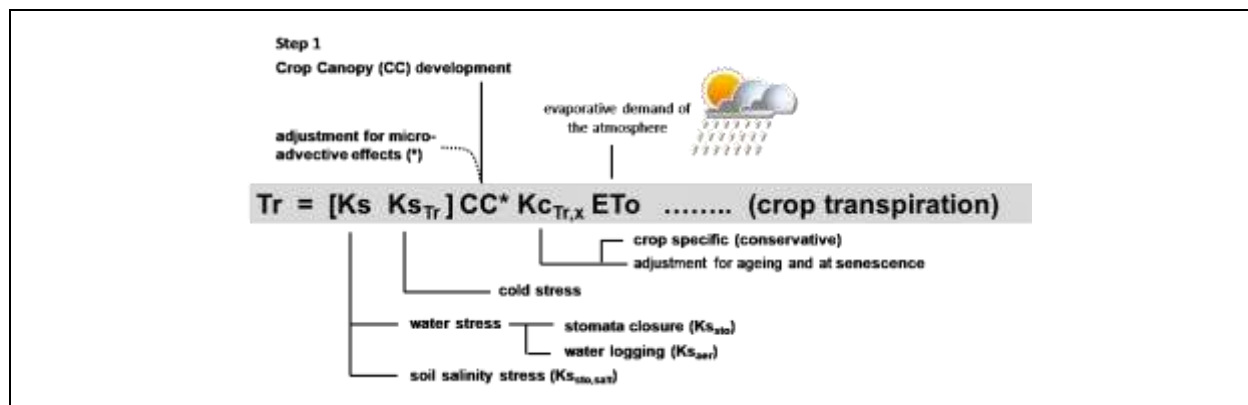


Figure 4.10 – Factors affecting the simulation of crop transpiration

4.5 Biomass production (Step 3)

Corresponding Training video Nr. 4.5 “Biomass production”

By separating ET into crop transpiration (Tr) and soil evaporation (E), AquaCrop avoids the confounding effect of the nonproductive consumption of water (E). The conceptual equation at the core of the AquaCrop, states that biomass production (B) is proportional to the cumulative amount of water transpired (ΣTr):

$$B = WP^* \Sigma \left(\frac{Tr_i}{ET_{o_i}} \right) \quad (\text{Eq. 4.5})$$

where WP^* is the biomass water productivity normalized for climate (Fig. 4.11). The goal of the normalization is to make the biomass water productivity (WP) applicable to diverse locations, seasons and CO_2 concentrations. The normalization for climate (location, season) is obtained by dividing the daily amount of water transpired (Tr) with the reference evapotranspiration (ET_o) for that day. The normalization for CO_2 consists in considering the water productivity for a reference atmospheric CO_2 concentration of 369.41 ppm (the atmospheric CO_2 concentration for the year 2000).

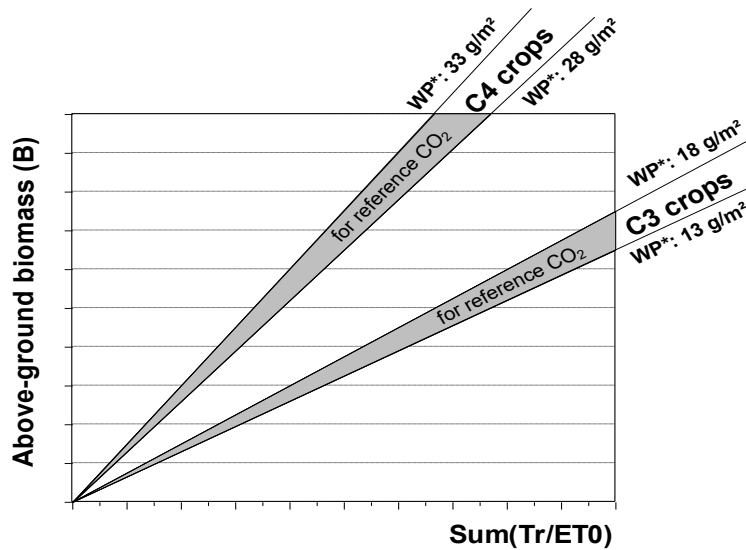


Figure 4.11 – The relationship between the above-ground biomass production and the total amount of water transpired for C3 and C4 crops after normalization for $[CO_2]$ and ET_o

Correction for $[CO_2]$: By multiplying WP^* with a correction factor (f_{CO_2}) AquaCrop adjusts WP^* when running simulations for a year at which $[CO_2]$ differs from its reference value (369.41 ppm) in the year 2000 (Fig. 4.12a). The correction factor f_{CO_2} is larger than 1 for higher $[CO_2]$ compared to 2000, and smaller than 1 for lower $[CO_2]$.

Adjustment for the type of products synthesized during yield formation (Fig. 4.12b): If products that are rich in lipids or proteins are synthesized during yield formation, considerable more energy per unit dry weight is required than for the synthesis of carbohydrates. This is simulated by multiplying WP^* , in the yield formation stage, with a reduction coefficient (f_{yield}).

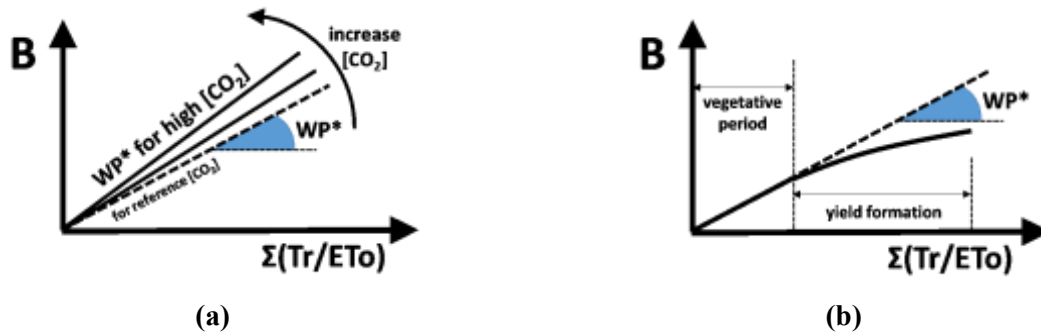


Figure 4.12 – The effect of (a) high [CO₂] and (b) synthesized products on WP*

In Figure 4.13 an overview is given of all factors affecting the simulation of the above-ground biomass production. The crop canopy (CC) development (Step 1) was discussed above in section 4.3, the crop transpiration (Step 2) in section 4.4, and the effect of soil fertility stress will be discussed below in section 5.2 (Field management), and 5.3 (Calibration for soil fertility).

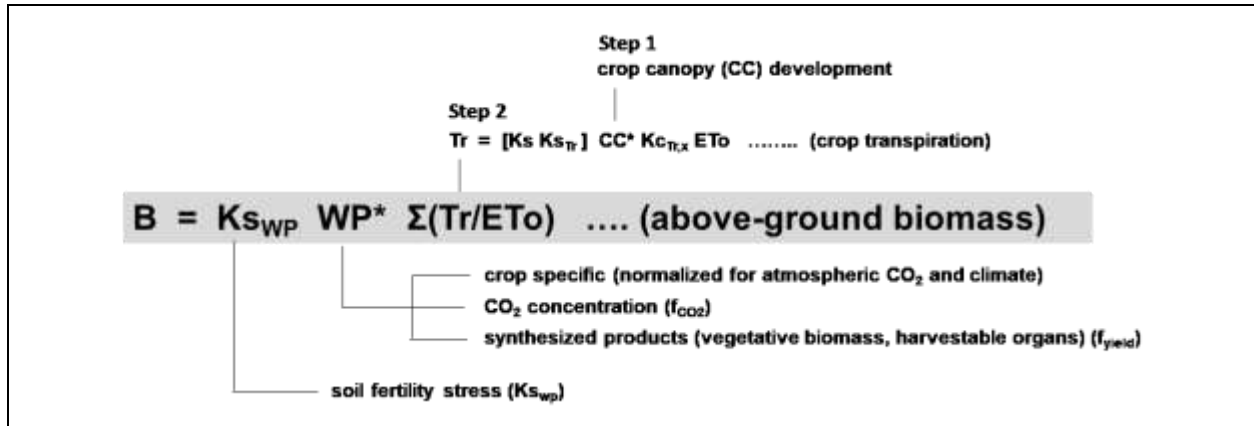


Figure 4.13 – Factors affecting the simulation of the dry above-ground biomass production

4.6 Yield formation (Step 4)

Corresponding Training video Nr. 4.6 “Yield response to water”

Since AquaCrop does not differentiate in the type of biological products that are accumulated throughout its growth cycle, the simulated dry above-ground biomass (B) refers to a conglomeration of stems, leaves, flowers, etc. Final crop yield (Y) is simulated by multiplying B with a Harvest Index (HI), which expresses the mass of the harvested product as a percentage of the total above-ground biomass (B):

$$Y = HI \cdot B \quad (\text{Eq. 4.6})$$

Water and temperature stresses during the growing cycle might alter HI from its reference value (HI_o). The effect of the stresses on HI is simulated with the help of a multiplier which value is continuously adjusted to the strength of the various stresses:

$$HI = multiplier \ HI_o \quad (Eq. 4.7)$$

4.6. 1 Reference Harvest Index (HI_o)

- For **fruit and grain producing crops** the Harvest Index starts to build up just after flowering (Fig. 4.14a). The value commonly reached at maturity under non stressed conditions is taken as the reference HI (HI_o) for that species. It is the representative HI reported in the literature for the chosen crop species under non-stress conditions. HI_o is conservative to a fair extent but can be cultivar specific;
- for **root and tuber crops**, the increase of HI starts at tuber formation or root enlargement and is described by a logistic function (Fig. 4.14b). When building up of HI is fast, the crop might have reached its reference value (HI_o) before the end of the crop cycle;
- for **leafy vegetable crops**, HI builds up quickly after germination and reaches already its reference value HI_o in the first stage of the growing cycle ((Fig. 4.14c).

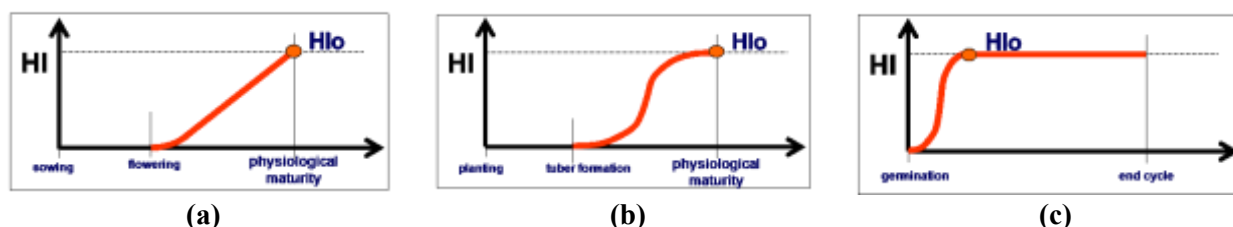


Figure 4.14 – Building up of the harvest index for (a) fruit and grain producing crops, (b) root and tuber crops, and (c) leafy vegetables

If severe water stress trigger early canopy senescence, the remaining green canopy cover (CC) might drop below a minimum threshold value, below which HI can no longer increase. As a result, the HI which is reached at the end of the crop cycle might be smaller than HI_o (Fig. 4.15).

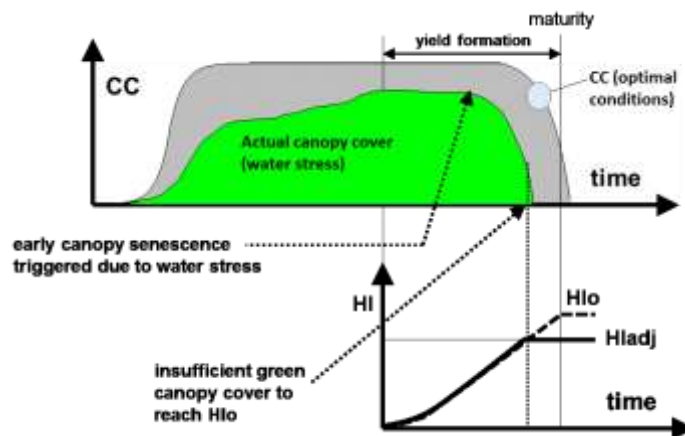


Figure 4.15 – Adjustment of HI_o for insufficient green canopy cover

4.6.2 Period of potential vegetative growth

Some of the stresses affecting yield formation can only alter the Harvest Index during the period of potential vegetative growth. The length of this period depends on the crop type (Fig. 4.16):

- For **determinant crops**, once peak flowering is passed and fruits or grain begin to fill, the green canopy cover has reached its maximum. If the achievement of the maximum canopy cover was delayed, because stresses reduced canopy expansion, CC_x might not be reached at all;
- For **indeterminant crops**, where the crop determinancy is unlinked with flowering, the vegetative period stretches from sowing till canopy senescence.

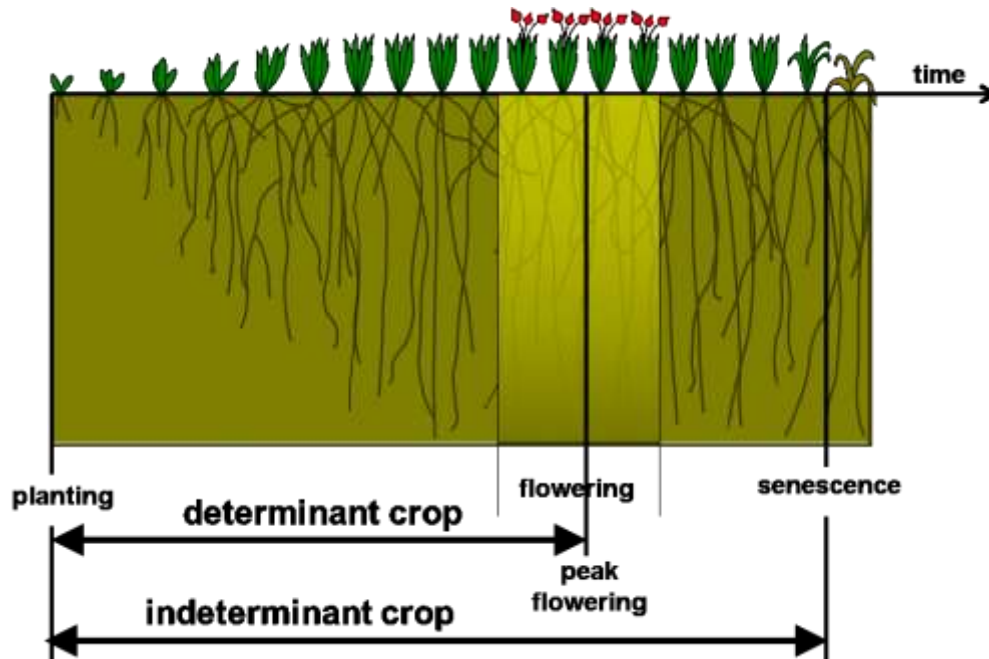


Figure 4.16 – Period of potential vegetative growth for different crop types

4.6.3 Stresses affecting yield formation

□ Water stresses during yield formation (for fruit/grain and root/tuber crops):

Water stress after flowering or after the start of tuber formation or root enlargement, might affect the Harvest Index (HI). Depending on (i) when the water stress occurs during yield formation, (ii) the magnitude of the stress, and (iii) the sensitivity of the crop the adjustment can be upwards or downwards (Fig. 4.17):

- As long as vegetative growth is still possible (Fig. 4.16), the daily rate with which HI increases might be adjusted upwards if water stress affects leaf expansion. The enhancement of HI is the result of a decrease of the competition of leaf growth with reproductive growth;
- The daily rate with which HI increases during yield formation, might be adjusted downwards if water stress induces stomatal closure. It is the corresponding reduction in assimilate supply which will slow down the increase in HI. At permanent wilting point the reduction becomes 100%.

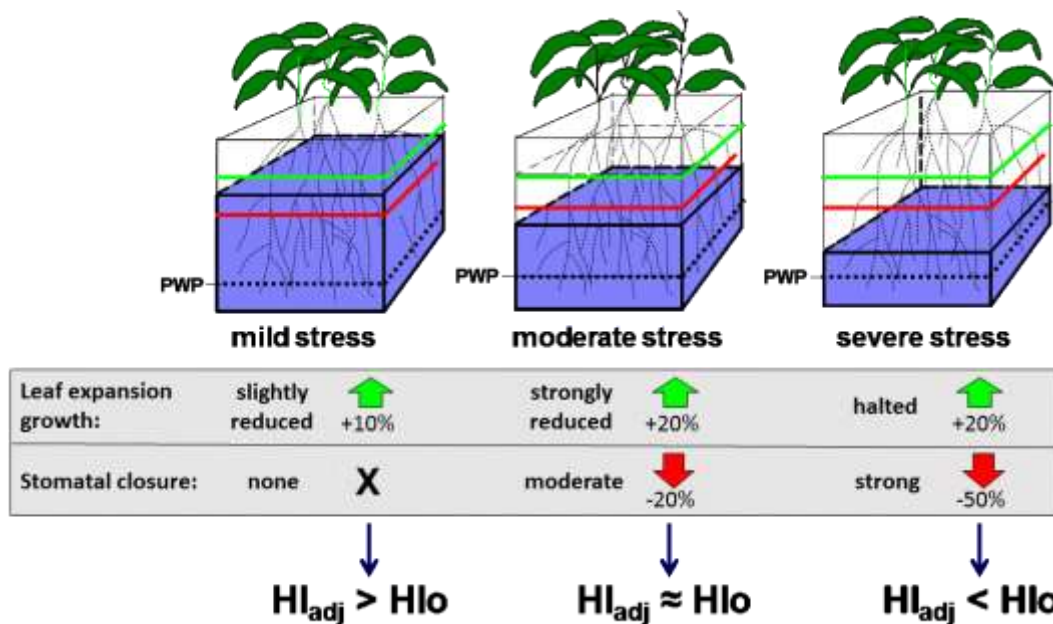


Figure 4.17 – The effect of water stress on leaf expansion growth and stomatal closure, examples of the corresponding effect on the increase (arrow upwards) or decrease (arrow downwards) of HI, and the corresponding HI at physiologic maturity (HI_{adj}).

□ Stresses during flowering (for fruit/grain producing crops):

Severe water stress, cold stress, or heat stress during flowering might induce a reduction in the reference harvest index because insufficient flowers are pollinated to reach HI_o (Fig. 4.18). The magnitude and duration of the stress, and the excess of flowers determine the effect on HI.

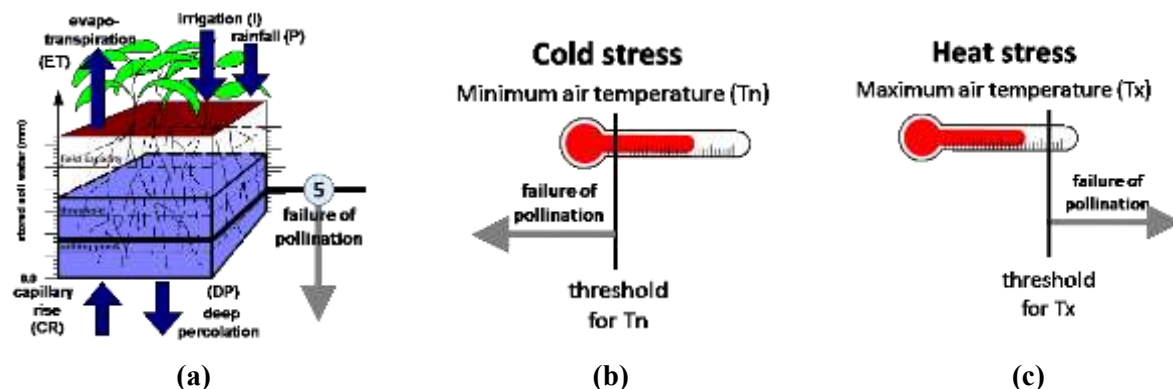


Figure 4.18 – Thresholds for failure of pollination due to (a) water stress, (b) cold stress and (c) heat stress

□ Water stress before the reproductive phase (for fruit/grain and root/tuber crops):

When the crop has spent less energy in its vegetative growth because of water stress before the reproductive phase, the Harvest Index might be higher than HI_o .

In Figure 4.19 an overview of the effect of stresses on HI is presented. In Figure 4.20 an overview is given of all factors affecting the simulation of final crop yield. The crop canopy (CC) development (Step 1) is discussed in section 4.3, the crop transpiration (Step 2) in section 4.4, the above-ground biomass production (Step 3) in section 4.5.

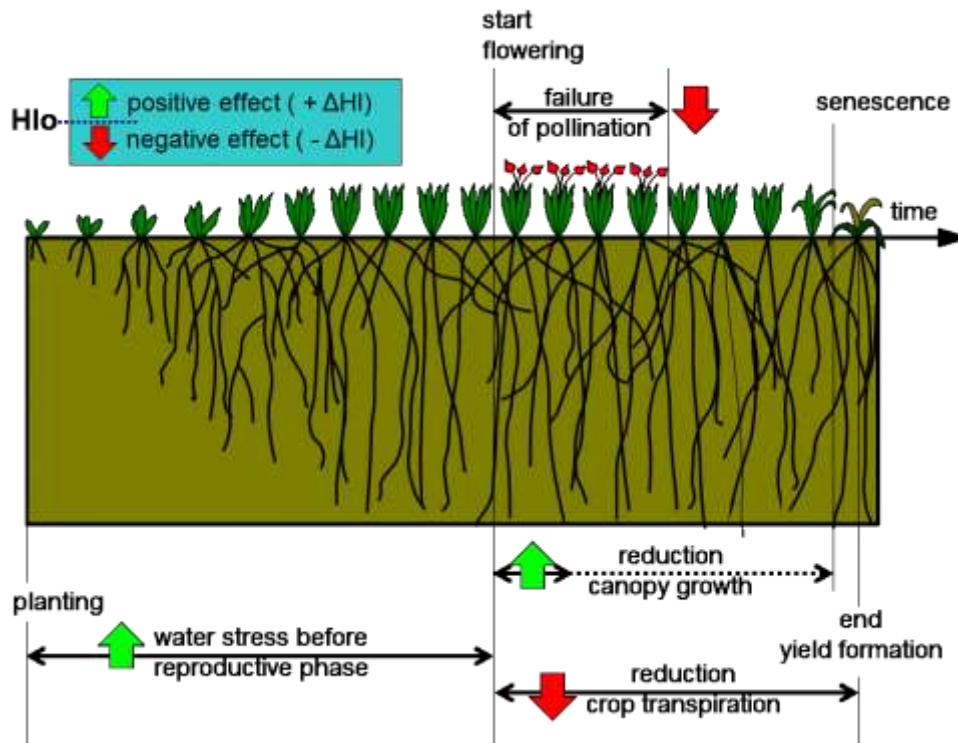


Figure 4.19 – Overview of the effect of stresses on HI.

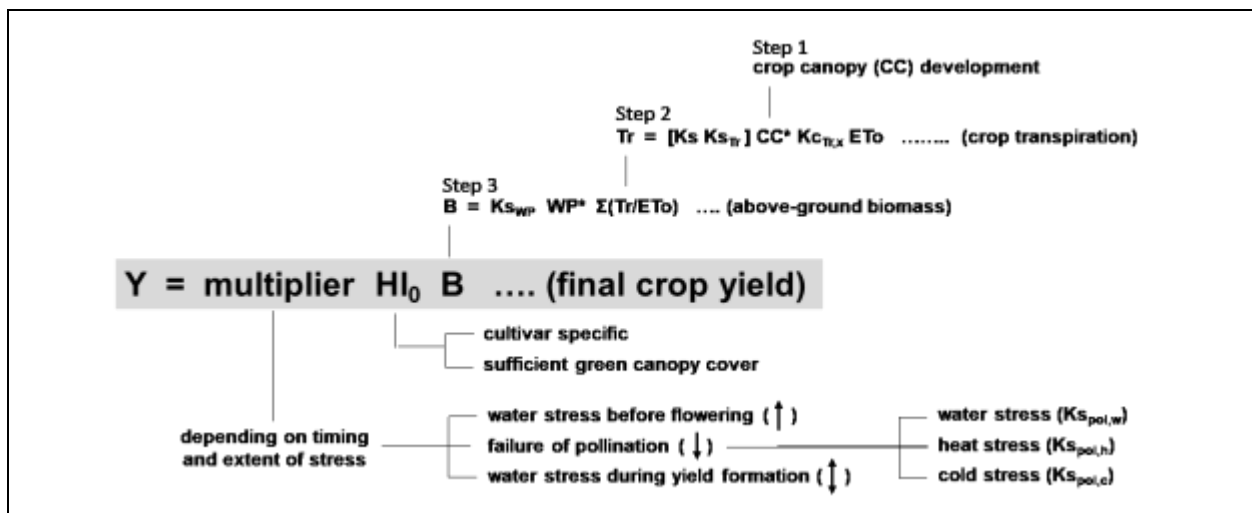


Figure 4.20 – Factors affecting the simulation of the final crop yield.

4.7 Water productivity

Corresponding Training video Nr. 4.7 ‘Water productivity’.

In AquaCrop distinction is made between biomass water productivity (WP), and ET water productivity (WP_{ET} or also called water use efficiency WUE):

- The **biomass water productivity (WP)** refers to the amount of biomass that can be obtained with a certain quantity of water transpired (Fig. 4.21). It is expressed as kg (biomass) per m³ of water (transpired). This is the conceptual relation at the core of AquaCrop ($B = WP \times \Sigma(Tr)$), and allows the model to estimate above ground biomass production (B) from the cumulative amount of water transpired (ΣTr);

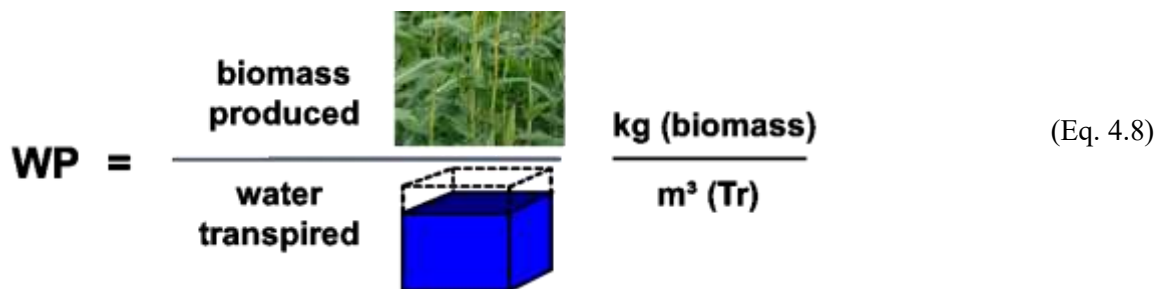
$$WP = \frac{\text{biomass produced} \quad \text{kg (biomass)}}{\text{water transpired} \quad \text{m}^3 (Tr)} \quad (\text{Eq. 4.8})$$


Figure 4.21 – Biomass water productivity (WP)

- **ET water productivity (WP_{ET})**, is the relationship between crop yield and evapotranspiration (Fig. 4.22). It is expressed as kg (yield) per m³ of water (evapotranspired). Yield is used in this equation since it is often the output in which one is most interested. ET (instead of crop transpiration) is used since soil evaporation needs to be considered as well, since water will evaporate from the crop and soil surface each time the soil is wetted by rainfall or irrigation. WP_{ET} is typically used as an indicator to assess the performance of a system. AquaCrop uses WP_{ET} to identify the environments in which (or management strategies by which) the yield per unit water (ET) can be maximized. This type of performance indicator is useful under conditions of scarcity of water resources. In literature WP_{ET} is often referred to as water use efficiency (WUE).

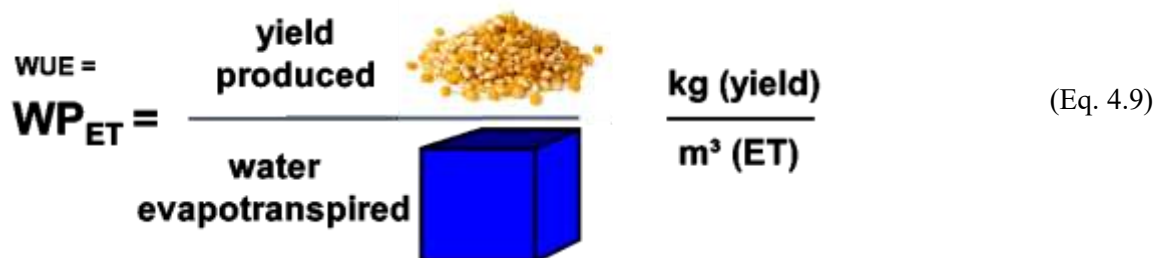
$$WUE = WP_{ET} = \frac{\text{yield produced} \quad \text{kg (yield)}}{\text{water evapotranspired} \quad \text{m}^3 (ET)} \quad (\text{Eq. 4.9})$$


Figure 4.22 –ET water productivity (WP_{ET})

Chapter 5. Management



5.1 Irrigation management

Corresponding Training video Nr. 5.1 ‘Irrigation management’.

AquaCrop can run simulations in different irrigation modes. The default mode is ‘rainfed cropping’ in which irrigation is not considered. In the other modes, (i) the irrigation water requirement can be determined, (ii) an existing irrigation schedule can be assessed, or (iii) an irrigation schedule can be automatically generated.

5.1.1 Irrigation method

When assessing or generating irrigation schedules, the irrigation method needs to be specified since it affects the simulation of the soil water balance (i.e. soil evaporation from the percentage of the soil surface wetted by irrigation).

5.1.2 Determination of net irrigation requirement

Net irrigation water requirement are calculated in AquaCrop by adding a small amount of water to the soil profile each day (time step) when the root zone depletion exceeds a specified threshold (Fig 5.1). The small amount of water that is added when the root zone depletion exceeds the specified threshold, corresponds with the net irrigation water requirement for that time step (day). The seasonal irrigation water requirement is given by the total amount of water added during that period. The net irrigation water requirement, determined by AquaCrop, does not consider extra water that has to be applied to the field to account for conveyance losses or the uneven distribution of irrigation water on the field.

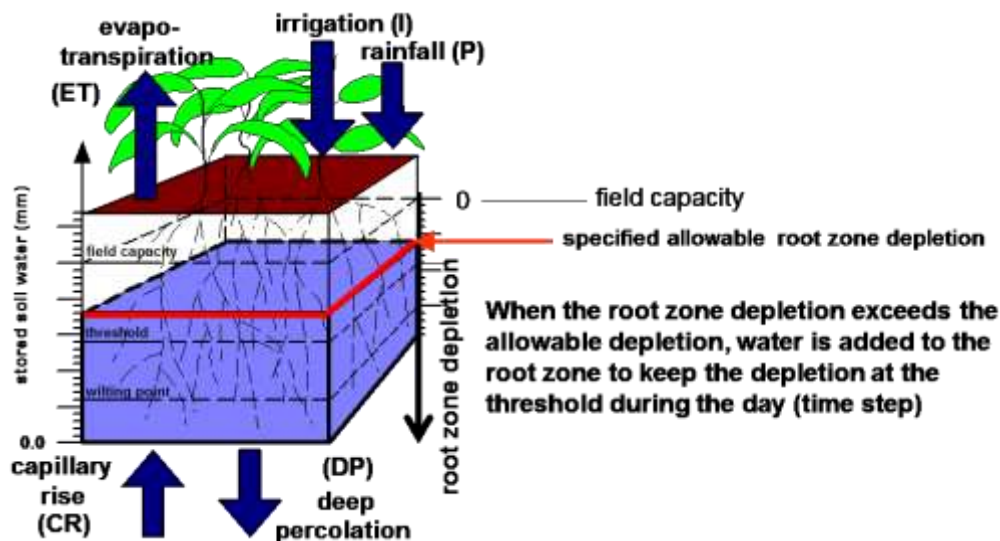


Figure 5.1 – Specified allowable root zone depletion for the determination of the net irrigation requirement

5.1.3 Irrigation schedule (specified events)

The irrigation schedule mode is used to assess an existing irrigation schedule. For each irrigation event the user specifies:

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

The performance of the irrigation schedule and crop response can be assessed by examining the results in the ***Simulation run*** menu. The user can study the simulated and plotted root zone depletion (Dr), canopy development (CC), and crop transpiration (Tr). The simulated biomass (B), crop yield (Y) and ET water productivity (WP_{ET}) might give valuable information about the performance of the schedule.

By adding/removing irrigation applications, and/or increasing/decreasing irrigation intervals or irrigation application doses, it can be checked if crop yield and WP_{ET} can be improved.

5.1.4 Generation of irrigation schedules

Generating irrigation schedules is a practical mode for planning or evaluating a potential irrigation strategy. In this mode AquaCrop will generate at run time irrigations according to the specified time and a depth criteria:

- The time criterion specifies ‘When’ irrigation has to be applied. Irrigations can be applied after a fixed interval or when a certain amount of water has been depleted out of the root zone;
- The depth criterion determines ‘How much’ water has to be applied. The applied irrigation amount can be fixed, or expressed as the amount of irrigation water required to bring the soil water content in the root zone at Field Capacity.

5.1.5 Deficit irrigation

Deficit irrigation allows the farmer to stabilize the crop yield using less water. In deficit irrigation, the applied irrigation water is insufficient to cover the full crop water requirement. This inevitably results in plant water stress and consequently in production loss. Although the level at which the yield can be stabilized is lower than under full irrigation, the evapotranspiration water productivity (WP_{ET}) can be maximized with deficit irrigation (Fig. 5.2).

For the correct design of a deficit irrigation strategy, AquaCrop can be a valuable tool. From the plots in the ***Simulation run*** menu, the user can follow at selected times the effects of water stress on crop development and production.

An example of (deficit) irrigation strategies for winter wheat cultivation in Syria is illustrated in Figure 5.2. By implementing full irrigation the grain yield can be increased from less than 2 under rainfed conditions to more than 4 ton per hectare. However, the results indicate that without proper guidance, farmers might not irrigate efficiently. With irrigation guidelines, more yield can be produced with 25 % less water. This is the result of a proper planning of the irrigation applications assuring a 100% fulfillment of the crop water requirement at all times.

Moreover, water losses leaching nutrients out of the root zone will be kept at a minimum. Finally, when applying a deficit irrigation strategy, grain yield drops a bit but the total amount of water applied dropped to 1 third. The ET water productivity (WP_{ET}) increased from 0.5 kg/m³ under rainfed agriculture to 1.8 kg/m³ for deficit irrigation.

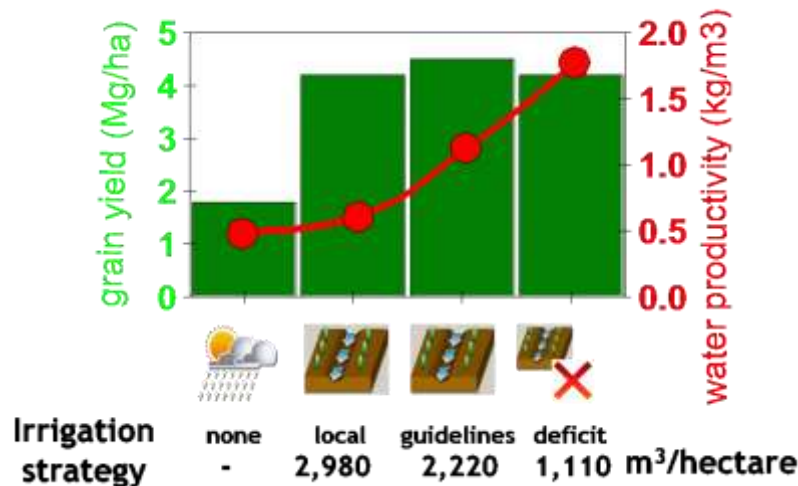


Figure 5.2 – Grain yield (bars) and ET water productivity (line) for winter wheat in Syria for various irrigation strategies (Source IWMI, annual report 2002/2003).

5.2 Field management

Corresponding Training video Nr. 5.2 ‘Field management’.

The type of field management considered in AquaCrop are: field surfaces practices, mulches, weed management and soil fertility. The required field parameters vary with the type of management.

5.2.1 Field surface practices

The part of rainfall lost by surface runoff, is estimated by means of the curve number method (Fig. 3.3b). The Curve number (CN) is based on soil profile characteristics (CN_{soil}). If field surface practices affect surface runoff, CN_{soil} needs to be adjusted. The adjustment is expressed as a percent increase/decrease (CN_{man}) of CN_{soil} ($CN = CN_{soil} \times (100 + CN_{man})/100$). When characterizing field management, the user can specify:

- the percent increase/decrease of CN_{soil} as a result of field surface practices (such as crop type, treatment and practices affecting infiltration);
- field surface practices which prevent surface runoff. If for example irrigation consists in applying water to tied ridges, surface runoff from rainfall should be switched off;
- field surface practices which block surface runoff and store excess water on top of the field. Soil bunds are built to store water on the field, as is the case in rice paddy fields. Any excess rainfall and/or irrigation water that cannot infiltrate during the day, remains stored on top of the field between the bunds until all stored water has infiltrated or is lost by soil evaporation.

To estimate surface runoff, AquaCrop does not only consider the specified CN but also the wetness of the topsoil at the time of rainfall (Fig. 3.4).

5.2.2 Mulches

AquaCrop simulates the reduction of evaporation when mulches cover the soil surface. Mulches are composed of organic plant materials, synthetic materials consisting of plastic sheets, or any other material that reduces soil evaporation. Depending on the type of mulches and the fraction of the soil surface covered by mulches, the reduction in soil evaporation might be more or less substantially. The user specifies in the **Field management** menu:

- the degree of soil cover (in percentage);
- the type of surface mulches, which determines the magnitude of evaporation reduction. Plastic mulches efficiently reduce evaporation of water from the soil surface (100 %). Organic mulches may consist of unincorporated plant residues or foreign material imported to the field such as a straw, and reduce soil evaporation by 50% (by default).

As a result of the reduction of soil evaporation, the ET water productivity (WP_{ET}) will increase when the soil surface is covered with mulches.

5.2.3 Weed management

Weeds affect crop development and production through competition for the available resources (water, light, and nutrients). In AquaCrop the competition 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 (Fig. 5.3). RC is easily determined by estimating the fraction of the total canopy cover that is weed (visually or by analyzing photographs taken from above).

To simulate weed infestation, the user has to specify in the **Field management** menu:

- the Relative Cover (RC) of weeds in season (which can change throughout the season);
- 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 (Fig. 5.3).

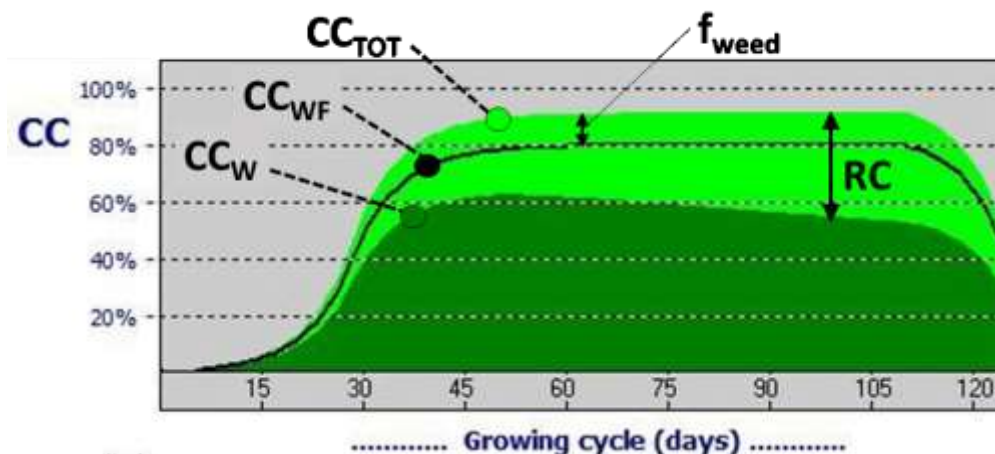


Figure 5.3 – Total canopy cover of crop and weeds (CC_{TOT}), crop canopy cover under weed-free conditions (CC_{WF} which is a reference), and crop canopy cover in a weed infested field (CC_W), with indication of the adjustment factor for canopy expansion (f_{weed}) and the relative cover of weeds (RC)

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 in AquaCrop, the total transpiration of crop and weeds and the soil evaporation in the weed-infested field is considered to simulate correctly the soil water balance. To compute the crop above-ground biomass and crop yield, only crop transpiration is taken into account.

5.2.4 Multiple harvests

Perennial herbaceous forage crops are harvested several times during the growing period. The individual harvest events can be specified or generated with some criteria.

5.2.5 Soil fertility

Simulating stresses caused by low soil fertility (nutrient deficiencies) using nutrient balances is not possible, while keeping the model relatively simple. Therefore, AquaCrop employs an indirect approach by mimicking the effects of soil fertility stress on canopy development (CC) and biomass water productivity (WP^*).

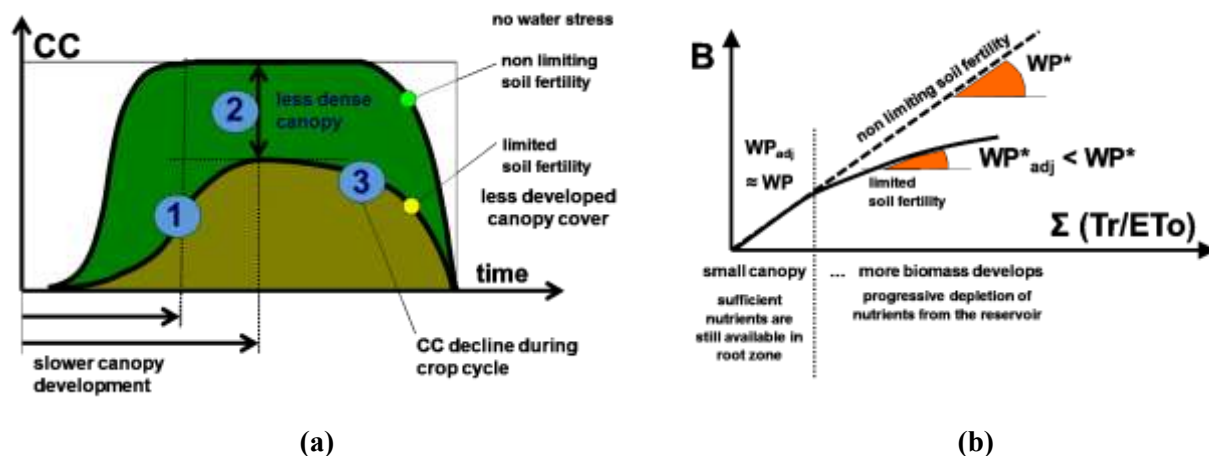


Figure 5.4 – The effect of soil fertility stress on (a) canopy development and (b) biomass water productivity

The effect of soil fertility stress on canopy development is simulated in AquaCrop by mimicking what is observed in the field (Fig. 5.4a): (i) slower canopy development, i.e. requiring more time to reach maximum canopy cover (CC_x); (ii) less dense canopy cover (lower CC_x); and (iii) the canopy cover undergoes a steady decline once CC_x is reached at mid-season.

Mineral nutrient stress, particularly the lack of N, can also reduce the biomass water productivity (WP^*). Because the reservoir of nutrients gradually depletes when the crop develops, the effect of soil fertility on the adjustment of WP^* is not linear throughout the season (Fig 5.4b). As long as the canopy is small, the daily biomass production will be rather similar to the daily production for non-limited soil fertility. This is the case early in the season when sufficient nutrients are still available in the root zone. If the crop does not experience water stress, the canopy will further develop during the season, but this will result in a progressive depletion of nutrients from the

reservoir. Consequently, the daily biomass production will gradually decline when more and more biomass is produced.

The soil fertility level is selected in the **Field management** menu, by specifying a relative biomass production (B_{rel}). The relative biomass production ($B_{rel} = B_{stress}/B_{ref}$) refers to the maximum dry aboveground biomass (B_{stress}) that can be expected at the end of the growing season in a field with soil fertility stress with reference to stress-free conditions (B_{ref}). Both B_{stress} and B_{ref} are to be observed in well watered fields (no soil water stress) and free of any other stress factors like weeds, pests, diseases and salinity. B_{stress} can be easily obtained from farmers, experimental fields or agricultural statistics on local crop production (it is B in a good rainy year with small or none existing water stress during the growing cycle). B_{ref} can be obtained from nearby experimental fields, published potential yield levels, or by applying a full nutrient strip in one part of the farmer's field. Also, model simulations can provide an estimation of the biomass levels for the local farming conditions under stress-free conditions.

The easily obtainable input makes the semi-quantitative AquaCrop approach user-friendly and accessible to users worldwide. Moreover, the approach integrates the effect of various soil nutrients (and not merely nitrogen) and mineralization processes without requirement of vast amounts of input data, initialization of the soil nutrient conditions and elaborate parameterization.

5.3 Calibration for soil fertility

Corresponding Training video Nr. 5.3 'Calibration for soil fertility'.

Because AquaCrop does not simulate nutrient cycles and balances, but only mimics the effect of soil fertility stress on the canopy development and biomass production, the crop response to soil fertility needs to be calibrated. Since the effect of soil fertility stress depends on which nutrient is deficient, and on the environmental conditions such as climate and soil type, the calibration most likely will have to be repeated for each type of environment.

Limited soil fertility results in a smaller canopy cover (CC) and a decrease of the biomass water productivity (WP*) during the growing cycle (Fig. 5.4). This is simulated with the help of four stress coefficients (Ks). The calibration consists in fixing the shape of the 4 stress curves for a specific soil fertility level in the **Crop characteristics** menu. This specific level is expressed by the maximum possible biomass production (B_{stress}) that can be expected at the end of the growing cycle in a field with that soil fertility level.

For the calibration, the user specifies (Fig. 5.5):

1. the **relative biomass production**, it is B_{stress} with reference to the potential biomass (B_{ref}) that can be obtained in a reference field (stress-free conditions);
- and the observed effect of the soil fertility stress on canopy development
2. The **maximum canopy cover** that can be obtained in the stressed field ($CC_{X_{stress}}$)
3. The **decline of the canopy cover** (qualitative class) in the season.

When launching the calibration, AquaCrop searches automatically, by means of an iterative optimization algorithm, for a setting of the four stress coefficients which results in a relative

biomass production equal to the specified B_{rel} . The user may vary the balance between the four K_s curves to ensure that the displayed pattern of CC progression over time is realistic and corresponds to the observations.

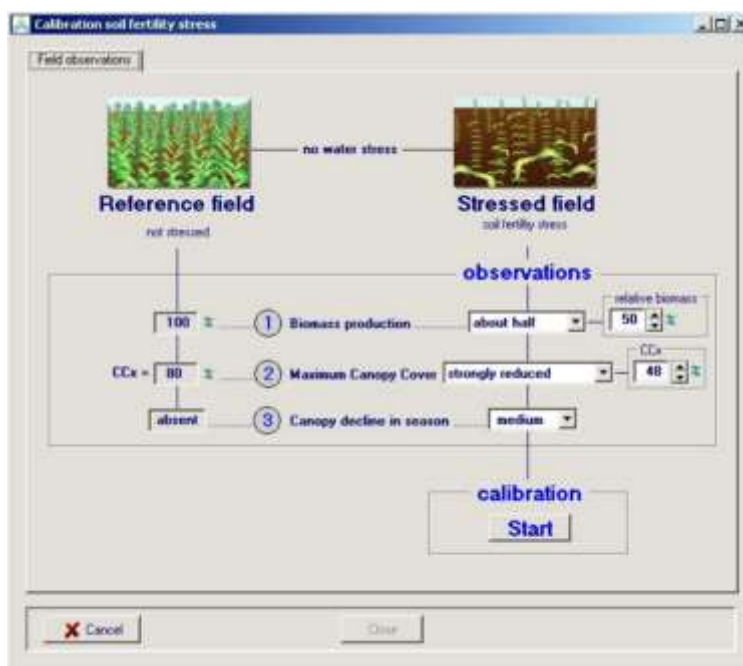


Figure 5.5 – Calibration for soil fertility stress is based on the (1) reduction in biomass, and (2 and 3) the reduced canopy cover, as observed in a field with soil fertility stress.

How the development of the crop canopy and the biomass production is affected by fertility stress is a crop characteristic. Hence the calibration is done in the ***Crop characteristics*** menu (Tab. 5.1). The actual soil fertility level in the field (required for the simulation), needs to be provided when specifying the field management. It is specified in the ***Field management*** menu.

Table 5.1 – Crop characteristics and specification of field management

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

Chapter 6. Simulation



6.1 Initial conditions at start of simulation period

Corresponding Training video Nr. 6.1 'Initial conditions at start of simulation period'.

To start the simulation of the soil water and salt balance of the root zone, the initial conditions need to be specified. Given the initial soil water and salt content, AquaCrop calculates the amount of water and salts retained in the root zone for the rest of the simulation period.

6.1.1 Sampling of the soil profile

The initial soil water and salt content can be obtained by measuring the soil water and salt content in the soil profile. Ideally sampling is done at the day of sowing/planting (Fig. 6.1). In that case, the start of the simulation period should coincide with the sowing/planting date (i.e. linked with the growing cycle).

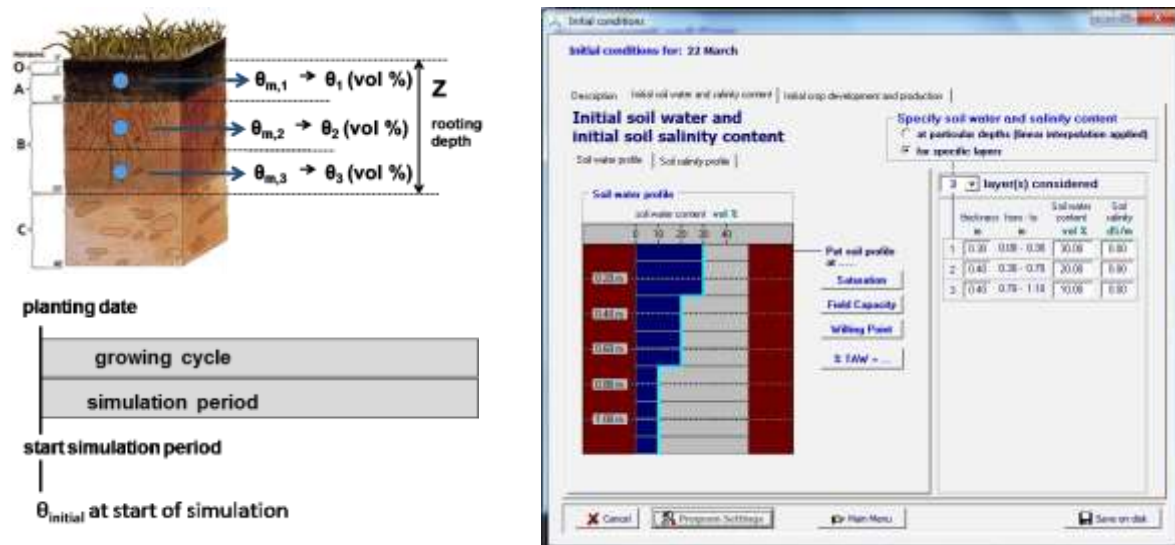


Figure 6.1 – Specifying measured soil water and salt content in the *Initial conditions* menu

In the absence of observations at the time of sowing/planting, measurements or samples collected earlier can be used to determine the initial soil water content. In this case the simulation should start at the day the sampling was done (before the sowing/planting) and the simulation period is no longer linked with the growing cycle (Fig. 6.2). The initial soil water content at sowing/planting is estimated by updating $\theta_{initial}$, for every day before the start of the growing cycle, with the infiltrated rainfall, (pre)-irrigation, soil evaporation, deep percolation and capillary rise.

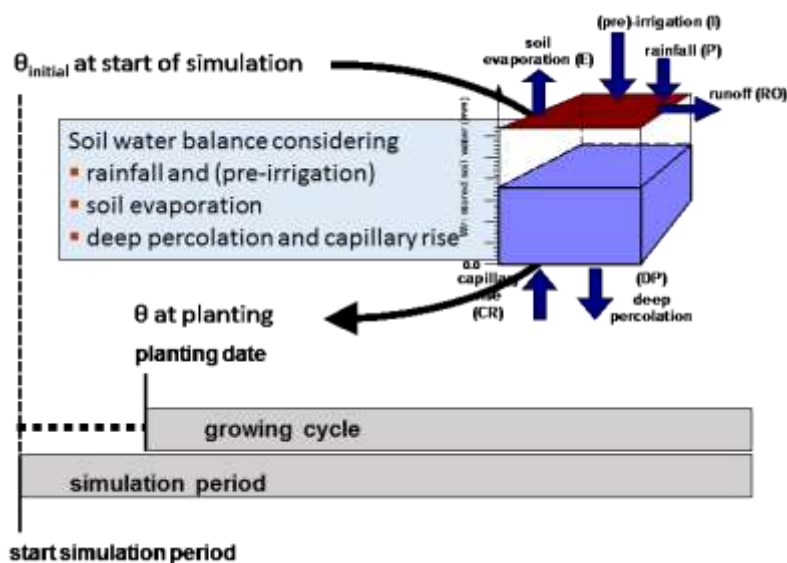


Figure 6.2 – Determination of the soil water content at planting by considering the weather conditions between the start of the simulation and the sowing/planting date.

6.1.2 Estimation of the initial soil water content

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

- for a climate where the winter period is characterized by ample rainfall and a small to negligible evaporative demand of the atmosphere (i.e. with E_{To} close to zero) as is the case in Northwest Europe, it is safe to assume that in winter (January) the initial soil water content is close to Field Capacity. Although the crop is only sown/planted in spring (March/April), the simulation starts at 1 January since at that day the initial soil water can be assumed to be at Field Capacity;
- for a climate where the summer period is characterized by the absence of rainfall and a high evaporative demand of the atmosphere (with a reference evapotranspiration (E_{To}) of 5 mm/day or above) as is the case in the Mediterranean region, it is safe to assume that at the end of the summer period (mid-August), the initial soil water content will be close to Permanent Wilting Point (PWP). Although the crop is sown/planted when the winter rains have started (November/December), the simulation starts already at mid-summer (15 August) because at that moment a good estimate of the initial soil water content (PWP) can be made.

In both examples, the simulation starts well before the sowing/planting of the crop (Fig. 6.2).

6.2 Start of the growing cycle

Corresponding Training video Nr. 6.2 ‘Start of the growing season’.

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

To determine the likely time of planting in the various years of a simulation run, the onset can be specified directly, or a crop calendar file can be loaded in which the onset day is generated based on an evaluation of climatic data.

6.2.1 Generation based on rainfall

By selecting a criterion, the start of the growing cycle is determined by evaluating the rainfall data before planting/sowing. The following criteria can be selected:

- **cumulative rainfall** since the start of the search period is equal to or exceeds a specified value;
- observed **rainfall during a number of successive days** is equal to or exceeds a specified value. The value refers to the amount of rainfall that is required to wet the top of the soil profile ($Z_{\text{top}} \approx 0.2$ à 0.3 m) to field capacity. By assuming that the topsoil is air dry ($= 0.5 \theta_{\text{PWP}}$), the required rainfall is $1000 \times (\theta_{\text{FC}} - 0.5 \theta_{\text{PWP}}) \times Z_{\text{top}}$ mm, which is about 20 to 40 mm.
- **10-day rainfall** is equal to or exceeds a pre-set value;
- **10-day rainfall exceeds** the pre-set **fraction of the 10-day ETo**.

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

By specifying the first and last day in a ‘Search window’, only rainfall within the specified window is evaluated. Generating the onset based on rainfall might be useful not only for estimating the planting dates for current years but also for future years, since climate change is likely to alter the rainfall pattern in many regions.

6.2.2 Generation based on air temperature

By selecting a criterion, the start of the growing cycle is generated by evaluating the air temperature data before planting/sowing. The following criteria can be selected:

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

By specifying the first and last day in a ‘Search window’, only temperature within the specified window is evaluated. This option might be well suited to estimate for future years the planting dates for spring crops in cool climates, since climate change is likely to increase the air temperature in many regions.

6.2.3 Occurrence

The first occurrence of the onset date is the first date for which the selected criterion holds. AquaCrop also offers the option to select the 2nd or even 3rd occurrence, to avoid

- the selection of a too early onset date after a false start of the rainy season (when generation is based on rainfall);
- sowing or planting in the early stages of the spring, where air temperature might still drop sharply after an early start (when generation is based on air temperature).

6.3 Soil salinity

Corresponding Training video Nr. 6.3 ‘Soil salinity’.

Salts enter the soil profile as solutes with the irrigation water or through capillary rise from a shallow groundwater table. The extent to which salts accumulate in the soil depends on irrigation water quality and quantity that infiltrates into the soil, frequency of wetting, adequacy of leaching, magnitude of soil evaporation and crop transpiration (crop development and climatic conditions), soil physical characteristics of the various layers of the soil profile, and salt content and depth of the groundwater table. Salts are transported out of the soil profile (leached) by means of the drainage water.

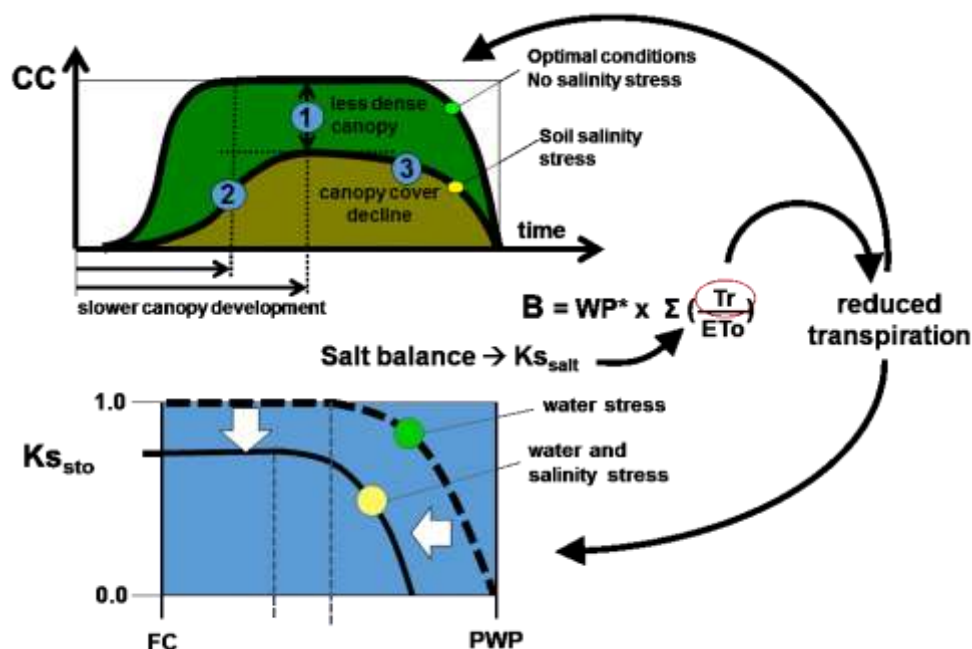


Figure 6.3 – Simulation of crop response to soil salinity stress

Soil salinity stress is simulated with a soil salinity stress coefficient ($K_{s_{salt}}$). The average electrical conductivity of the saturation soil-paste extract (EC_e) from the root zone is the indicator for soil salinity stress. The upper and lower threshold for EC_e are crop specific. Soil salinity stress results in smaller canopy cover (CC) and a closure of the stomata (Fig. 6.3):

- **Smaller canopy cover:** Soil salinity stress decreases the growing capacity of the crop as well as the maximum canopy cover (CC_x) that can be reached at mid-season. Due to the salinity stress in the soil, CC will steadily decline once CC_x is reached at mid-season;
- **Stomatal closure:** Due to osmotic forces, which lower the soil water potential, the salts in the root zone make the water less available to the crop. Soil salinity will decrease the soil water stress coefficient for stomatal closure ($K_{s_{sto}}$). Moreover, the osmotic forces are likely to alter also the upper and lower thresholds for root zone depletion at which soil water stress affects stomatal closure ($K_{s_{sto}}$). This will affect crop transpiration.

Since the individual effects of salinity stress on canopy cover and stomatal closure are not well documented in literature for simulation in AquaCrop, the user can calibrate the crop response to salinity stress in the **Crop characteristics** menu.

When soil salinity stress occurs, AquaCrop adjusts the values of stress coefficients (affecting canopy development and stomatal closure) so that the simulated crop transpiration and the corresponding biomass (B) becomes equal to the required reduction given by K_{salt} (Fig. 6.3).

6.4 Effect of climate change

Corresponding Training video Nr. 6.4 ‘Climate change’.

Simulations of future crop yields should consider (Fig. 6.4):

- **Altered weather conditions:** The expected increase in global air surface temperature during the 21st century is likely to increase the evaporating power of the atmosphere (i.e. ETo , the reference evapotranspiration), to alter the amount and pattern of rainfall, and to amplify the frequency and intensity of extreme weather events. The effect of altered weather conditions on crop production is considered by running simulations with future climatic data;
- **the increase of the atmospheric CO_2 concentration ($[CO_2]$):** The increase in $[CO_2]$, which induces CO_2 fertilization, reduces (slightly) the crop transpiration (Tr) and increases (strongly) the biomass water productivity (WP^*). The effect of the decrease in crop transpiration for elevated $[CO_2]$ concentration is considered by multiplying the crop transpiration coefficient ($Kc_{Tr,x}$) with an adjustment factor ($f_{CO_2,Tr} \leq 1$). When running a simulation with a $[CO_2]$ different from the reference value (i.e. 369.41 ppm for the year 2000), WP^* is adjusted with a correction factor ($f_{CO_2} > 1$ for $[CO_2] > 369.1$ ppm).

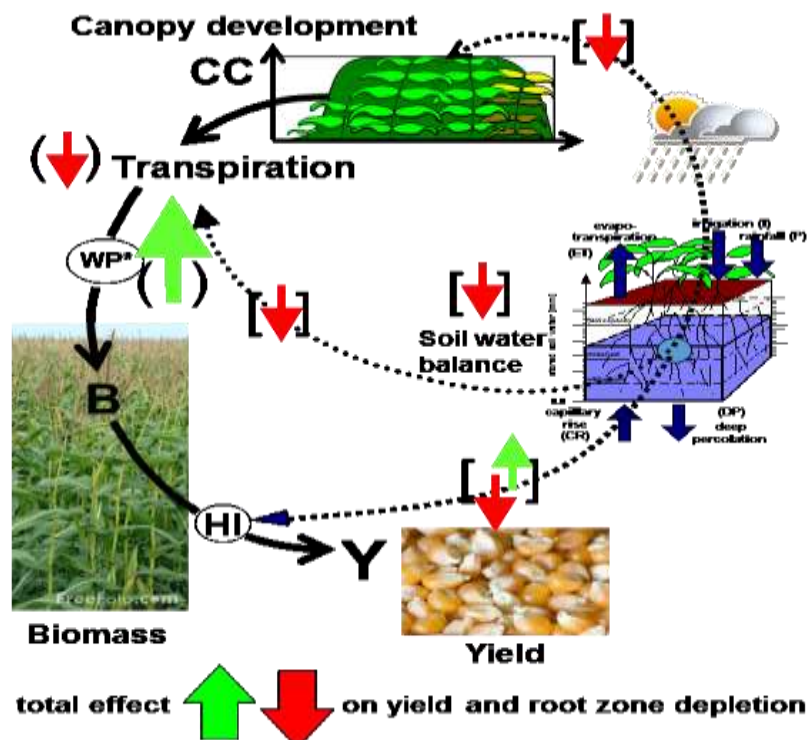


Figure 6.4 – The expected positive (arrow upwards) and negative (arrow downwards) effects of climate change on crop production. The arrows between (round) brackets indicate the effect of the increased CO_2 concentration, and between [square] brackets the effect of altered weather conditions

6.5 Evaluation of simulations

Corresponding Training video Nr. 6.5 ‘Evaluation of simulation results’.

When the simulated crop yield differs from the observed yield, some of the input data (Fig. 1.4) might be wrong. When examining the input, it is essential to do the checks along a sequence, which follows the order of the calculation scheme (sections 4.3 to 4.6). Fig. 6.5 shows the calculation scheme of AquaCrop, together with the crop parameters and stresses governing the:

1. Simulation of green Canopy Cover (CC): The expansion, ageing, conductance and senescence of CC are key determinants of the amount of water transpired and the amount of biomass produced. CC development is described by conservative and cultivar specific parameters. Water, soil salinity and soil fertility stress can reduce CC from its potential development;
2. Simulation of crop transpiration (Tr): Tr is proportional to CC. Cold stress, and shortage and excess of water and soil salinity in the root zone, can reduce Tr as a result of stomatal closure;
3. Simulation of the above ground biomass production (B): B is proportional to the cumulative amount of water transpired. Soil fertility stress can reduce B;
4. Simulation of crop yield (Y): Y is calculated as the product of final B and a harvest index (HI). The actual HI is obtained by adjusting, during the simulation, the reference Harvest Index (HI₀) with an adjustment factor for stress effects.

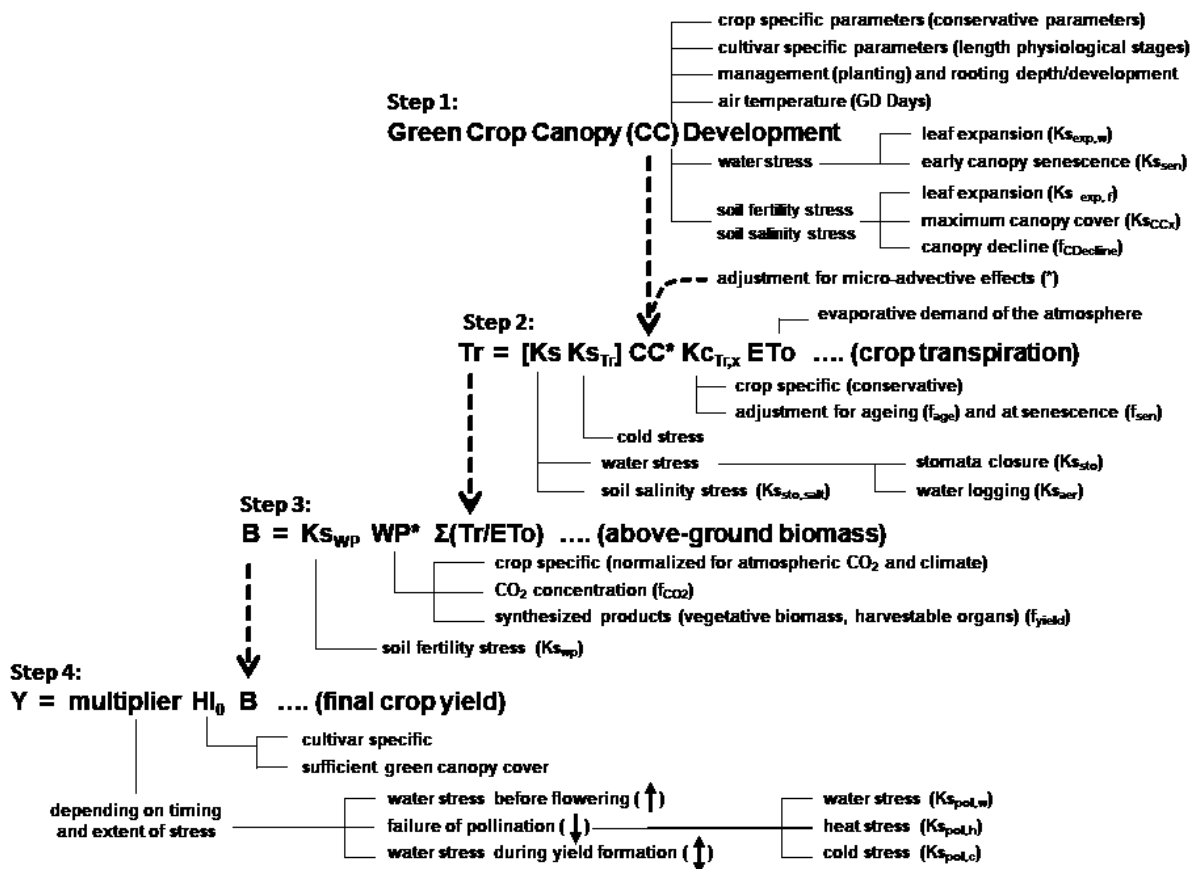


Figure 6.5 – AquaCrop calculation scheme

6.5.1 Green canopy cover (CC) – Step 1

☐ Check if crop parameters are properly tuned to the environment and cultivar:

A first check should consist in verifying if the non-conservative crop parameters were properly tuned to the selected cultivar, planting mode, field management, or conditions in the soil profile as outlined in Fig. 4.1.

☐ Compare observed with simulated CC:

The conservative and fine-tuned non-conservative parameters of the crop file describe the potential canopy development (CC) in the absence of any stress. When soil water, soil salinity and/or soil fertility stress affects crop development, the simulated CC (CC_{sim}) will be different from its potential value. Compare therefore CC_{sim} with data collected at the field (CC_{obs}). For the study of the evolution of CC, several observations (randomly distributed throughout the field) should be taken at several times during the growing cycle. CC_{obs} can be estimated in the field by eye, by evaluating the shadowed sections on a graduated ruler placed on the soil surface around midday, or by deriving it from pictures of the canopy taken overhead with a digital camera (Tab. 6.1).

Table 6.1 – Software and guidelines for deriving Canopy Cover (CC) from pictures

Available software packages, to estimate CC from pictures:

FREEWARE:

- Green Crop Tracker <http://www.flintbox.com/public/project/5470/>
- GIMP <http://www.gimp.org/downloads/>
- IMAGE J <http://rsb.info.nih.gov/ij/>
- CAN-EYE http://147.100.66.194/can_eye/index.php

OTHER OPTION (not freeware):

- SigmaScan Pro
- ENVI <http://www.ittvis.com/ProductServices/ENVI.aspx>
- ASSESS <http://www.apsnet.org/apsstore/shopapspress/Pages/43696m5.aspx>
- eCognition Developer <http://www.ecognition.com/products/ecognition-developer>
- Image processing toolbox Matlab:
http://www.mathworks.nl/products/image/index.html?s_tid=brdcrb

Guidelines:

- To avoid over-estimations caused by parallax distortions near the image borders, only the centres of the pictures should be analysed;
- By altering thresholds in a kind of colour histogram, the ‘green’ colour of the canopy cover can be identified;
- The setting of the thresholds allows to separate the image into bare soil and green matter.

When running a simulation, observed field data (specified in the ***Field data*** menu) and simulation results are plotted together in the ***Evaluation of simulation results*** menu (Fig. 6.6). Next to a visual check, statistical indicators (see AquaCrop reference manual) are available to evaluate the simulation. Since the development of canopy cover is affected by (i) soil fertility, (ii) soil salinity and (iii) soil water stress, a poor simulation of those stresses in the root zone might be the reason of a poor fit between observed and simulated canopy cover:

- (i) Check if the amount of fertilizers applied in the field is in agreement with the soil fertility level (relative potential biomass production) specified in the **Field management** menu;
- (ii) Adjust if required the initial ECe, and/or the ECw of the irrigation water and groundwater table, if there is a mismatch between the real and simulated incoming and outgoing salts;
- (iii) The evaluation of the simulated soil water content is discussed below in section 6.5.2.

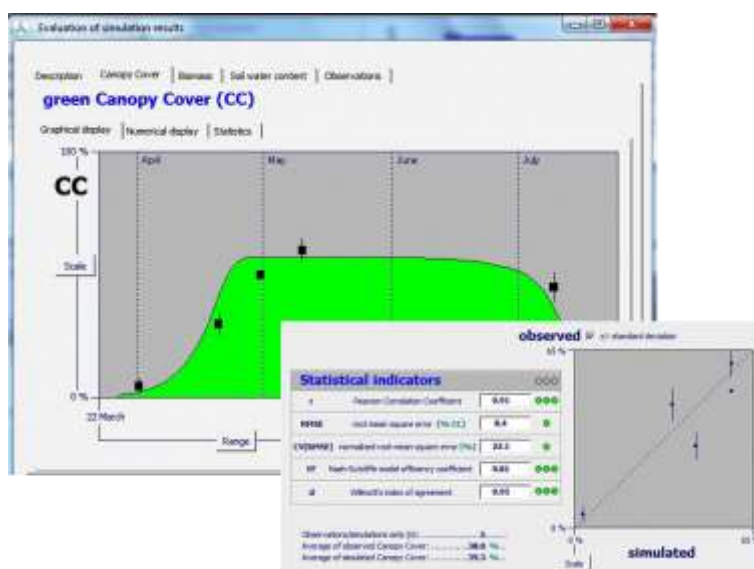


Figure 6.6 Evaluation of the simulated canopy cover

6.5.2 Crop transpiration (Tr) – Step 2

Crop transpiration (T_r) is calculated by multiplying the reference evapotranspiration (ETo) with the crop transpiration coefficient and by considering the effect of cold and water stress with the help of stress coefficients (Eq. 4.3). The crop transpiration coefficient is proportional with the green canopy cover (Eq. 4.4). The proportional factor and the thresholds and shapes of the stress functions are conservative crop parameters and should not be adjusted.

□ Check reference evapotranspiration (ETo):

AquaCrop runs with ETo estimated with the FAO Penman-Monteith method (see Chapter 2). To check if ETo is well calculated, the (daily) ETo values used for simulations can be compared with the mean monthly values specified in the New_LocClim software for the particular location (Tab. 6.2). The two sets should have the same order of magnitude.

Table 6.2 – New_LocClim: Local Climate Estimator (download from web)

	New_locClim is a software program and database, which provides estimates of average climatic conditions at locations in the world. Reference: FAO. 2005. New_locClim, Environment and Natural Resources, Working paper No. 20 (CD-ROM)
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□ Check the initial soil water content (at the start of the simulation period):

Simulations of the soil water balance are sensitive to the initial conditions. If the soil water content at the start of simulation is poorly defined, the estimated soil water content at the next days might be out of range as well. Since the simulated soil water content in the root zone strongly affects crop development (CC), transpiration (T_r), biomass production (B) and yield (Y)

the initial soil water content should be well estimated. Section 6.1 (Initial conditions at start of simulation period) provides guidelines for a proper estimation of the initial soil water content.

□ Check the soil water balance:

Soil water content in the root zone (W_r) affects canopy development and crop transpiration. By considering the incoming and outgoing fluxes the variation of W_r during the growing season is simulated (Eq. 3.5). If crop transpiration and/or canopy cover are not well simulated check:

- **the size of the root zone reservoir** which is determined by soil profile and crop characteristics. Soil type and variations of soil physical characteristics with soil depth are specified in the soil file. The development and the maximum depth of the root zone are specified in the crop file;
- **daily rainfall**. Since the temporal and spatial variability of rainfall is very high, the data should have been collected at or nearby the site, and preferably on a daily basis;
- **irrigation application depth and timing of the applications**. The irrigation depth refers to the net irrigation amount. Extra water applied to the field to account for conveyance losses or the uneven distribution of irrigation water on the field should not have been added;
- **surface runoff** which is determined by soil profile characteristics and field management. The Curve Number (CN), and the saturated hydraulic conductivity are specified in the soil file. Adjust, if required, CN by considering the slope, land use and cover. Field surface practices affecting runoff are specified in the Field management file;
- **capillary rise** which strongly depends on the depth of the groundwater table, which can vary throughout the simulation period and is specified in the Groundwater file. If required, calibrate 'capillary rise' in the *Soil profile characteristics* menu.

□ Compare the observed with simulated soil water content retained in the root zone (W_r):

By measuring (or collecting representative soil samples) at various depths, the soil water content in the root zone can be determined (see example in Tab. 3.2). The quality of the simulation can be evaluated by comparing $W_{r\text{sim}}$ with measured soil water content at particular days throughout the growing cycle. This corresponds with an evaluation of the crop evapotranspiration, since it is the only water flux which could not be checked directly.

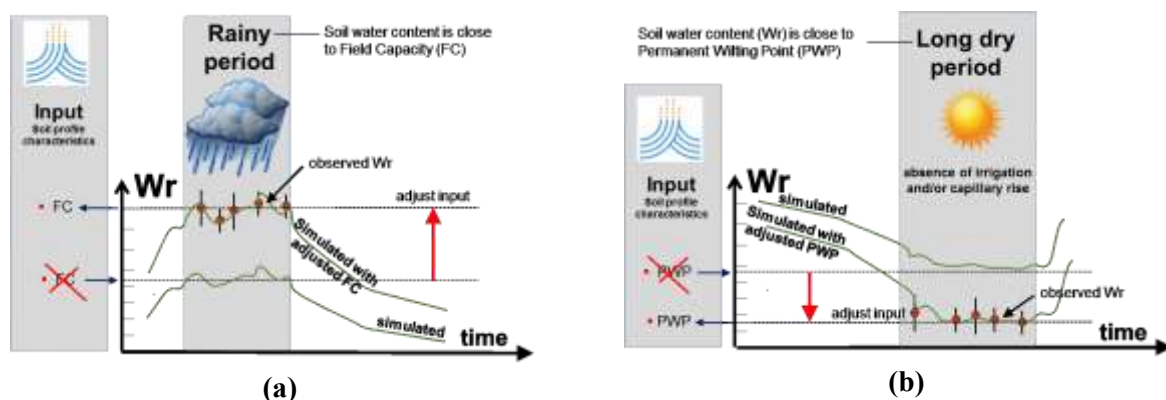


Fig. 6.7 – Comparing observed (points) with simulated (lines) soil water retained in the root zone (W_r), and the result on simulated W_r after the adjustment of (a) Field Capacity (FC) and (b) Permanent Wilting Point (PWP) in the soil profile characteristics.

When running a simulation, observed field data (specified in the *Field data* menu) and simulation results are plotted together in the *Evaluation of simulation results* menu. Next to a visual check,

statistical indicators (see AquaCrop reference manual) are available to evaluate the simulation. If the observed W_r is above or below the simulated W_r , check the values for Field Capacity and Permanent Wilting Point specified in the soil file:

- During a rainy period, the soil water content in the root zone remains close to Field Capacity (FC). If during such a period the observed W_r is above (or below) the simulated water content in the root zone, the specified value(s) for FC in the soil file are most likely wrong (Fig. 6.7a).
- The soil water content in the root zone will drop close to Permanent Wilting Point (PWP) at the end of a long dry period (and in the absence of irrigation or capillary rise). If during such a dry spell the observed W_r is above (or below) the simulated water content in the root zone, the specified value(s) for PWP in the soil file are most likely wrong (Fig. 6.7b).

6.5.3 Above-ground biomass production (B) – Step 3

Above ground biomass production (B) is obtained by multiplying the cumulative sum of (Tr/ETo), with the normalized biomass water productivity (WP^*).

☐ Compare observed with simulated above-ground biomass:

When running a simulation, observed field data and simulation results are plotted together. If the assessments in the previous steps, indicate a correct simulation of CC and Tr , detected differences between simulated biomass and observed biomass in the field, might be the result of:

- **poor sampling of the biomass:** Collecting field data of biomass consists in destructive sampling in a number of randomly selected small areas in the field, a few times during the growing cycle. The sampling areas should be large enough (at least 1 m²) and representative for the conditions in the field. To obtain dry above-ground biomass, the samples should stay in a well-ventilated oven for 48 hours at 65°C. Any biomass lost at the field by wind or removed by animals should be estimated, and accounted for when determining B;
- **occurrence of events not simulated by AquaCrop:** such as pests and diseases, and damage by hail storms.

6.5.4 Crop yield (Y) – Step 4

Crop yield (Y) is obtained by multiplying the total above-ground biomass (B), produced at crop maturity, with a Harvest Index (Eq. 4.6). If stresses developed during the growing cycle, HI has been adjusted to the stresses at run time (multiplier $\neq 1$), which makes that HI differs from the reference harvest index (Eq. 4.7). Conservative crop parameters and the correct simulation of the soil water balance, should guarantee a correct adjustment for HI.

☐ Check the reference harvest index (HIo):

If after all previous checks, the observed final yield is still different from the simulated yield, the inaccuracy might be due to the selected value for the reference harvest index (HIo). This might be the case when the simulated crop is of a different cultivar class than the crop specified in the crop file. Due to plant breeding and biotechnology, HIo is likely to increase in the future. On the other hand, local land races are likely to have a smaller HIo than the default specified in the crop files.

Annex I. AquaCrop training videos

The (43) training modules (MP4 videos) are posted in an 'AquaCrop Training' channel of YouTube. You can find the playlist and videos at the following link:

<https://www.youtube.com/playlist?list=PLzp5NgJ2-dK7H85cyEmGc8KSodqm8gCf2>

Unit 1. Introduction		
Video	Learning objective	Length [min:sec]
01. Introduction to AquaCrop	Discover AquaCrop	-
– Part 1. Need for Models		05:16
– Part 2. Practical applications		04:00
– Part 3. Calculation scheme		22:58
– Part 4. Input requirements		05:24
Unit 2. Climate - Conditions at the upper boundary		
Video	Learning objective	Length [min:sec]
02.1 Required weather data	Know the required weather data	08:33
02.2 Reference evapotranspiration	Understand the concept of the reference evapotranspiration (ET _o)	10:21
02.3 Determination of reference evapotranspiration	Become familiar with the determination of reference evapotranspiration	19:49
02.4 Import climatic data	Know how to import climatic data	19:35
Unit 3. Soil - Soil profile and lower boundary conditions		
Video	Learning objective	Length [min:sec]
03.1 Water retention and movement	Understand how AquaCrop describes water retention and water movement	-

	in the soil profile	
– Part 1. Soil physical characteristics		06:18
– Part 2. Soil water content		09:28
– Part 3. Soil water retention, soil water balance and required physical characteristics		15:36
– Part 4. Soil water movement and required physical characteristics		10:01
03.2 Soil profile characteristics	Know the required soil profile characteristics	10:23
03.3 Depth and quality of the groundwater table	Know the required conditions at the lower boundary	04:56
Unit 4. Crop		
Video	Learning objective	Length [min:sec]
04.1 Crop parameters	Know the required crop parameters	-
– Part 1. Type of crop parameters		06:23
– Part 2. Tuning of crop parameters		15:59
– Part 3. Crop development adjustment to temperature regimes		08:15
04.2 Stress coefficients	Understand the way the stress is simulated	06:52
04.3 Crop development	Understand how AquaCrop simulates crop development	13:23
04.4 Crop transpiration	Understand how AquaCrop simulates crop transpiration	09:22
04.5 Biomass production	Understand how AquaCrop simulates biomass production	10:59
04.6 Yield response to water	Understand how AquaCrop simulates yield and adjust the Harvest Index to stresses	-
– Part 1. Reference Harvest Index, Period of potential vegetative growth		07:35

– Part 2. Stresses affecting yield formation		17:19
04.7 Water productivity	Understand the concept of water productivity	06:56
Unit 5. Management		
Video	Learning objective	Length [min:sec]
05.1 Irrigation management	Know the required irrigation management parameters	-
– Part 1. Determination of net irrigation requirement		08:56
– Part 2. Evaluation of an irrigation schedule		12:11
– Part 3. Generation of an irrigation schedule, Deficit irrigation		19:54
05.2 Field management	Know the required field management parameters	-
– Part 1. Estimate of surface runoff, Practices affecting surface runoff		18:59
– Part 2. Mulches		05:19
– Part 3. Soil fertility		12:05
05.3 Calibration for soil fertility	Understand the procedure to calibrate the crop response to soil fertility stress	17:42
Unit 6. Simulation		
Video	Learning objective	Length [min:sec]
06.1 Initial conditions at start of the simulation period	Know the required initial conditions at the start of the simulation period	17:30
06.2 Start of the growing season	Understand how to determine the start of the growing cycle	06:40
06.3 Soil salinity	Understand how AquaCrop simulates soil salinity	not available
06.4 Climate change	Understand how AquaCrop simulates the effects of climate change on crop	09:44

	production	
06.5 Evaluation of simulation results	Understand how to evaluate simulations with field data	-
– Part 1. Green canopy cover		12:46
– Part 2. Crop transpiration		10:46
– Part 3. Above ground biomass production, Yield		05:37
06.6 Applications	Grasp the kind of applications that can be developed	-
– Part 1. Deficit irrigation		05:03
– Part 2. Scenario for policy makers		03:06
– Part 3. Improving water productivity		04:18
– Part 4. Scenario analysis for optimizing field management		not available
– Part 5. Effect of climate change		06:26
– Part 6. Yield forecast		04:59
– Part 7. Regional applications		07:41