Food and Agriculture Organization of the United Nations

Chapter 3
Calculation procedures

AquaCrop
Version 7.1

Reference manual

August 2023

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

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Calculation procedures

AquaCrop is a general model, in that it is meant for a wide range of herbaceous crops, including forage, vegetable, grain, fruit, oil, and root and tuber crops.

Chapter 3 presents the software of AquaCrop for which:
- the concepts and underlying principles are described by Steduto et al. (2009);
- the structure and algorithm are found in Raes et al. (2009), and
- the parameterization for maize (the crop on which the efforts of parameterization were focused during the early phase of model development) are reported by Hsiao et al. (2009).

Examples of crop development and production for specific climate and growing conditions estimated by AquaCrop are given in a lot of papers published in peer reviewed journals. A digital library of references to all AquaCrop publications can be found on: https://www.zotero.org/groups/aquacrop_publications

A set of training videos are posted in an 'AquaCrop training' channel of YouTube. The list of videos is provided in Chapter 5 of the AquaCrop Reference Manuel. For the playlist go the AquaCrop website of FAO: http://www.fao.org/nr/water/aquacrop.html

List of principal symbols

Symbol	Description	Unit
B	Dry (above-ground) biomass	Mg ha^{-1}
B_W	Crop dry (above-ground) biomass in weed infested field	Mg ha^{-1}
CC	Green Canopy Cover	m^2 m^{-2}
CC*	Green Canopy Cover adjusted for micro advection	m^2 m^{-2}
CC_{TOT}	Total canopy cover of crop and weeds	m^2 m^{-2}
CC_W	Green crop Canopy Cover in weed infested field	m^2 m^{-2}
cc_o	Canopy size of the average seedling at 90% emergence	cm^2
CC_o	Canopy Cover at 90% emergence or after transplanting	m^2 m^{-2}
CC_x	Maximum green Canopy Cover	m^2 m^{-2}
CDC	Canopy Decline Coefficient	d^{-1} or °C-d^{-1}
CGC	Canopy Growth Coefficient	d^{-1} or °C-d^{-1}
CN_{II}	Curve Number for antecedent moisture class II	-
CR	Capillary Rise	mm d^{-1}
Dr	Soil water depletion in root zone	mm
D_{Ztop}	Soil water depletion in top soil	mm
DP	Deep percolation	mm d^{-1}
E	Soil evaporation	mm d^{-1}
E_{TOT}	Soil evaporation in weed infested field	mm d^{-1}
E_x	Soil evaporation in Stage I (wet soil surface)	mm d^{-1}
ECe_n	Electrical conductivity of the saturated soil-paste extract: lower threshold (at which soil salinity stress starts to occur)	dS m^{-1}
ECe_x	Electrical conductivity of the saturated soil-paste extract: upper threshold (at which soil salinity stress has reached its maximum effect)	dS m^{-1}
EC_w	Electrical conductivity of the irrigation water	dS m^{-1}
ET	Evapotranspiration (soil water evaporation and crop transpiration)	mm d^{-1}
ET_o	Reference crop evapotranspiration (evaporating power of the atmosphere)	mm d^{-1}
f	Adjustment factor	-
f_{age}	Reduction coefficient describing the effect of ageing, nitrogen deficiency, etc. on the crop transpiration coefficient	d^{-1}
f_{sen}	Reduction coefficient describing the effect of canopy senescence on the crop transpiration coefficient	-
f_{weed}	Adjustment factor for canopy cover in a weed infested field	-
f_{yield}	Reduction coefficient describing the effect of the products synthesized during yield formation on the normalized water productivity	-

FC	Field Capacity	
GDD	Growing Degree Days	°C-d
HI	Harvest Index	%
HI_o	Reference Harvest Index	%
I	Irrigation	mm d^{-1}
K_{sat}	Saturated hydraulic conductivity	mm d^{-1}
Kc_{Tr}	Crop transpiration coefficient	-
$Kc_{Tr,x}$	Crop transpiration coefficient when complete canopy cover (CC = 1) but prior to senescence	-
Ke	Soil evaporation coefficient for fully wet soil surface	-
Ke_x	Soil evaporation coefficient for fully wet and non-shaded soil surface	-
Kr	Evaporation reduction coefficient	-
Ks	Stress coefficient	-
Ks_{aer}	Water stress coefficient for water logging (aeration stress)	-
Ks_{CCx}	Soil fertility stress coefficient for maximum Canopy Cover	-
$Ks_{exp,f}$	Soil fertility stress coefficient for canopy expansion	-
$Ks_{exp,w}$	Water stress coefficient for canopy expansion	-
$Ks_{pol,c}$	Cold stress coefficient for pollination	-
$Ks_{pol,h}$	Heat stress coefficient for pollination	-
$Ks_{pol,w}$	Water stress coefficient for pollination	-
Ks_{salt}	Soil salinity stress coefficient	-
Ks_{sen}	Water stress coefficient for canopy senescence	-
Ks_{sto}	Water stress coefficient for stomatal closure	-
$Ks_{sto,salt}$	Soil salinity stress coefficient for stomatal closure	-
Ks_{Tr}	Cold stress coefficient for crop transpiration	-
Ks_{WP}	Soil fertility stress coefficient for crop biomass Water Productivity	-
$p_{exp,\ lower}$	Fraction of TAW depleted at which CGC becomes 0	-
$p_{exp,\ upper}$	Fraction of TAW depleted at which CGC starts to be reduced	-
p_{pol}	Fraction of TAW depleted at which pollination starts to fail	-
p_{sen}	Fraction of TAW depleted at which early canopy senescence is triggered	-
p_{sto}	Fraction of TAW depleted at which stomata start to close	-
P	Precipitation	mm.d^{-1}
PWP	Permanent Wilting Point	
RAW	Readily Available soil Water in the root zone	mm
RC	Relative cover of weeds	
REW	Readily Evaporable Water	mm
RO	Surface runoff	mm.d^{-1}
S	Root extraction term	$m^3.m^{-3}.d^{-1}$
S_x	Maximum root extraction term	$m^3.m^{-3}.d^{-1}$

t	Time	GDD or d
T	Air temperature	°C
T_{avg}	Average air temperature	°C
T_{base}	Base temperature (below which crop development does not progress)	°C
T_n	Daily minimum air temperature	°C
T_{upper}	Upper temperature (above which crop development no longer increases with an increase in air temperature)	°C
T_x	Daily maximum air temperature	°C
Tr	Crop transpiration	$mm.d^{-1}$
Tr_{TOT}	Total transpiration of crop and weeds	$mm.d^{-1}$
Tr_W	Crop transpiration in weed infested field	$mm.d^{-1}$
Tr_x	Maximum crop transpiration (for a well-watered crop)	$mm.d^{-1}$
TAW	Total Available soil Water (between FC and PWP) in the root zone	mm
Wr	Soil water content in the root zone expressed as an equivalent depth	mm
WP	Crop biomass water productivity	$Mg\ ha^{-1} mm^{-1}$
WP^*	Crop biomass water productivity normalized for ET_o and air CO_2 concentration	$Mg\ ha^{-1}$
Y	Dry crop yield	$Mg\ ha^{-1}$
Y_W	Dry crop yield in weed infested field	$Mg\ ha^{-1}$
$Z_{e,surf}$	Evaporating soil surface layer	m
$Z_{e,top}$	Top soil layer from which water flows to the evaporating surface layer	m
Ztop	Top soil layer for determining soil water stress	m
Zr	Effective rooting depth	m
Zr_n	Minimum effective rooting depth	m
Zr_x	Maximum effective rooting depth	m
Δz	Thickness of soil compartment	m
θ	Volumetric soil water content	$m^3.m^{-3}$
$\theta_{air\ dry}$	Soil water content when air dry	$m^3.m^{-3}$
θ_{FC}	Soil water content at FC	$m^3.m^{-3}$
θ_{PWP}	Soil water content at PWP	$m^3.m^{-3}$
θ_{sat}	Soil water content at soil saturation	$m^3.m^{-3}$
τ	Drainage coefficient	-

The calculation scheme of AquaCrop

The calculation approach of AquaCrop consists of the successive simulation of (1) the green canopy cover, (2) crop transpiration, (3) biomass production and (4) crop yield, all for each day of the growing cycle, as previously described by Steduto et al., (2009) and Raes et al., (2009).

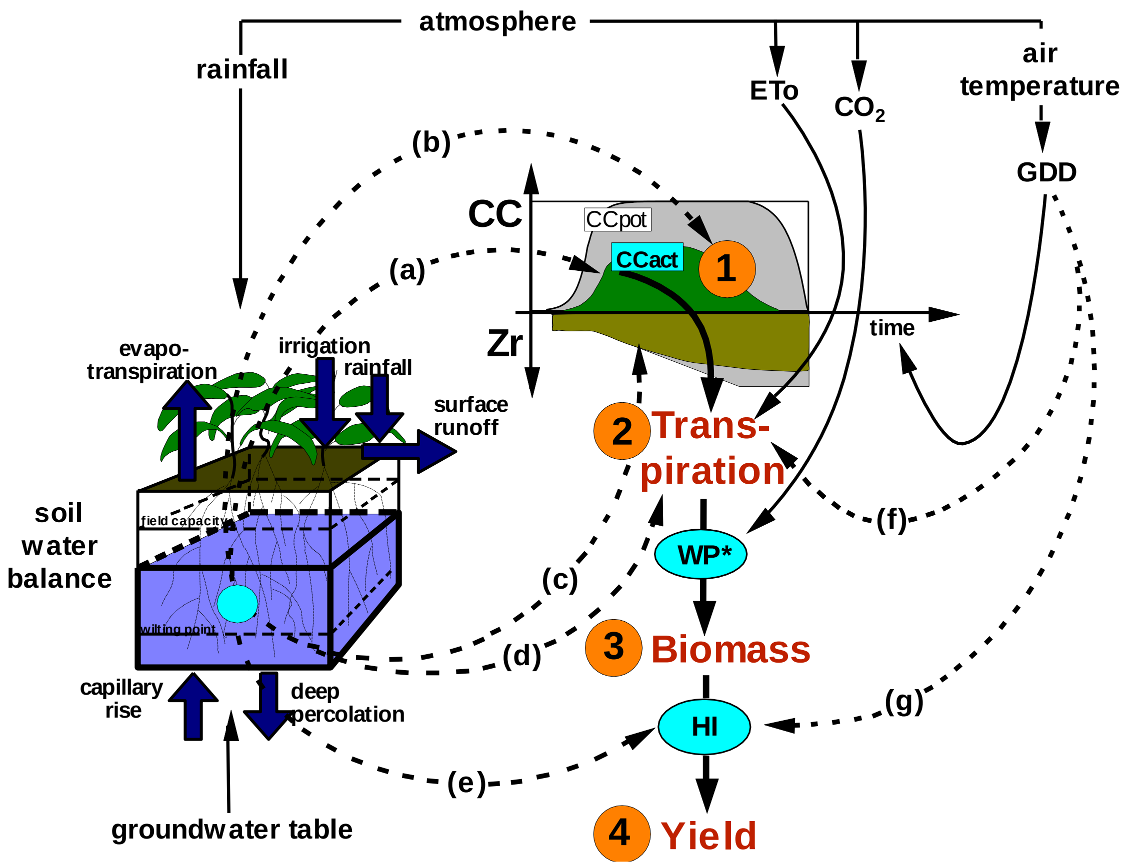


Figure 1. – Calculation scheme of AquaCrop with indication of the 4 steps, and the processes (dotted arrows) affected by water stress (a to e) and temperature stress (f to g). CC is the green canopy cover; Zr the rooting depth; ETo the reference evapotranspiration; WP* the normalized biomass water productivity; HI the harvest index; and GDD the 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. AquaCrop considers also the effect of ***weed infestation***, ***soil fertility*** and ***soil salinity stress*** on canopy development, crop transpiration and biomass production.

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. Driven by temperature (GDD), CC increases from the canopy cover at germination to a maximum value which can be 1 if 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 proportional to the simulate CC at that day. 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):** By using a normalized biomass water productivity factor (WP*), AquaCrop calculates the daily above-ground biomass from daily transpiration. The water productivity factor 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 growing cycle. By using a Harvest Index (HI), which is the fraction of B that is the harvestable product, crop yield (Y) is obtained from B. Water and temperatures stresses adjust daily the HI.

3.1 The root zone as a reservoir

3.1.1 Incoming and outgoing water fluxes

In a schematic way, the root zone can be considered as a reservoir (Fig. 3.1a). By keeping track of the incoming and outgoing water fluxes at the boundaries of the root zone, the amount of water retained in the root zone (Wr) and the root zone depletion (Dr) can be calculated at any moment of the season by means of a soil water balance.

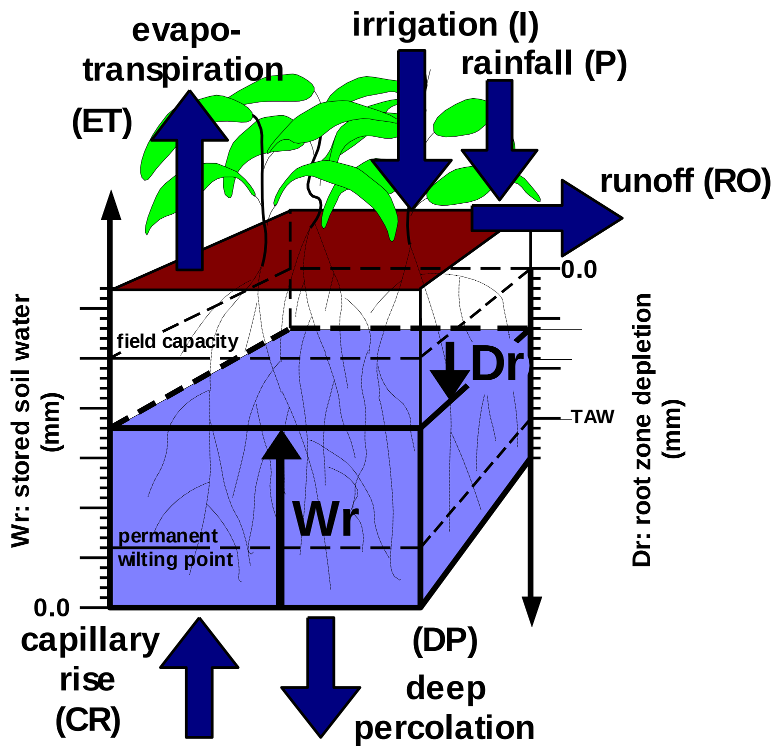


Figure 3.1a – The root zone as a reservoir

Water is added to the soil reservoir by rainfall and irrigation. When the rainfall intensity is too high, part of the precipitation might be lost by surface runoff and only a fraction will infiltrate. The infiltrated water cannot always be retained in the root zone. When the root zone is too wet, part of the soil water percolates out of the root zone and is lost as deep percolation. Water can also be transported upward to the root zone by capillary rise from a shallow groundwater table. Processes such as soil evaporation and crop transpiration remove water from the reservoir.

3.1.2 Stored soil water and soil water depletion

When calculating the soil water balance, the amount of water stored in a soil volume (e.g. top soil or root zone, Fig. 3.1b) can be expressed as stored soil water (W) or as soil water depletion (D).

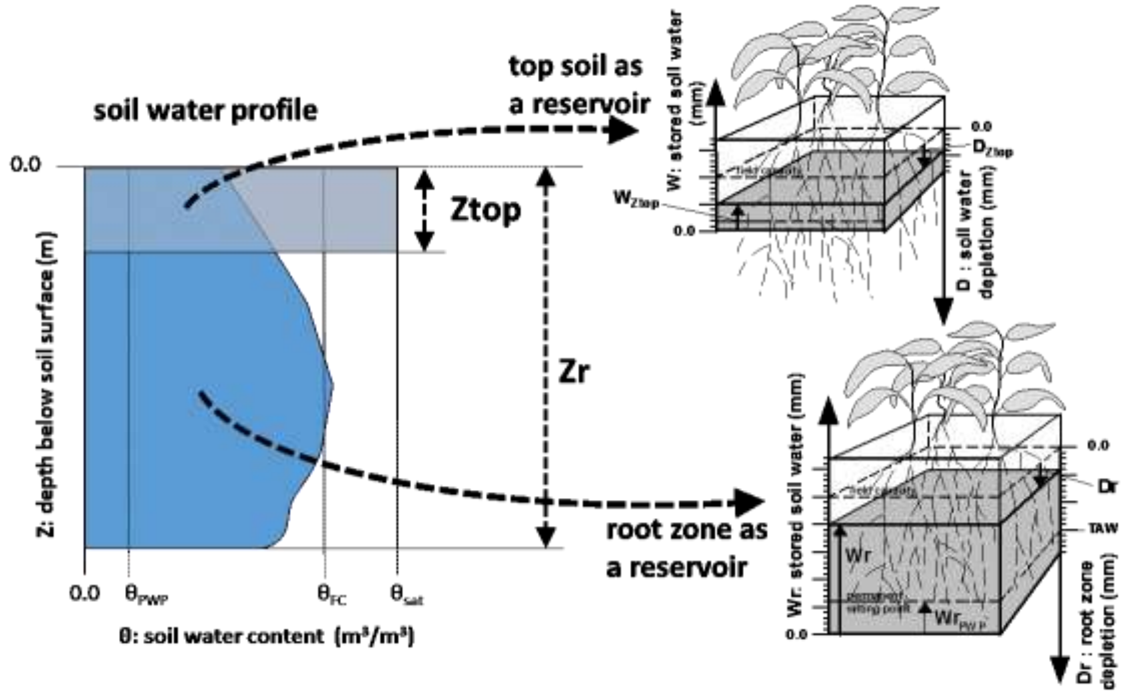


Fig. 3.1b – Soil water profile (θ-z) and the top soil and root zone depicted as a reservoir with indication of the stored water (W) and depletion (D)

- **Stored soil water expressed as an equivalent depth**

Expressing the water content in a particular soil volume as an equivalent depth is useful when computing the soil water balance of the root zone. It makes the adding and subtracting of gains and losses of water straightforward since the various parameters of the soil water balance such as rain and evapotranspiration are usually expressed in terms of water depth.

The stored soil water in the root zone expressed as a depth is given by:

$$Wr = 1000\,\theta\,Zr\left(1 - \frac{Vol\%_{gravel}}{100}\right) \qquad \text{(Eq. 3.1a)}$$

where	Wr	soil water content of the root zone expressed as a depth [mm];
	θ	average volumetric water content in the fine soil fraction of the root zone [m^3(water)/m^3(fine soil)];
	Zr	effective rooting depth [m];
	$Vol\%_{gravel}$	volume percentage of the gravel fraction in the root zone.

The stored soil water in the top soil expressed as a depth is given by:

$$W_{Ztop} = 1000\,\theta_{top}\ Ztop\left(1 - \frac{Vol\%_{gravel}}{100}\right) \qquad \text{(Eq. 3.1b)}$$

where W_{Ztop} soil water content of the top soil expressed as a depth [mm];
θ_{top} average volumetric water content in the fine soil fraction of the top soil [m^3(water)/m^3(fine soil)];
Ztop thickness of the top soil [m];
$Vol\%_{gravel}$ volume percentage of the gravel fraction in the top soil.

- **Soil water depletion**

Expressing the soil water content in the root zone as a shortage is useful for irrigation planning and to assess water stresses. The soil water depletion refers to the amount of water that is required to bring the water amount in the considered soil volume back to the reference level which is field capacity. Field capacity is selected as the reference since it expresses the maximum amount of water that can be retained against the gravitational forces.

The root zone depletion is given by:

$$Dr = Wr_{FC} - Wr = 1000\left(\theta_{FC} - \theta\right) Zr\left(1 - \frac{Vol\%_{gravel}}{100}\right) \qquad \text{(Eq. 3.1c)}$$

where Dr root zone depletion [mm];
Wr_{FC} soil water content of the root zone at field capacity [mm]: = 1000 θ_{FC} Zr (1- $Vol\%_{gravel}$/100);
Wr soil water content of the root zone expressed as depth [mm];
θ_{FC} volumetric water content at field capacity [m^3/m^3(fine soil)];
θ average volumetric water content in the fine fraction of the root zone [m^3(water)/m^3(fine soil)].

The soil water depletion in the top soil is given by:

$$D_{Ztop} = W_{top,\,FC} - W_{Ztop} = 1000\left(\theta_{top,\,FC} - \theta_{top}\right) Ztop\left(1 - \frac{Vol\%_{gravel}}{100}\right) \qquad \text{(Eq. 3.1d)}$$

where D_{Ztop} soil water depletion [mm] in the top soil;
$W_{top,\,FC}$ soil water content of the top soil at field capacity [mm]: = 1000 $\theta_{top,FC}$ Ztop (1- $Vol\%_{gravel}$/100);
W_{Ztop} soil water content in the top soil expressed as depth [mm];
$\theta_{top,FC}$ volumetric water content at field capacity [m^3/m^3(fine soil)];
θ_{top} average volumetric water content in the fine fraction of the top soil [m^3(water)/m^3(fine soil)].

After heavy rainfall or the application of a large amount of irrigation water, the water content in the considered soil volume can be temporarily above field capacity. This results in negative root zone depletion (i.e. excess of water).

- **Total Available soil Water (TAW)**

The total available soil water or plant extractable water is the amount of water a crop can theoretically extract from the fine soil fraction of the considered soil volume (Fig. 3.1b). Since (i) the water content above field capacity cannot be retained in the soil and will be lost by drainage, and (ii) the water content below permanent wilting point is so strongly attached to the soil matrix that it cannot be extracted by plant roots, the Total Available soil Water is the amount of water held in the fine soil fraction of the considered soil volume between field capacity and permanent wilting point:

$$TAW = 1000\left(\theta_{FC} - \theta_{WP}\right) Z \left(1 - \frac{Vol\%_{gravel}}{100}\right) = W_{FC} - W_{PWP} \qquad \text{(Eq. 3.1e)}$$

where	TAW	total available soil water in the considered soil volume [mm];
	θ_{FC}	volumetric water content at field capacity [m^3/m^3(fine soil)];
	θ_{WP}	water content at permanent wilting point [m^3/m^3(fine soil)];
	Z	depth of the considered soil volume (e.g. top soil or root zone) [m];
	W_{FC}	soil water content in the soil volume at field capacity [mm];
	W_{PWP}	water content in the soil volume at permanent wilting point [mm];
	$Vol\%_{gravel}$	volume percentage of the gravel fraction in the soil volume.

At permanent wilting point the root zone depletion is equal to TAW.

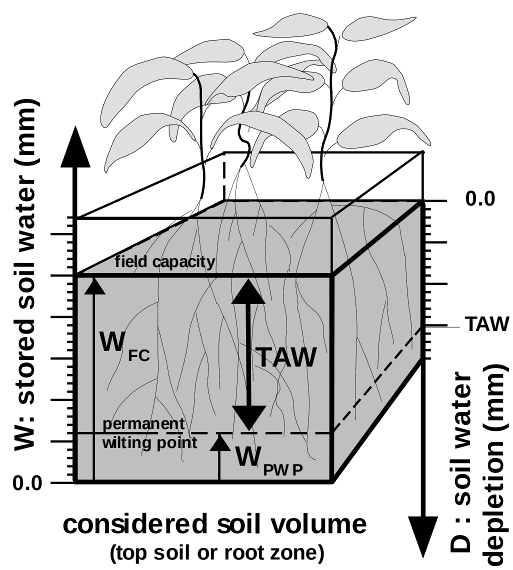


Figure 3.1c – The soil water content in the considered soil volume at Field Capacity (W_{FC}) and at Permanent Wilting Point (W_{PWP}), and the Total Available soil Water (TAW)

3.2 Stresses

Crop growth might be affected by soil water stress, air temperature stress, soil fertility stress or soil salinity stress.

3.2.1 Stress response functions

Effects of stresses on crop growth are described by stress coefficients Ks. In essence, Ks is a modifier of its target model parameter, and varies in value from one (no stress) to zero (full stress). Above the upper threshold of a stress indicator, the stress is non-existent and Ks is 1. Below the lower threshold, the effect is maximum and Ks is 0 (Fig. 3.2a).

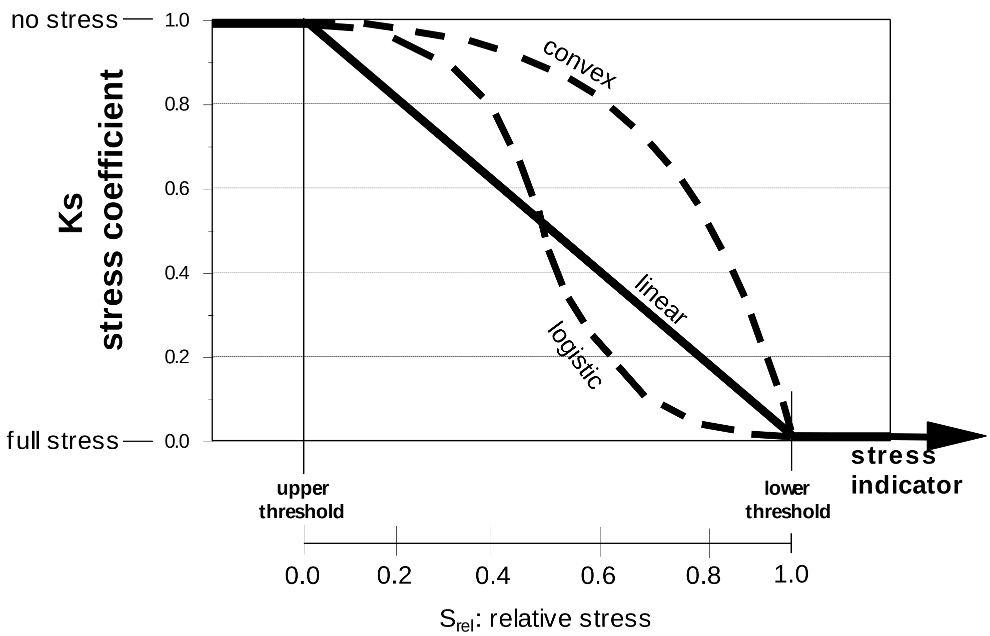


Figure 3.2a – The stress coefficient (Ks) for various degrees of stress and for different shapes of the Ks curve

The relative stress level (S_{rel}) and the shape of the Ks curve determines the magnitude of the effect of the stress on the process between the thresholds. S_{rel} is 0.0 at the upper threshold and 1.0 at the lower threshold (Fig. 3.2a). The shape can be linear, convex, or logistic.

- **Linear shape**

If a ***linear shape*** is considered, the effect of stress on the process is directly proportional to the relative stress:

$$Ks = 1 - S_{rel} \qquad \text{(Eq. 3.2a)}$$

- **Convex shape**

Convex curves (curves outwards) make that the process is only strongly affected when the stress becomes severe. The shape and degree of curvature of the Ks curve are described by:

$$Ks = 1 - \frac{e^{S_{rel}\ f_{shape}} - 1}{e^{f_{shape}} - 1} \qquad \text{(Eq. 3.2b)}$$

where S_{rel} (≤ 1) is the relative stress level and f_{shape} is the shape factor. The shape factor is positive ($f_{shape} > 0$) for convex curves.

- **Logistic shape**

For the logistic shape, Ks for various S_{rel} is given by:

$$Ks = \frac{S_n\ S_x}{S_n + \left(S_x - S_n\right)\exp^{-r\left(1-S_{rel}\right)}} \qquad \text{(Eq. 3.2c)}$$

where S_n and S_x are the relative stress levels at the lower and upper threshold respectively, and r the rate factor. Given that Ks is 0.5 midway the lower and upper threshold, the rate factor can be obtained by solving Eq. 3.2c for Ks = 0.5 and S_{rel} = 0.5. Since S_{rel} is zero at the lower threshold, a small value for S_n has to be considered. After solving Eq. 3.2c, Ks has to be corrected for the considered small value.

3.2.2 Soil water stress

- **Soil water stress coefficients**

Soil water stress affects the development of the canopy cover, the expansion of the root zone, results in stomata closure and a reduction of crop transpiration rate, and alters the Harvest Index. If the soil water stress is severe it can result in failure of pollination, and can trigger early canopy senescence. The soil water stress coefficients considered by AquaCrop and their effects on crop growth are presented in Table 3.2a.

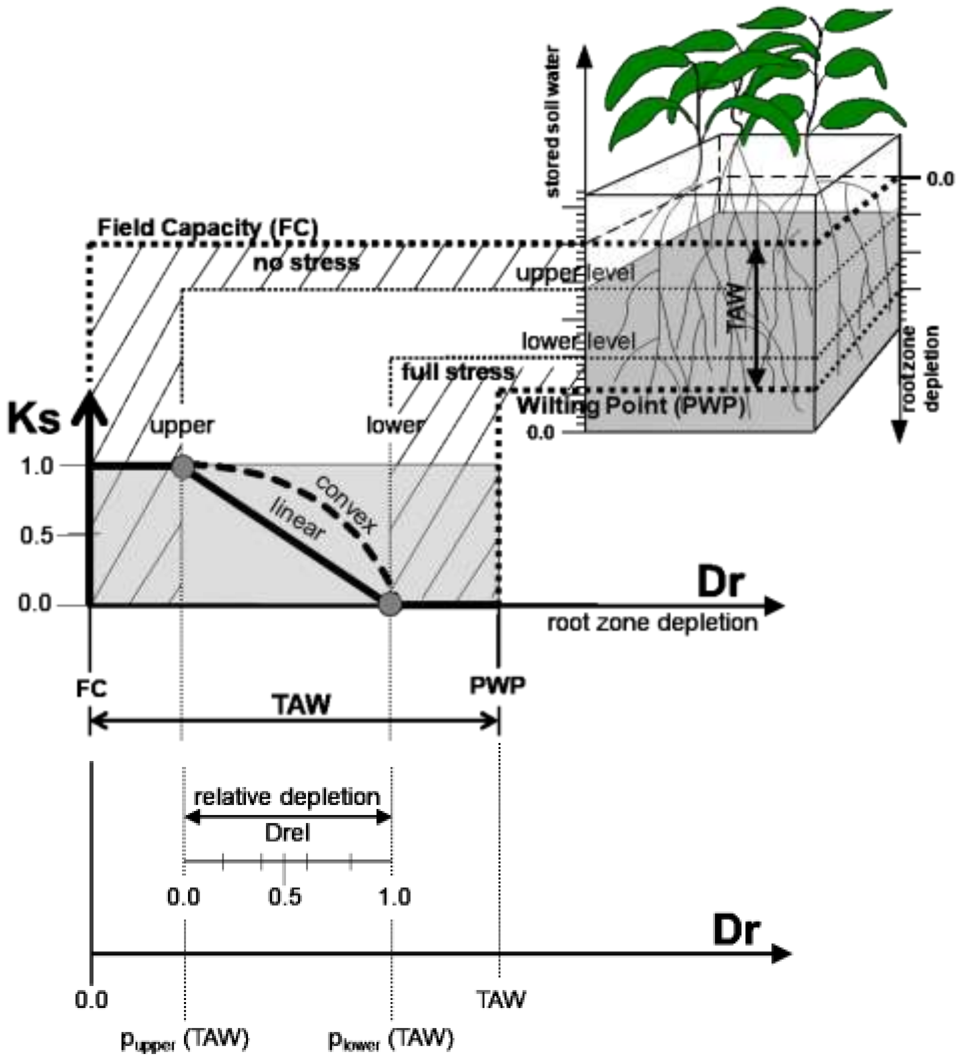


Figure 3.2b – The water stress coefficient (Ks) for various degrees of root zone depletion (Dr)

The stress indicator for soil water stress is depletion (shortage versus field capacity) which is expressed as a fraction (p) of TAW depleted. Water stress starts to affect the process when the soil water depletion (in the root zone or top soil) exceeds p_{upper} TAW. At the lower threshold, when the depletion is equal to p_{lower} TAW, the effect of water stress is at its full strength (Fig. 3.2b). Each of the processes affected by soil water stress has its own threshold levels. For leaf and hence canopy growth ($Ks_{exp,w}$) the lower threshold is above PWP, whereas for stomata closure (Ks_{sto}), senescence (Ks_{sen}) and failure of pollination ($Ks_{pol,w}$) the lower threshold is fixed at PWP. The shape of the Ks curve can be linear or convex.

Since the stress response curves are defined for an evaporating power of the atmosphere (ET_o) of 5 mm/day, the upper and lower thresholds for water stress (p) needs to be adjusted for ET_o:

$$0 \leq p_{adj} = p_{given} + f_{adj} \left(0.04 \left(5 - ET_0\right)\right) \left(\log_{10}\left(10 - 9\, p_{given}\right)\right) \leq 1 \qquad \text{(Eq. 3.2d)}$$

where f_{adj} (default value = 1) is a program parameter which can be varied to increase (> 1) or decrease (< 1) the adjustment. The log term in the equation makes the adjustment greater when the soil is wet then when it is dry, based on the likely restriction of transpiration (and hence less impact of evaporative demand) when the soil is dry.

Table 3.2a – Considered soil water stress coefficients and their effect on crop growth

Soil water stress coefficient	Direct effect	Target model parameter
$\mathbf{Ks_{aer}}$ Soil water stress coefficient for water logging (aeration stress)	Reduces crop transpiration	Tr_x
$\mathbf{Ks_{exp,w}}$ Soil water stress coefficient for canopy expansion	Reduces canopy expansion and (depending on timing and strength of the stress) might have a positive effect on the Harvest Index	CGC and HI
$\mathbf{Ks_{pol,w}}$ Soil water stress coefficient for pollination	Affects pollination and (depending on duration and strength of the stress) might have a negative effect on the Harvest Index	HI_o
$\mathbf{Ks_{sen}}$ Soil water stress coefficient for canopy senescence	Reduces green canopy cover	CC
$\mathbf{Ks_{sto}}$ Soil water stress coefficient for stomatal closure	Reduces crop transpiration and the root zone expansion, and (depending on timing and strength of the stress) might have a negative effect on the Harvest Index	Tr_x, dZ and HI

- **Determination of soil water stress**

To allow a light rain to reduce the soil water stress of deep rooted crops, the root zone depletion (Dr) is compared with the depletion in the top soil (D_{Ztop}) at each time step of the simulation. The comparison determines which part of the soil profile is the wettest and controls the water stress. To allow comparison between Dr and D_{Ztop}, the depletions are relative and expressed as the fraction of TAW depleted in the root zone or in the top soil (Fig. 3.2c):

- If Dr (expressed in fraction of TAW depleted) is smaller than $D_{ZTop,}$, then the root zone is relative wetter than the top soil, and determines the water stresses. By comparing the soil water content in the root zone (Wr) with the threshold soil water contents, the degree of soil water stress affecting leaf expansion, inducing stomatal closure and triggering early senescence is obtained, and the corresponding crop response can be simulated.
- IF D_{Ztop} is smaller than Dr, then the top soil is relative wetter than the whole root zone (Fig. 3.2c). Consequently, the soil water content in the top soil (W_{Ztop}) is considered to determine if one or more water stresses occur and how severe they are.

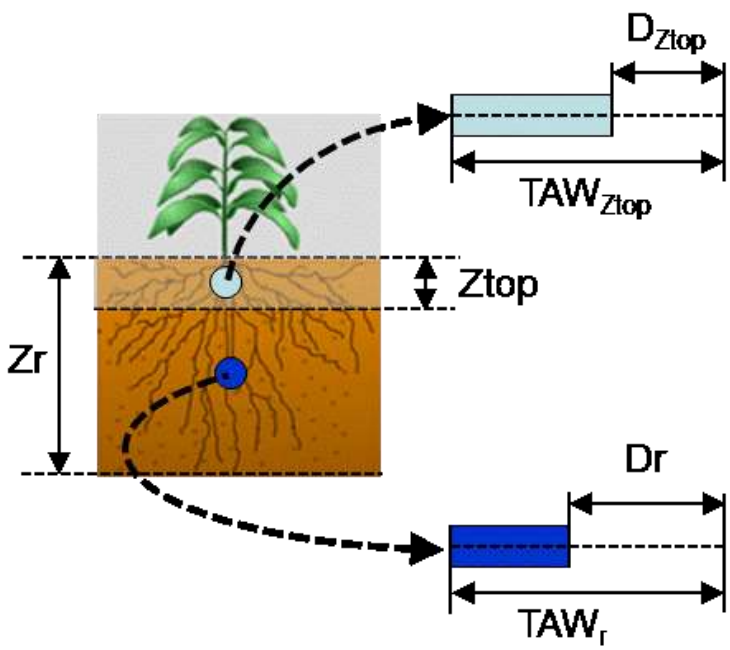


Figure 3.2c – Comparison between the root zone depletion (Dr) and the depletion in the top soil (D_{Ztop}) to determine which part of the soil profile is the wettest and controls the water stress

The thickness of the top soil (Ztop), is a program parameter, which can be altered by the user.

3.2.3 Air temperature stress

Crop transpiration and pollination of flowers might be affected by air temperature stress. The air temperature stress coefficients considered by AquaCrop and their effects on crop growth are presented in Table 3.2b.

Table 3.2b – Considered air temperature stress coefficients and their effect on crop growth

Air temperature stress coefficient	Direct effect	Target model parameter
Ks_{Tr} Cold stress coefficient for crop transpiration	Reduces crop transpiration	$Kc_{Tr,x}$
$Ks_{pol,c}$ Cold stress coefficient for pollination	Affects pollination and (depending on duration and strength of the stress) might have a negative effect on the Harvest Index	HI_o
$Ks_{pol,h}$ Heat stress coefficient for pollination	Affects pollination and (depending on duration and strength of the stress) might have a negative effect on the Harvest Index	HI_o

Stress indicators for air temperature stress are growing degrees (Ks_{Tr}), minimum air temperature ($Ks_{pol,c}$) or maximum air temperature ($Ks_{pol,h}$). If it is a cold stress, the process is completely halted (Ks = 0) at and below the lower threshold, and not affected (Ks = 1) at and above the upper threshold (Fig. 3.2d). For heat stress it is the other way round: below the lower threshold of the maximum air temperature Ks is 1, and above the upper threshold Ks becomes zero. For air temperatures stresses a logistic shape of the Ks curve is considered.

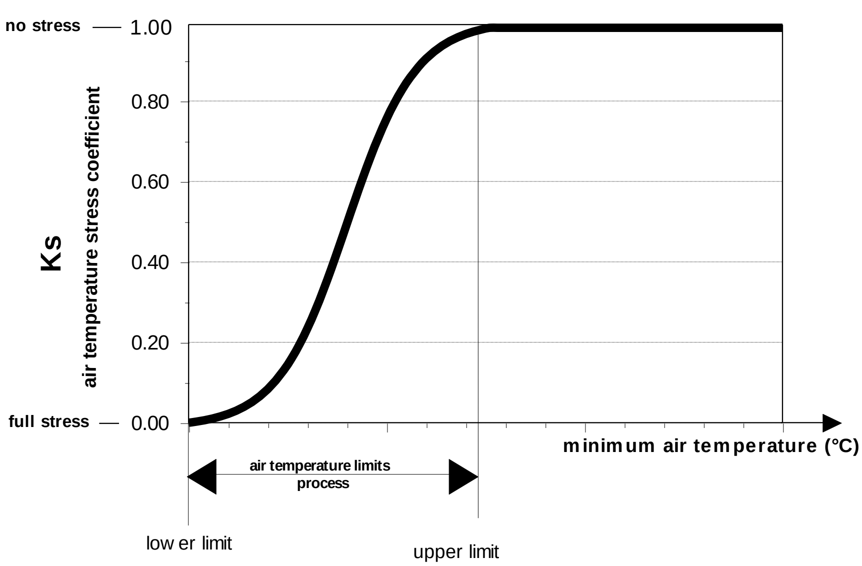


Figure 3.2d – The cold stress coefficient (Ks) for various air temperatures

3.2.4 Soil fertility stress

Canopy development and biomass production might be affected by soil fertility stress. The stress coefficients considered by AquaCrop and their effects on crop growth are presented in Table 3.2c. Next to the 3 stress coefficients (Ks), AquaCrop considers also a decline coefficient ($f_{CDecline}$) which uses the same stress indicator and is also a modifier of a model parameter.

Table 3.2c – Considered soil fertility stress coefficients and their effect on crop growth

Soil fertility stress coefficient	Direct effect	Target model parameter
Ks_{CCx} Stress coefficient for maximum Canopy Cover	Reduces canopy cover	CC_x
$Ks_{exp,f}$ Stress coefficient for canopy expansion	Reduces canopy expansion	CGC
Ks_{WP} Stress coefficient for Biomass Water Productivity	Reduces biomass production	WP*
$f_{CDecline}$ Decline coefficient of canopy cover	Decline of the canopy cover once the maximum canopy cover is reached	CC

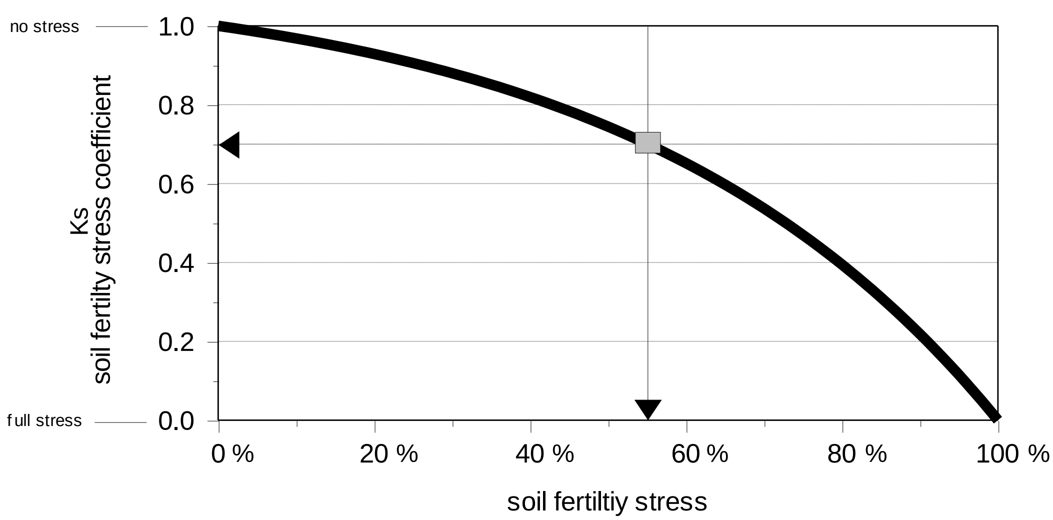


Figure 3.2e – The soil fertility stress coefficient (Ks) for various levels of stress, with indication of the calibration point (square) determining the shape of the Ks curve

The stress indicator for soil fertility stress is the degree of soil fertility stress which varies from 0 %, when soil fertility is non-limiting, to a theoretical 100 % when soil fertility stress is so severe that crop production is no longer possible (Fig 3.2e). Between the upper and lower limits for soil fertility, Ks varies from 1 (no stress) to 0 (full stress).

The shape of the Ks curves is determined at calibration by specifying a Ks value between 1 and 0 for the particular soil fertility stress at which the crop response is calibrated (see Chapter 2, 'Calibration for soil fertility'). Once a curve is calibrated, the Ks corresponding to other degrees of soil fertility stress is obtained from the curve.

The simulation of the effect of soil fertility stress is described in section 3.14 ('Simulation of the effect of soil fertility stress') of this chapter.

3.2.5 Soil salinity stress

Crop production might be affected by soil salinity stress. The soil salinity stress coefficient considered by AquaCrop and its effect is presented in Table 3.2d.

Table 3.2d – Soil salinity stress coefficient and its effect on crop production

Soil salinity stress coefficient	Direct effect	Target model parameter
Ks_{salt} Soil salinity stress coefficient	Reduces biomass production	CC and Kc_{Tr}

The average electrical conductivity of saturation soil-paste extract (ECe) from the root zone is the indicator for soil salinity stress. At the lower threshold of soil salinity (ECe_n) the stress starts to affect biomass production and Ks_{salt} becomes smaller than 1. At and above the upper threshold for soil salinity (ECe_x) the stress becomes so severe that biomass production ceases and Ks_{salt} is zero (Fig. 3.2f). The shape of the Ks curve is linear. Values for ECe_n and ECe_x for many agriculture crops are given by Ayers and Westcot (1985) in the Irrigation and Drainage Paper Nr. 29 (see Annex III).

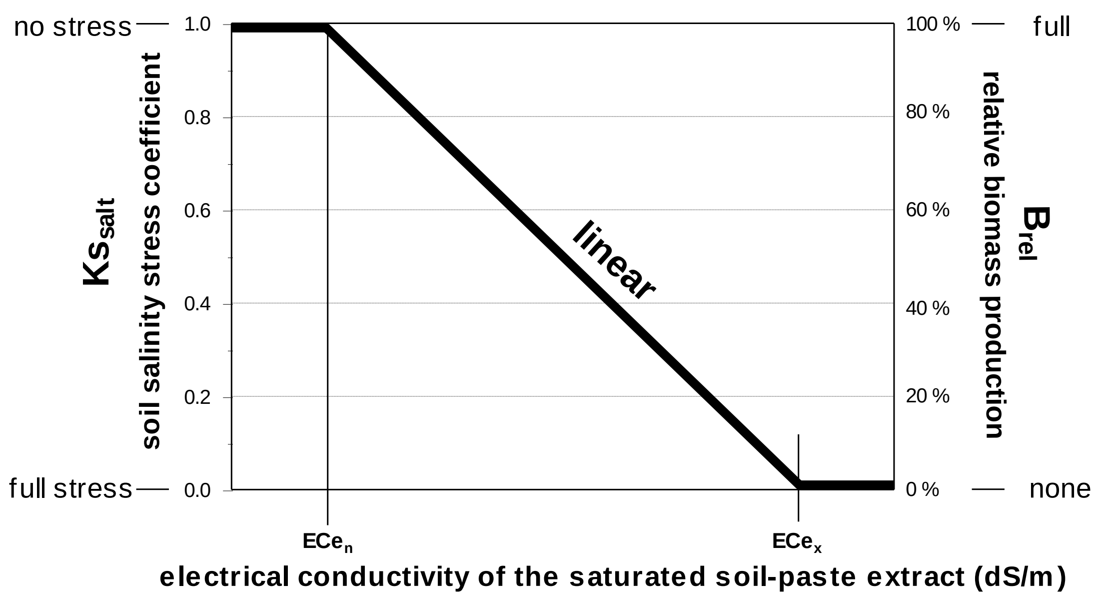


Figure 3.2f – Soil salinity stress (Ks_{salt}) and relative biomass production for various electrical conductivity of the soil-paste extract

To simulate the effect of soil salinity on biomass production (B), AquaCrop considers a set of stress coefficients which (i) affect canopy development (similar as the effect of soil fertility stress) and (ii) induces stomatal closure. The stress coefficients considered by

AquaCrop and their effects on crop growth are presented in Table 3.2e. Next to the 3 stress coefficients (Ks), AquaCrop considers also a decline coefficient ($f_{CDecline}$) which uses the same stress indicator and is also a modifier of a model parameter. To consider the effect of the concentration of the salts in the remaining soil water when the root zone dries out, the value for $Ks_{sto,salt}$ is further adjusted by considering the average electrical conductivity of the soil water in the root zone (ECsw).

Table 3.2e – Considered soil salinity stress coefficients and their effect on crop growth

Soil salinity stress coefficient	Direct effect	Target model parameter
$\mathbf{Ks_{CCx}}$ Stress coefficient for maximum Canopy Cover	Reduces canopy cover	CC_x
$\mathbf{Ks_{exp,f}}$ Stress coefficient for canopy expansion	Reduces canopy expansion	CGC
$\mathbf{Ks_{sto,salt}}$ Soil salinity stress coefficient for stomatal closure	Reduces crop transpiration	Ks_{sto}
$\mathbf{f_{CDecline}}$ Decline coefficient of canopy cover	Decline of the canopy cover once the maximum canopy cover is reached	CC_x

The simulation of the effect of soil salinity stress is described in section 3.15 (‘Simulation of the effect of soil salinity stress’) of this chapter.

The simulation of the effect of soil fertility and soil salinity stress is described in section 3.16 (‘Simulation of the effect of soil fertility and soil salinity stress’) of this chapter.

3.3 Growing Degree Days

Heat units, expressed in growing degree-days (GDD), can be used in AquaCrop to describe crop development. With this method, the duration of a process or the time required to reach a particular stage is expressed in GDD (°C day) instead of number of days.

Growing degree days (GDD) are calculated by subtracting the base temperature (T_{base}) from the average air temperature, T_{avg} (Fig. 3.3):

$$GDD = T_{avg} - T_{base} \qquad \text{(Eq. 3.3a)}$$

The base temperature (T_{base}) is the temperature below which crop development does not progress. In AquaCrop an upper threshold temperature (T_{upper}) is considered as well. The upper temperature threshold specifies the temperature above which crop development no longer increases with an increase in air temperature.

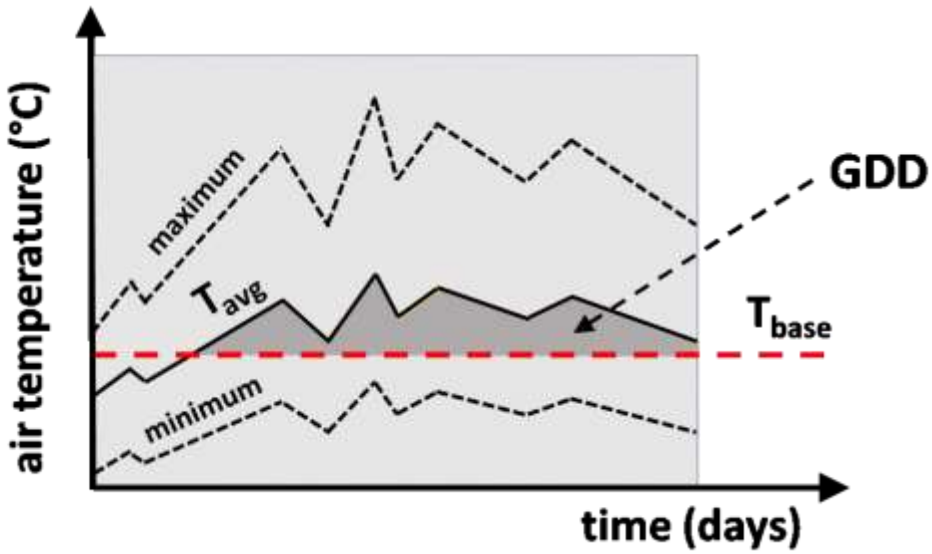


Figure 3.3 – Average temperature (T_{avg}), base temperature (T_{base}) and corresponding growing degree-days (GDD)

McMaster and Wilhelm (1997) present two methods for calculating T_{avg} in Eq. 3.3a. The authors report that Method 1 predominates among researchers and practitioners involved with small grain cereals such as wheat and barley. Method 2 is the most commonly used in calculating GDD for corn, but it is used for other crops as well. In AquaCrop a 3rd method is added.

3.3.1 Method 1

The average air temperature (T_{avg}) is given by:

$$T_{avg} = \frac{(T_x + T_n)}{2} \qquad \text{(Eq. 3.3b)}$$

where T_x is the daily maximum air temperature and T_n the daily minimum air temperature. Once T_{avg} is calculated, it is checked if the average air temperature is between T_{base} and T_{upper}. If T_{avg} is less than T_{base}, then T_{avg} is taken as T_{base} (resulting in 0 °C day for that day). If T_{avg} is greater than T_{upper}, then T_{avg} is taken equal to T_{upper} and the growing degrees for that day are at its maximum (T_{upper} - T_{base}).

3.3.2 Method 2

In this method the comparison to T_{base} and T_{upper} occurs before the calculation of the average temperature. T_n and T_x are adjusted if they drop below T_{base} or exceed T_{upper} before T_{avg} is calculated. The average temperature is given by:

$$T_{avg} = \frac{\left(T_x^* + T_n^*\right)}{2} \qquad \text{(Eq. 3.3c)}$$

where T_x^* and T_n^* are the adjusted maximum and/or minimum air temperatures. The following rules apply:

- T_x^* is the maximum air temperature ($T_x^* = T_x$)
  If T_x is greater than T_{upper}, then $T_x^* = T_{upper}$,
  If T_x is smaller than T_{base}, then $T_x^* = T_{base}$
- T_n^* is the minimum air temperature ($T_n^* = T_n$)
  If T_n is greater than T_{upper}, then $T_n^* = T_{upper}$,
  If T_n is smaller than T_{base}, then $T_n^* = T_{base}$

3.3.3 Method 3

As in method 2, the comparison to T_{base} and T_{upper} occurs before the calculation of the average temperature. However the check is only on the maximum air temperature. The average temperature is given by:

$$T_{avg} = \frac{\left(T_x^* + T_n\right)}{2} \qquad \text{(Eq. 3.3d)}$$

where T_x^* is the adjusted maximum air temperature and T_n the minimum air temperature. The following rules apply:

- T_x^* is the maximum air temperature ($T_x^* = T_x$)
  If T_x is greater than T_{upper}, then $T_x^* = T_{upper}$,
  If T_x is smaller than T_{base}, then $T_x^* = T_{base}$
- T_n is not adjusted. However if T_n exceeds T_{upper}, T_n will be set equal to T_{upper}.

Once T_{avg} is calculated, it is checked if the average air temperature is above the base temperature. If T_{avg} is less than T_{base}, then T_{avg} is taken as T_{base} (resulting in 0 °C day on that day).

3.4 Green canopy cover for optimal conditions

3.4.1 Green canopy cover throughout the crop cycle

The development and senescence of the green canopy under optimal conditions (Fig 3.4a) is described by four parameters:

- CC_o : initial canopy cover at the time of 90% crop emergence [fraction or percentage ground cover]. The initial canopy cover is the product of plant density and the size of the canopy cover per seedling;
- CGC : canopy growth coefficient [fraction or percentage ground cover increase per day or growing degree day];
- CC_x : maximum canopy cover for that plant density under optimal conditions [fraction or percentage ground cover];
- CDC: canopy decline coefficient [fraction or percentage ground cover decline per day or growing degree day];

and the moment when green canopy senescence is triggered (i.e. the start of canopy senescence counting from sowing or transplanting).

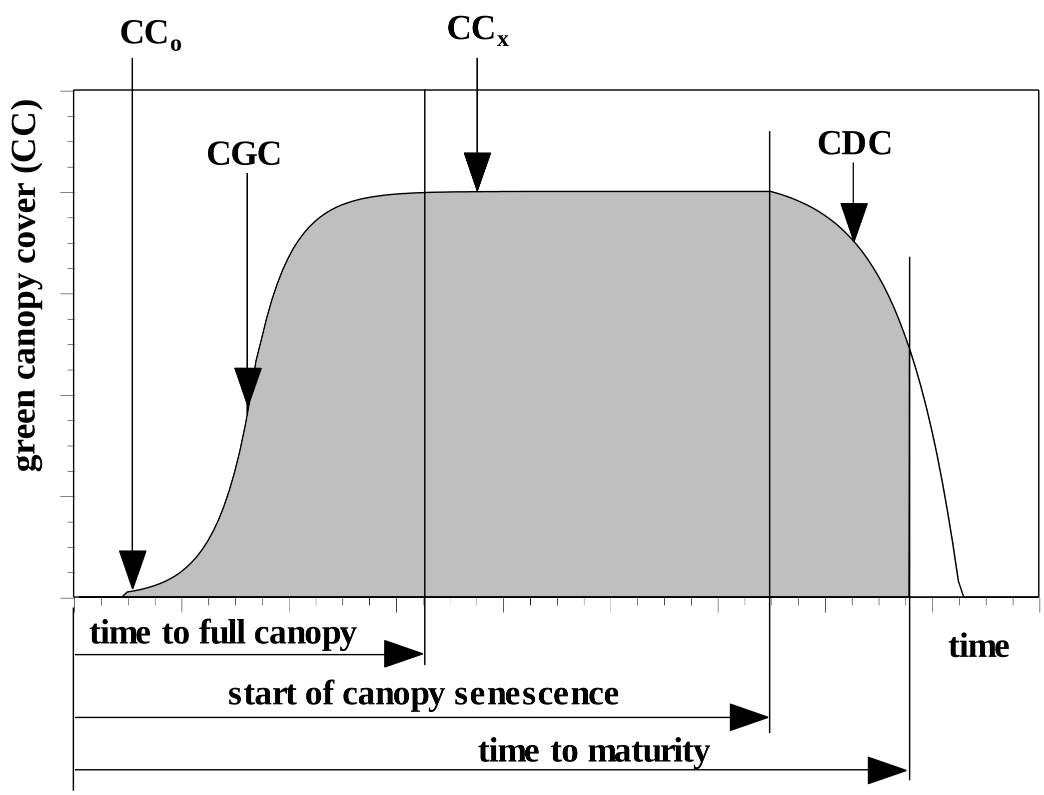


Figure 3.4a – Variation of green canopy cover throughout the growing cycle under non-stress conditions

CC_o, CGC and CC_x determine the time required to reach maximum canopy cover. If CC_o and CGC are large, the maximum canopy (CC_x) is reached quickly. If crop development starts with a small CC_o, the period to reach maximum canopy cover will be longer. The canopy decline coefficient CDC determines the rate of the green canopy decline in the late season. Often crops will be mature and be ready to harvest before the full canopy decline is achieved.

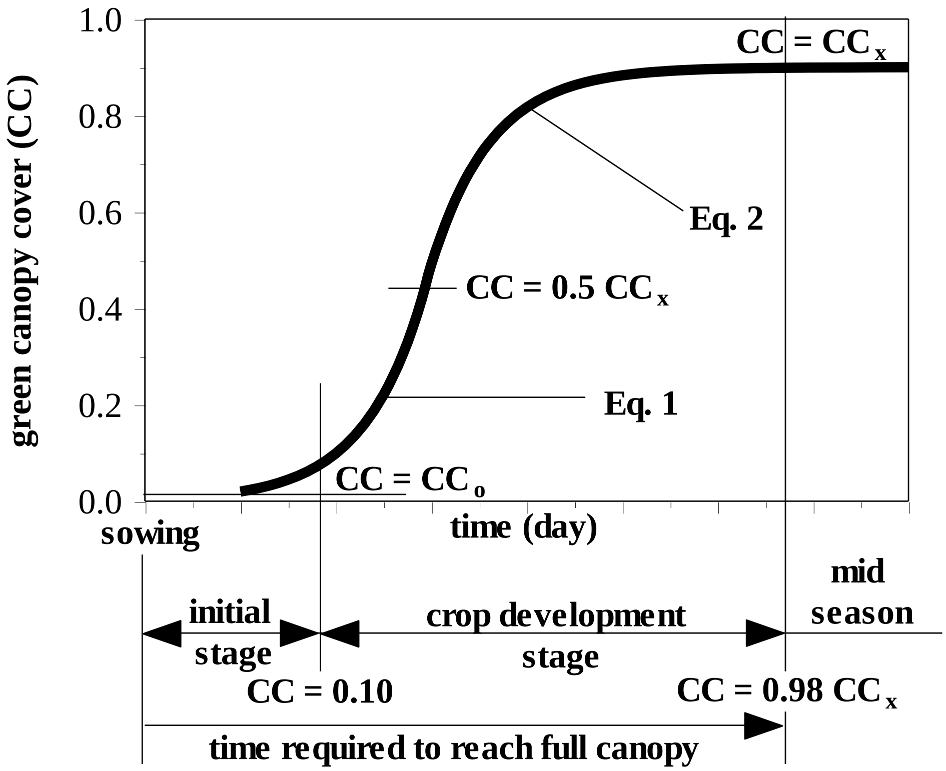


Figure 3.4b – Schematic representation of canopy development during the exponential growth (Eq. 1) and the exponential decay (Eq. 2) stages

3.4.2 Canopy development

Canopy development (Figure 3.4b) is simulated by two equations:

- Equation 1 (exponential growth) is valid when CC $\leq$ $CC_x/2$

$$CC = CC_o \, e^{t\,CGC} \qquad \text{(Eq.3.4a)}$$

- Equation 2 (exponential decay) is valid when CC $>$ $CC_x/2$

$$CC = CC_x - 0.25 \frac{(CC_x)^2}{CC_o} e^{-t\,CGC} \qquad \text{(Eq. 3.4b)}$$

where CC canopy cover at time t [fraction ground cover];

CC_o initial canopy size at t=0 [fraction ground cover];

CC_x maximum canopy cover [fraction ground cover];

CGC canopy growth coefficient [increase of fraction ground cover per day or growing degree day];

t time [day or growing degree day].

3.4.3 Germination and initial canopy cover at 90% crop emergence

- **The initial canopy cover at germination**

The initial canopy cover at germination is determined by the sowing or planting density. CC_o is estimated from the sowing or planting density (plants per hectare) and the canopy cover of the seedling (cm^2). Options are available to estimate the planting density from sowing rate and approximate germination rate, or from plant spacing.

- **Required soil water content for triggering germination**

To trigger germination during a simulation run, the soil water content in the top soil needs to be above a threshold value. The threshold value for the soil water content is expressed as a fraction of TAW and is a program parameter. The top soil considered at germination is the effective rooting depth at planting (Z_n) and refers to the soil depth from which the germinating seed can extract water (see 3.6.1 – Effective rooting depth at planting).

- **Delayed germination**

When the soil water content in the top soil is below the threshold at the moment of the user specified or generated sowing date, germination is not simulated. The germination is delayed, as long as the soil water content in the top soil remains below the threshold. During the period of delayed germination, the time advances and the number of delayed days is tracked.

When, as a result of rain and/or irrigation, the soil water content raises above the threshold, the crop will germinate and AquaCrop (Fig. 3.4b/2):

(i) shifts the start of the growing cycle with the number of delayed days, but also adjusts the length of the growing cycle to the thermal regime of the shifted growing cycle. If due to the delayed germination, part of the crop development ends up in a warmer/cooler period than before, the growing cycle becomes shorter/longer than previously determined, and

(ii) extends the simulation period so that its end coincides with the adjusted date of maturity.

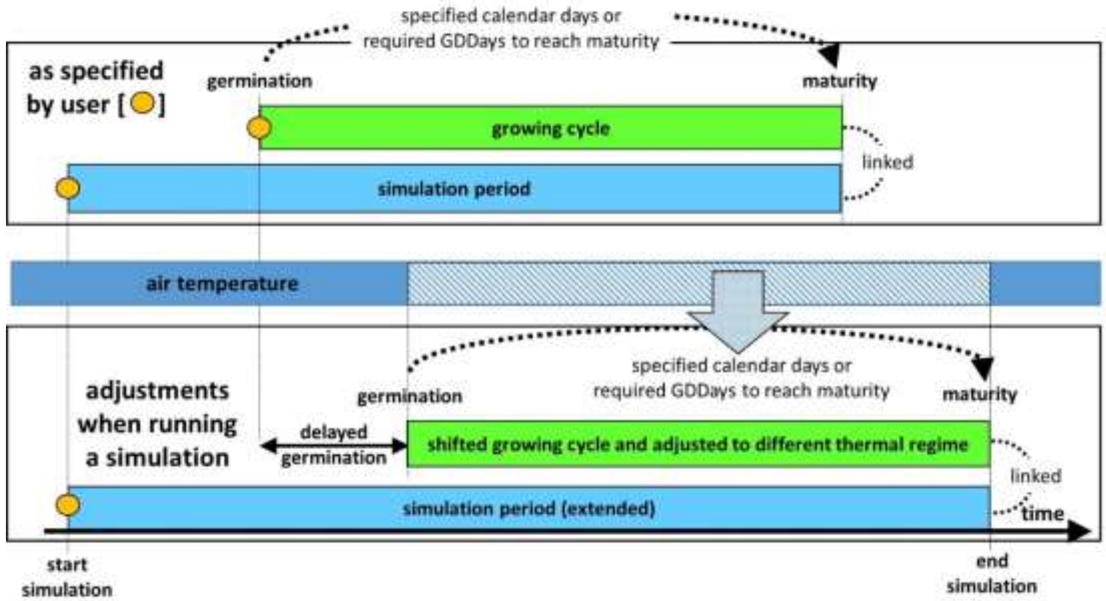


Figure 3.4b/2 – Adjustment of growing cycle to the required growing degree-days to reach maturity and expansion of the simulation period provoked by a delayed germination in AquaCrop.

3.4.4 Maximum canopy cover (CC_x)

For no stress conditions, the canopy cover will reach the maximum canopy cover, CC_x. For optimal conditions CC_x is determined by crop species and plant density.

3.4.5 Green canopy cover decline

The decline in green crop canopy is described by:

$$CC = CC_x \left[1 - 0.05 \left(e^{\frac{3.33\,CDC}{CC_x + 2.29}t} - 1 \right) \right] \qquad \text{(Eq. 3.4c)}$$

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

The Canopy Decline Coefficient (CDC) is a measure for the speed of decline of the green canopy once it is triggered. A large CDC results in a steep decline of the canopy, while the canopy senescence will be more gradually by selecting a smaller CDC (Fig. 3.4c).

The constants in the numerator and denominator of the exponent in Eq. 3.4c, makes the simulation of duration of senescence less divergent for different CCx (Fig. 3.4d).

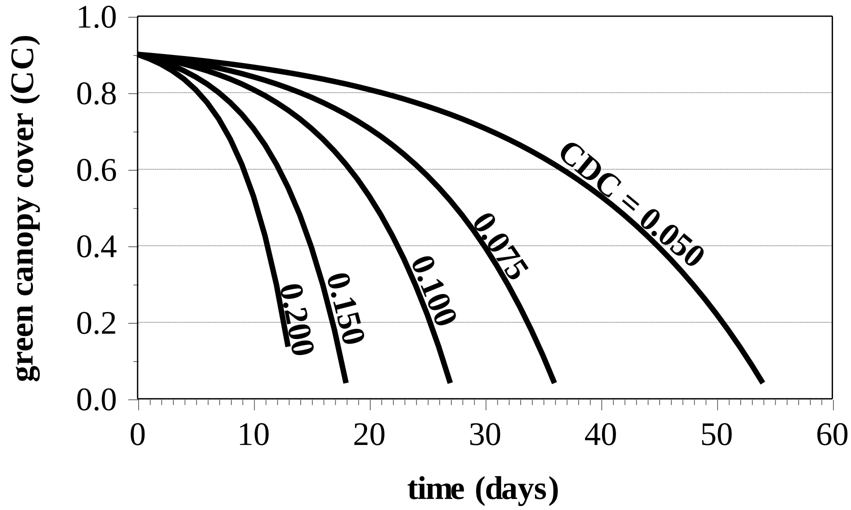


Figure 3.4c – Decline of green canopy cover during senescence for various canopy decline coefficients (CDC) as described by Eq. 3.4c. All lines have initial green canopy cover at 0.9 and starting time at 0

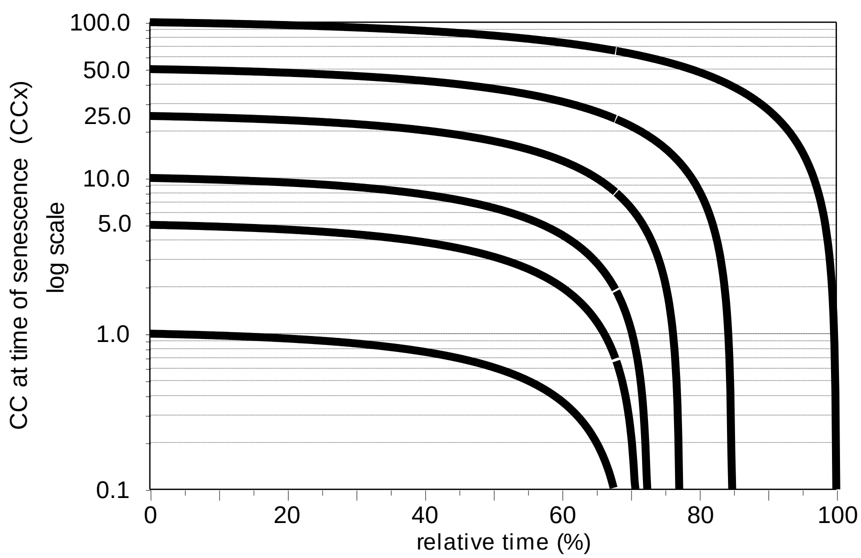


Figure 3.4d – Relative time for the canopy to reach zero%, for various CCx at the start of senescence (for CDC = 0.004 per GDD)

3.4.6 Green canopy cover for perennial herbaceous forage crops

- **Green canopy cover**

For the planting/sowing year (1st season), the development and senescence of the green canopy cover under optimal conditions is the same as for an annual crop (Fig. 3.4a). For a non-planting/sowing year (not 1st season), the canopy starts as regrowth (Fig. 3.4d/2).

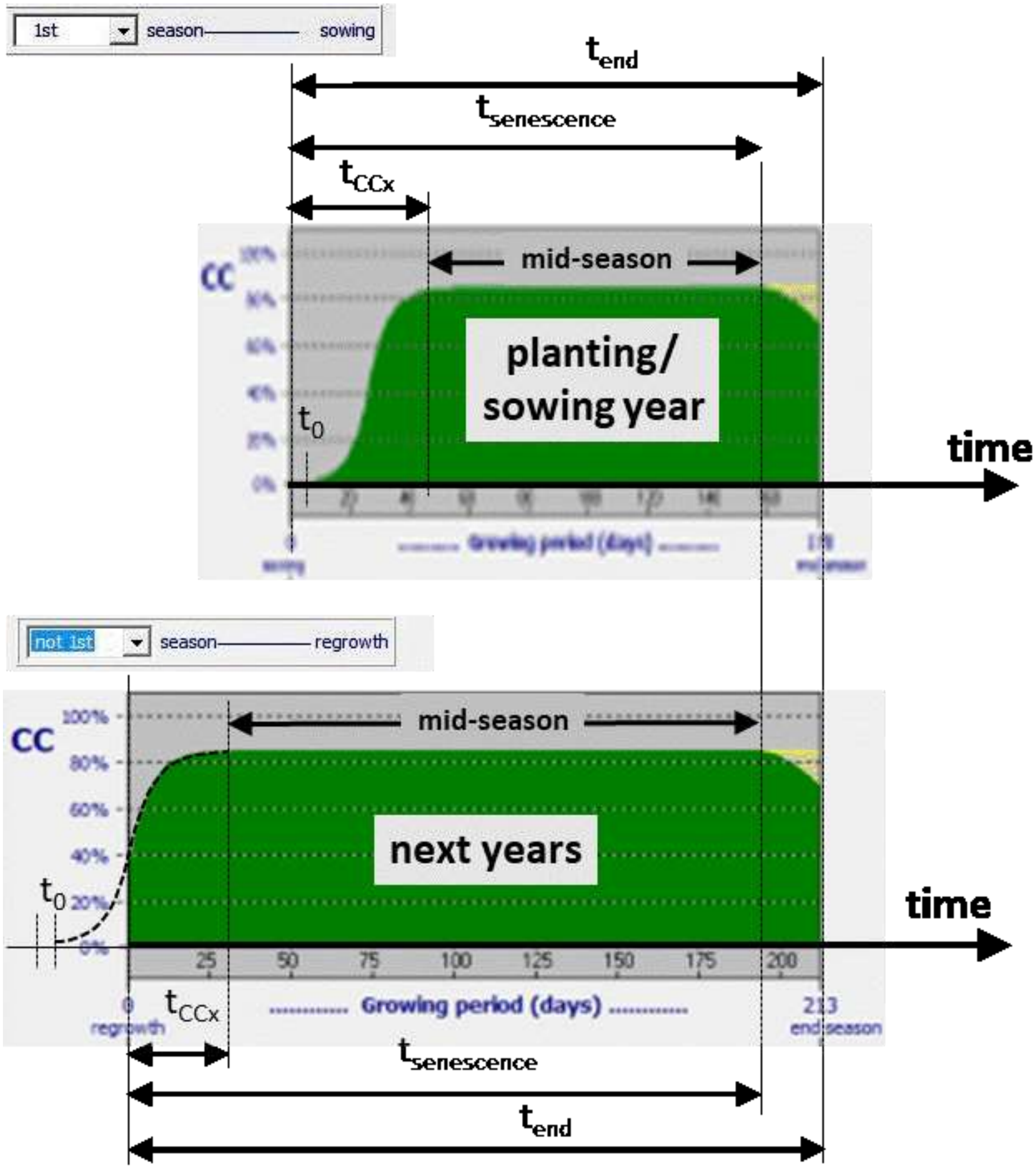


Figure 3.4d/2 – Canopy development for herbaceous forage crops in a 1st (planting/sowing year) and not a 1st season (non-planting/sowing year).

Procedures have been worked out to guarantee that the length of the season in any year remain between the (fixed or generated) start and end dates of the season. It consisted in stretching the length of the mid-season in a non-planting/sowing year, so that the time to reach senescence and crop maturity remains identical for a '1st' and a 'not 1st season' (Fig.

3.4d/2). The mid-season starts when the maximum canopy cover (CCx) is reached till the start of the natural canopy senescence at the end of the season.

The time ‘t_0’ in Figure 3.4d/2, is the time at which the crop germinates (in case of sowing) or recovers (in case of transplanting) in the 1st season (planting/sowing year). For a ‘not 1st season’, t_0 is still required to simulate the canopy development at the 1st day of regrowth

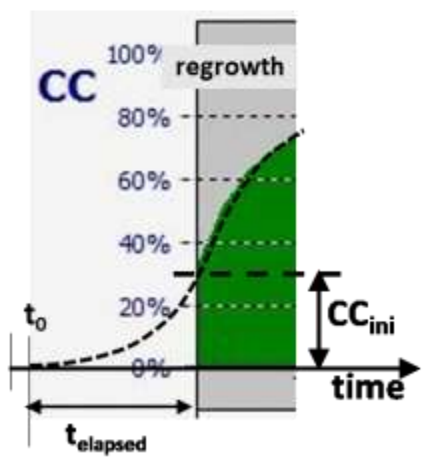
In AquaCrop, canopy development is simulated by two equations:

- Equation 1 (exponential growth) is valid when CC $\leq$ $CC_x/2$

$$CC = CC_o \, e^{t\,CGC} \qquad \text{(Eq.3.4a)}$$

- Equation 2 (exponential decay) is valid when CC $>$ $CC_x/2$

$$CC = CC_x - 0.25 \frac{(CC_x)^2}{CC_o} e^{-t\,CGC} \qquad \text{(Eq. 3.4b)}$$

<table>
<tr><td>For a ‘not 1st season’ (non-planting/sowing year), the time t (days or growing degree days) in equations 1 and 2 needs to be increased with the time required to reach CCini (at the 1st day of regrowth) starting from CCo. This so called elapsed time (time to reach CCini) is given by:</td><td rowspan="3">
</td></tr>
<tr><td>If $CC_{ini} \leq CCx/2$ (exponential growth):
$$t_{elapsed} = \frac{ln\left(\frac{CC_{ini}}{CC_0}\right)}{CGC} \qquad \text{(Eq. 3.4c/1)}$$</td></tr>
<tr><td>If $CC_{ini} > CCx/2$ (exponential decay):
$$t_{elapsed} = -\frac{ln\left(\frac{(CC_x - CC_{ini})\,CC_0}{0.25\,CC_x^2}\right)}{CGC} \qquad \text{(Eq. 3.4c/2)}$$</td></tr>
</table>

CC_{ini} is the canopy cover at the start of regrowth, and given by the plant density (at planting/sowing year) and the size of the individual plant (cm²) when regrowth starts (ccini). In the case of regrowth, ccini ≥ cc0.

▪ **Simulation of the natural self-thinning of the plant population over the seasons**

The initial plant population of perennials progressively self-thins over the years. In AquaCrop this natural self-thinning (induced by climatic factors such as killing frost) is specified in the crop file. The natural self-thinning of the plant population over the years is described by 2 crop parameter (Table 3.4d/1).

Table 3.4d/1 – Crop parameters describing the natural self-thinning

Symbol	Description	Type
n_y	The number of years at which the maximum canopy cover (CC_x) declines to 90% of its initial value of the 1st year	Dependent on environment and/or management
k_n	Shape factor describing the decline of the maximum canopy cover (CC_x) over the years	

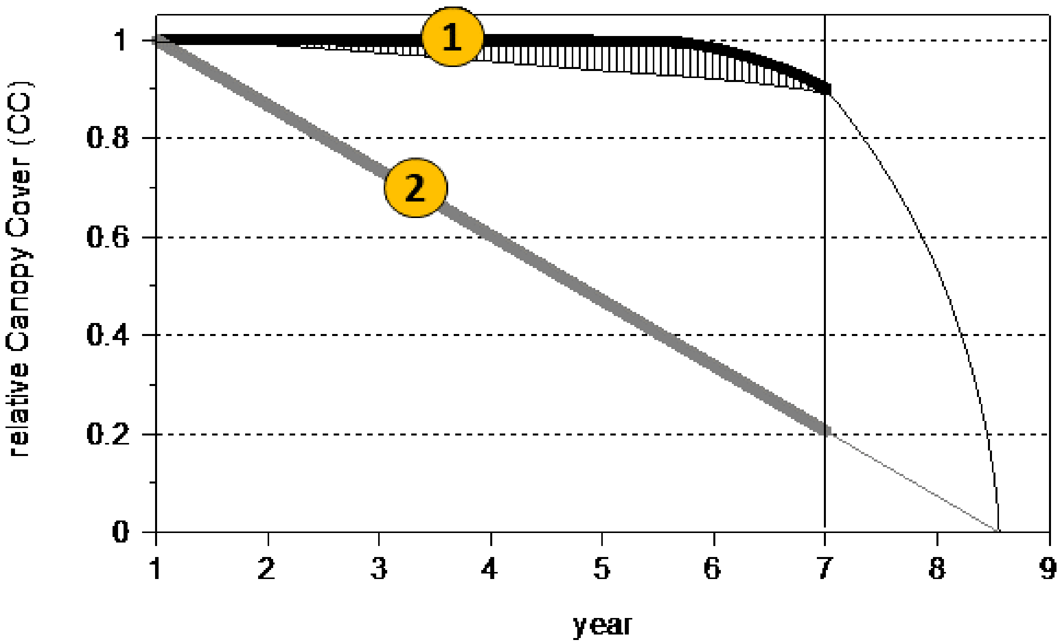


Figure 3.4d/3 – The correction factor f_{CCx} (Eq. 3.4c/3) adjusting the maximum canopy cover (line 1) and the correction factor f_{CCo} (Eq. 3.4c/4) adjusting the minimum canopy cover (line 2) for the successive years with n_y = 7 years and k_n = 0.1. The arched area gives the range for k_n (from 0.05 at the top to 0.80 at the bottom of the area).

The canopy development over the successive years (with n_x = 7 years and k_n = 0.1) as simulated by AquaCrop is plotted in Figure 3.4d/4. To maintain high yielding stands, re-establishment of the stand might be required after 6 to 7 years.

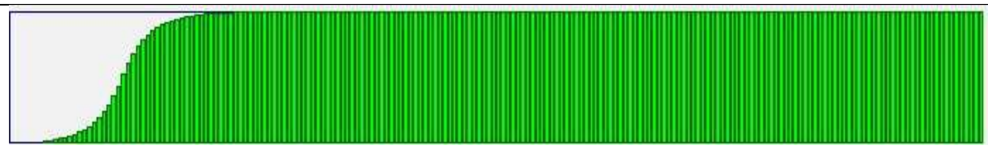
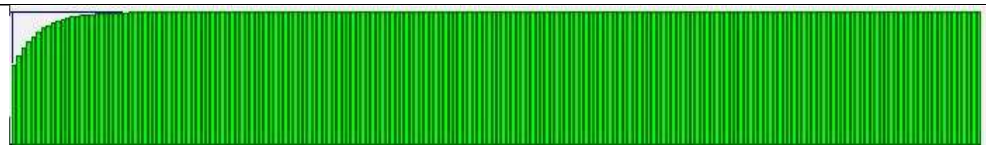
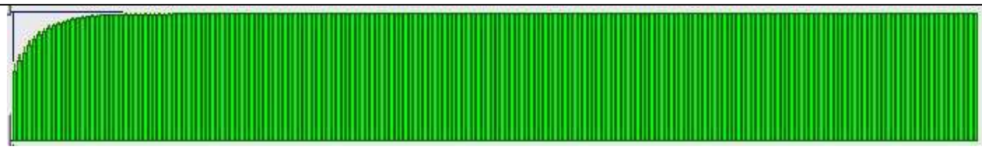
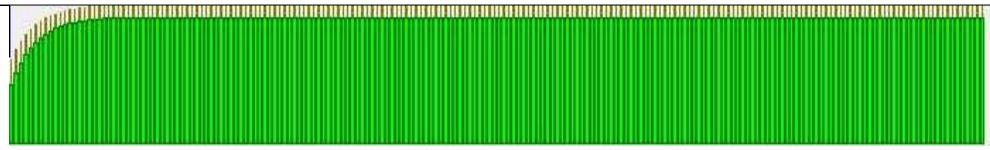
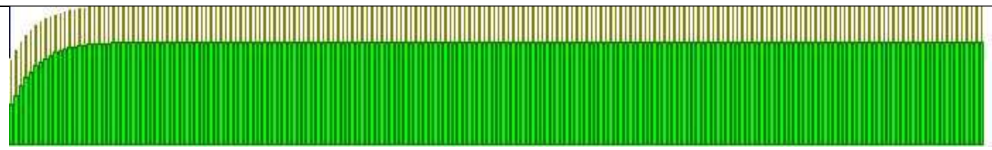
Season	Canopy cover
1	
2	
5	
10	
15	

Figure 3.4d/4 – Reduction of canopy cover (CC) of perennial herbaceous forage crops in various seasons, due to the natural self-thinning of the plant population as simulated by AquaCrop (with n_y = 7 years and k_n = 0.45).

The natural self-thinning results in a gradual decrease of the maximum canopy cover (CC_x) that can be reached without water stress over the years. Since initially the self-thinning is compensated by an increase in the number of shoots per plant, the decrease of CC_x does not decrease from the first year, but becomes only visible in later years when the plant population becomes smaller (Fig. 3.4d/3). The correction factor to adjust CC_x for year i is given by:

$$f_{CCx,i} = 0.9 + 0.1\left(1 - \sqrt[k_n]{\frac{(n_i - 1)}{(n_y - 1)}}\right) \qquad \text{(Eq. 3.4c/3)}$$

where n_i is the year number (from 1 to n_y), and n_y the number of years at which CC_x declines to 90% of its initial value of the 1st year. Since the decline of the initial canopy cover (CC_o) is directly proportional to the natural self-thinning, its correction factor decreases linear in time (Fig. 3.4d/3) and is given by:

$$f_{CCo,i} = 1 - \frac{n_i - 1}{n_o - 1} \qquad \text{(Eq. 3.4c/4)}$$

where n_i is the year number (from 1 to n_y) and n_o the year where CC_x and CC_o both becomes zero:

$$n_o = 1 + (n_y - 1)10^{k_n} \qquad \text{(Eq. 3.4c/5)}$$

The number of years (n_y) at which the maximum canopy cover (CC_x) declines to 90% of its initial value of the 1st year, is a crop parameter which is not conservative but mainly depends on the environment (climate). Its range is set from 3 to a maximum of 127 years. If not relevant, as for climates where the conditions in dormant season do not result in natural self-thinning and for non-perennial crops, the self-thinning can be switches off.

The shape factor (k_n) can vary between 0.05 (decline becomes only important in years close to n_y) to a maximum of 0.80 (decline approaches a linear decrease and is already significant from the 2nd year onwards).

- **Multiple harvests**

For crops that are cut several times per season, AquaCrop simulates regrowth after each cut (Fig. 3.4d/5)

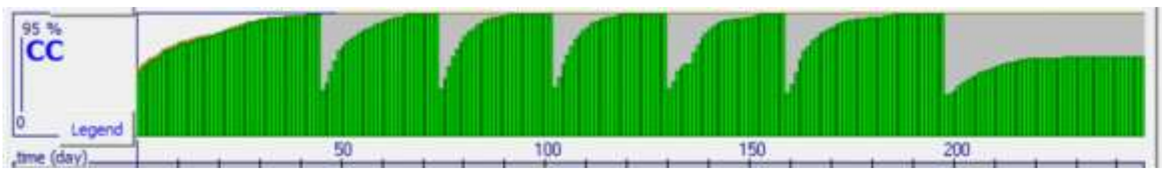


Figure 3.4d/5 – Simulated regrowth after cuts in the season

The canopy cover after cutting (CCini), and the generation or timing of the harvest events are specified in the field management file. By considering the CCini from the input in the field management file, the development of the canopy cover is simulated after each cut (Equation 1 and 2). Soil water, soil fertility, soil salinity stress may slow down the canopy development (see 3.5 "Green canopy cover for stress conditions").

- **Transfer of assimilates**

Perennial herbaceous forage crops transfer a considerable fraction of the assimilates to their below-ground parts after mid-season (Fig. 3.4d/6). At the start of the next season, a fraction of the stored assimilates are remobilized by transferring them from the below-ground parts to the above-ground parts of the crop (see Section 3.11.4 "Transfer of assimilates for perennial herbaceous forage crops").

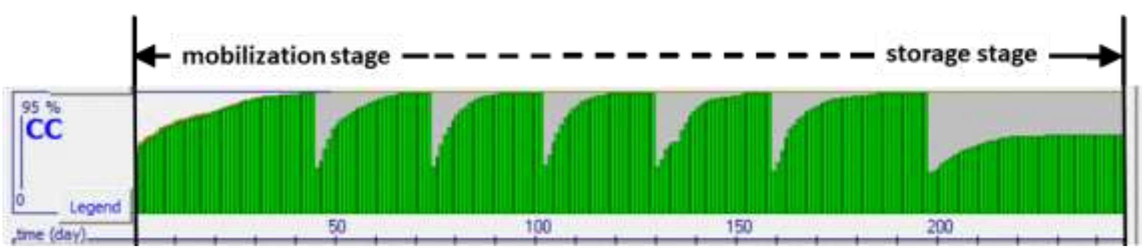


Figure 3.4d/6 – Mobilization and storage stage during which assimilates are transferred between the above and below ground parts of the crop

3.4.7 Green canopy in weed infested fields

- **Annual crops**

In the presence of unlimited soil fertility, the total canopy cover of crop and weeds (CC_{TOT}) can be larger than the crop canopy cover in weed free conditions (CC_{WF}) especially when weeds not only suppress the crop but also expand in the free space between the individual plants (Fig. 3.4e).

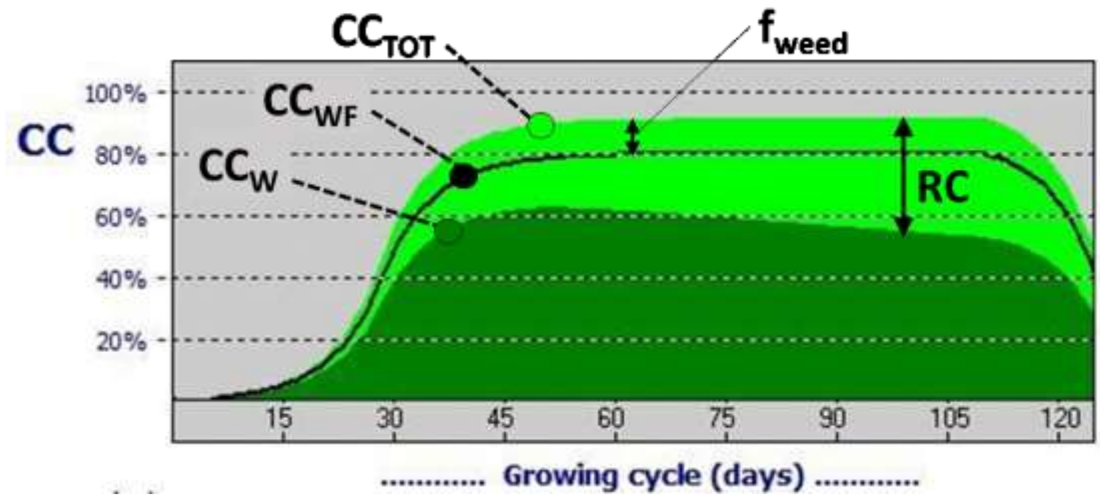


Figure 3.4e – Total canopy cover of crop and weeds (CC_{TOT}), crop canopy cover under weed-free conditions (CC_{WF} – reference) and crop canopy cover in a weed infested field (CC_W), with indication of the adjustment factor for canopy expansion (f_{weed}) and the relative cover of the weeds (RC).

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

$$CCo_{TOT} = f_{weed}\; CCo_{WF} \qquad \text{(Eq. 3.4d)}$$

$$CCx_{TOT} = f_{weed}\; CCx_{WF} \qquad \text{(Eq. 3.4e)}$$

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

$$f_{weed} = 1 - \left(1 - \frac{1}{CCx_{WF}}\right)\left(\frac{e^{f_{shape}\,RC} - 1}{e^{f_{shape}} - 1}\right) \quad \leq \quad \frac{1}{CCx_{WF}} \qquad \text{(Eq. 3.4f)}$$

where CCx_{WF} (fraction) is the maximum crop canopy cover under weed-free conditions, RC the relative cover of weeds (fraction) and f_{shape} a shape factor (Fig. 3.4f) expressing the expansion of the canopy cover due to weed infestation. Given that CC_{TOT} cannot exceed 1, the maximum value of f_{weed} is ($1/CCx_{WF}$).

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

$$RC = \frac{WC}{WC + CC_W} = \frac{WC}{CC_{TOT}} \quad \text{(Eq. 3.4g)}$$

where WC (m^2/m^2) is the area covered by weeds per unit ground area, CC_W (m^2/m^2) the area covered by the crop canopy per unit ground area in the weed infested field, and CC_{TOT} (m^2/m^2) the total green canopy cover of crop and weeds per unit ground area.

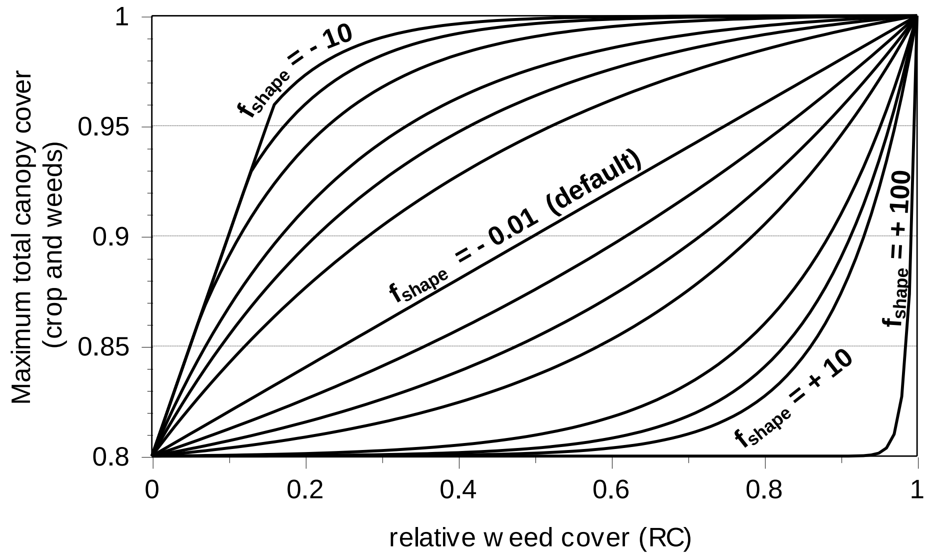


Figure 3.4f – Maximum total canopy cover of weeds and crop at mid-season ($CC_{x,TOT}$) for different relative weed covers (RC) and different shape factors (f_{shape}) for a field that in weed-free conditions would have a CC_x of 0.8.

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

$$CDC_{TOT} = CDC_{WF} \frac{(CCx_{TOT} + 2.29)}{(CCx_{WF} + 2.29)} \quad \text{(Eq. 3.4h)}$$

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

The crop canopy development in the weed-infested field (CC_W) can be derived at any time from CC_{TOT} (Fig. 3.4e) by considering the relative cover of weeds (RC):

$$CC_W = CC_{TOT}\,(1 - RC) \quad \text{(Eq. 3.4i)}$$

- **Perennial herbaceous forage crops**

As a result of natural self-thinning of perennial herbaceous forage crops in the successive seasons, the weed cover might increase as weeds take over the empty spots in the field by unchanged weed management. This correction is automatically applied in AquaCrop when running a simulation. At run time, AquaCrop uses therefore the particular percentage of open spots taken over by weeds, as specified in the field management files (Fig. 3.4f/2).

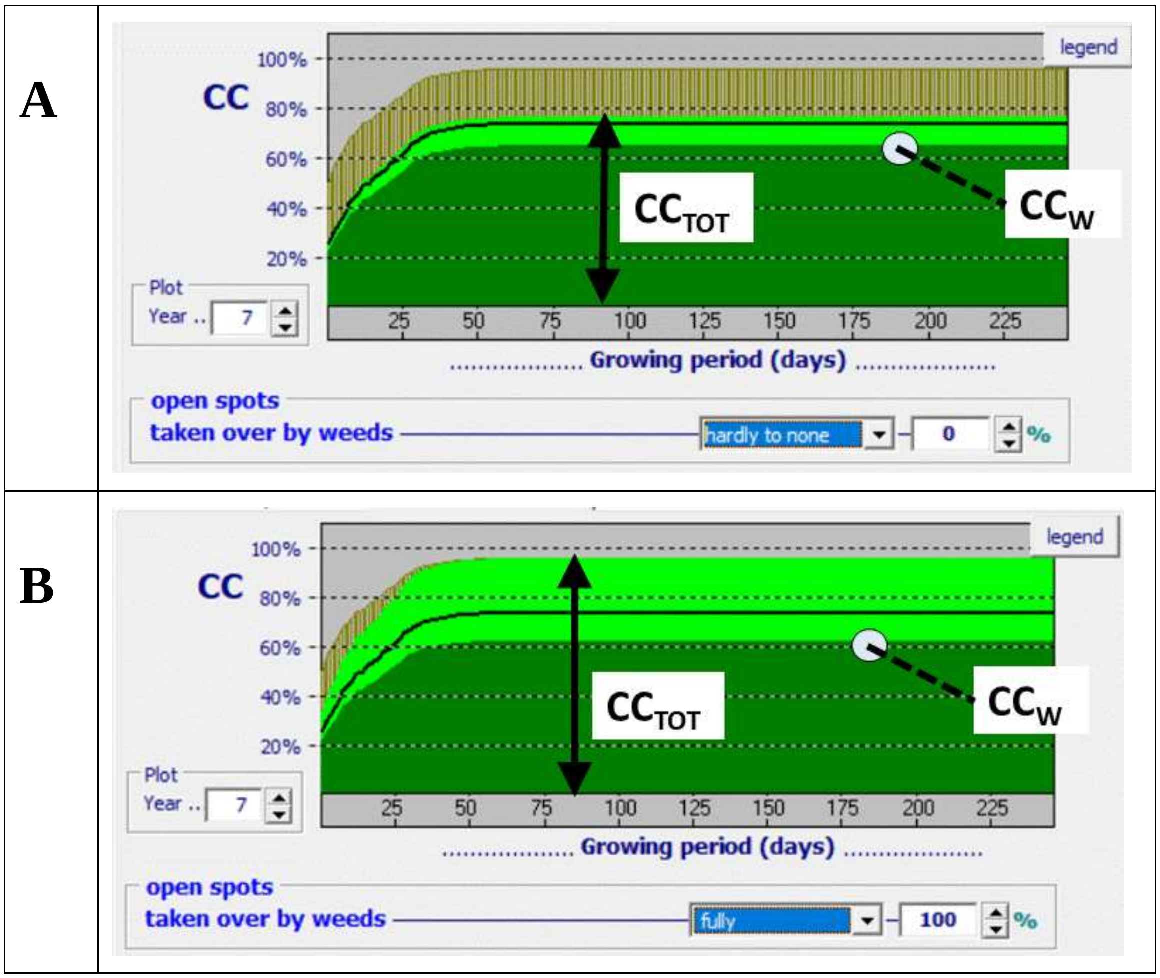


Figure 3.4f/2 – Total canopy cover of crop and weeds (CC_{TOT}) of a perennial herbaceous forage crop in year 7, where the open spots (as a result of natural self-thinning) are taken over by weeds by (A) 0 % and (B) 100 %. In both cases the crop canopy cover under weed-free conditions (CC_{WF} – bold line for reference at year 7) and crop canopy cover in a weed infested field (CC_W) are identical.

3.5 Green canopy cover for stress conditions

The effects of stress on canopy development are manifested through series of stress coefficients. Stress coefficients (Ks) are indicators of the relative intensity of the effect. In essence, Ks is a modifier of its target model parameter, and varies in value from one, when the effect is non-existent, to zero when the effect is maximum (see 3.2 Stresses).

Soil water, soil fertility and soil salinity stress decrease canopy expansion. As a result, the expected maximum canopy cover CC_x might not be achieved or achieved much later in the season:

- The adjustment on canopy expansion is simulated by multiplying the target model parameter CGC (canopy growth coefficient) with the corresponding stress coefficient (Ks < 1);
- Soil fertility and soil salinity stress do not only decrease the growing capacity of the crop but affect as well the maximum canopy that can be reached (CC_x) and result in a steady decline of the canopy cover once CC_x is reached at mid-season. The effect of stresses on green canopy cover (CC) is schematically presented in Fig. 3.5a;
- Under severe water stress, the canopy development might be brought to a standstill and canopy senescence might even be triggered;
- When the crop transpiration is fully inhibited CC no longer can increase;
- Weed infestation affects the crop canopy cover.

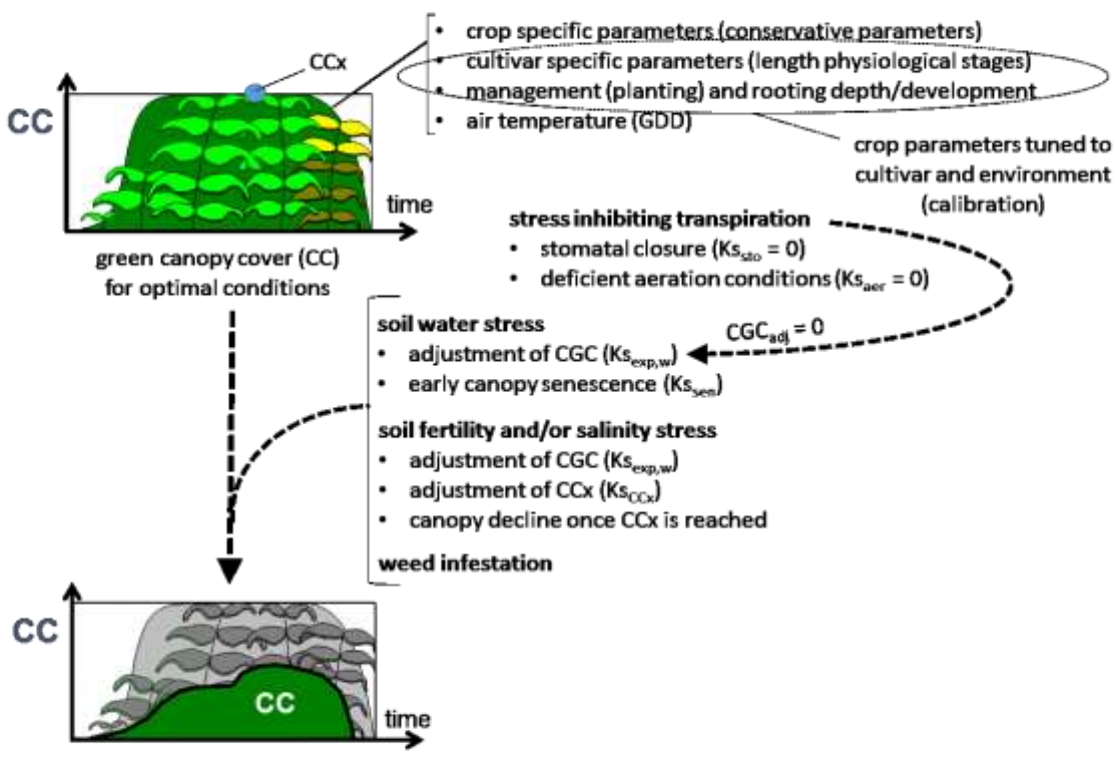


Figure 3.5a – Stresses affecting green canopy cover (CC)

3.5.1 Period of potential vegetative growth

The achievement of the maximum canopy cover CC_x is delayed when stresses affect the canopy growth coefficient CGC and reduce leaf growth. If the period of potential vegetative growth is too short, CC_x might not be achieved at all.

The period of potential vegetative growth depends on how determinant is the crop's growth habit. For determinant crops, once peak flowering is passed and fruits or grain begin to fill, CC has reached its maximum regardless of whether the CC at that time has or has not been reduced by stress. For indeterminant crops the canopy development stage is stretched till canopy senescence (Fig. 3.5b).

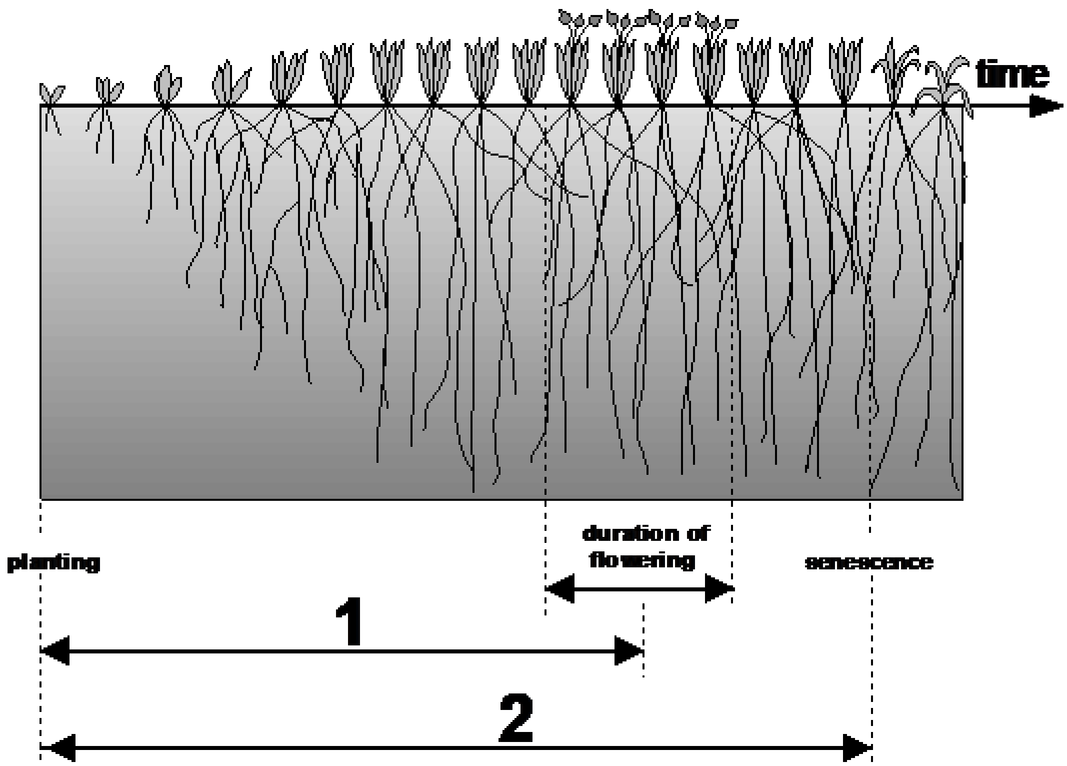


Figure 3.5b – Period of potential vegetative growth for (1) determinant crops and (2) indeterminant crops

3.5.2 Adjustment of canopy growth coefficient due to water stress

To allow light rain to reduce the soil water stress of deep rooted crops, the root zone depletion is continuously compared with the depletion in the top in the simulation (Fig. 3.2c). The comparison determines which part of the soil profile is the wettest and controls the water stress (see section 3.2.2 ‘Soil water stress’).

- **Protection at germination:**

When the crop germinates, the expansion rate of the canopy cover (CC) of the seedling is not limited by water stress. Thanks to nutrients available in the seed, it is assumed that the expansion of the canopy cover is its maximum rate (given by the Canopy Growth Coefficient, CGC). Any reduction of leaf expansion due to water stress, are disregarded till CC is 25% above the initial canopy cover (i.e. CC > 1.25 CCo).

- **After germination:**

Once CC is above 1.25 of CCo, the protection of the germinating seedling is switched off, and the leaf growth by area expansion and therefore canopy development is sensitive to water stress. To simulate the reduction in leaf growth as a result of water stress, the crop growth coefficient (CGC) is adjusted for the stress effect by multiplying it with the water stress coefficient for leaf expansion growth ($Ks_{exp,w}$):

$$CGC_{adj} = Ks_{\exp,w}\ CGC \qquad \text{(Eq. 3.5a)}$$

where $Ks_{exp,w}$ water stress coefficient for leaf expansion growth;
CGC CGC for optimal conditions [fraction or percentage ground cover increase per day or growing degree day];
CGC_{adj} CGC adjusted for water stress [fraction or percentage ground cover increase per day or growing degree day].

Between the upper and lower threshold of the considered soil volume (top soil or root zone), the water stress coefficient decreases gradually from one to zero (Fig 3.5c). $Ks_{exp,w}$ is zero when depletion is at or exceeds its lower threshold. Canopy development is reduced as soon as the depletion (D) in the considered soil volume exceeds the upper threshold:

$$D_{\exp,upper} = p_{\exp,upper}\ TAW \qquad \text{(Eq.3.5b)}$$

where $D_{exp,upper}$ upper threshold expressed as depletion [mm];
$p_{exp,upper}$ fraction of TAW that can be depleted from the considered soil volume before leaf expansion starts to be limited;
TAW total available soil water in the considered soil volume [mm].

When the depletion (D) reaches its lower limit, leaf expansion is completely halted:

$$D_{\exp,lower} = p_{\exp,lower}\ TAW \qquad \text{(Eq.3.5c)}$$

where $D_{exp,lower}$ lower threshold expressed as depletion [mm];
$p_{exp,lower}$ depletion fraction of TAW at which there is no longer any leaf expansion growth.

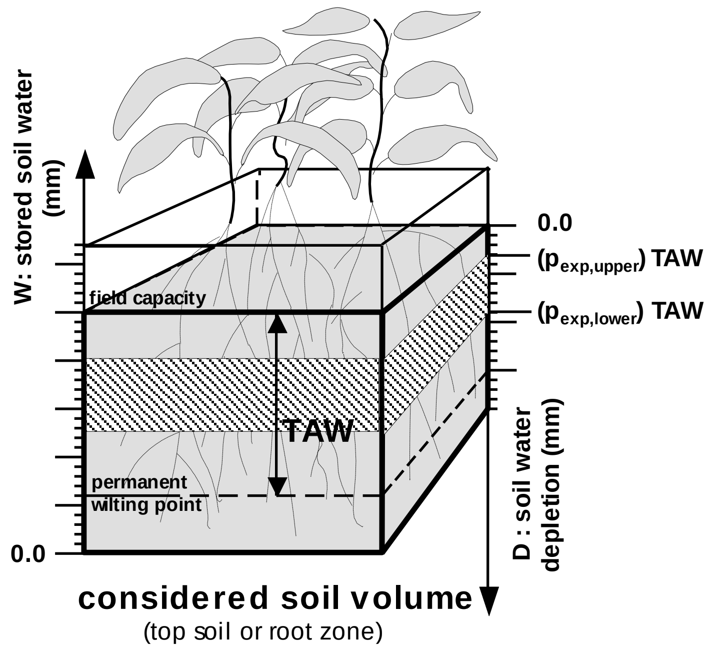


Figure 3.5c – The upper and lower threshold for soil water depletion in the considered soil volume affecting leaf growth by area expansion

Between the upper and lower thresholds the shape of the Ks curve determines the magnitude of the stress (Fig. 3.5d). In AquaCrop the shape of the Ks curve can be selected as linear or concave (see 3.2 Stresses).

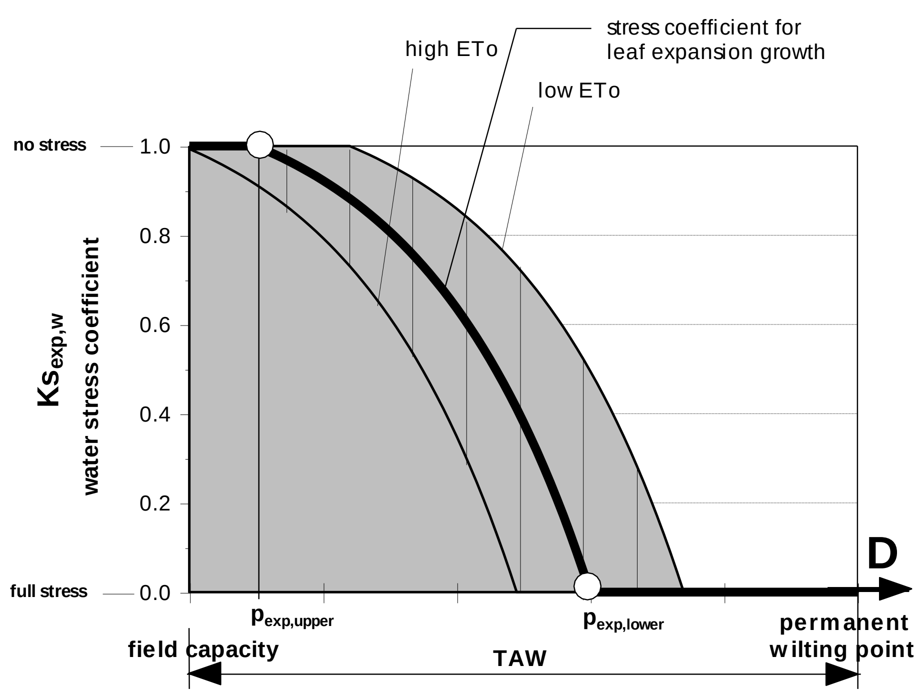


Figure 3.5d – Water stress coefficient for leaf expansion growth ($Ks_{exp,w}$) for various degrees of depletion (D) in the considered soil volume

When water stress reduces leaf growth, the expected maximum canopy cover CC_x might not be achieved or achieved only much later in the season. Therefore the program will stretch the canopy development to the time when CC_x can be reached with the adjusted CGC. Once CC_x is reached, it is assumed in the model that reduced leaf growth has virtually no direct effect on canopy cover anymore (and consequently on crop transpiration, soil evaporation and biomass production).

3.5.3 Early canopy senescence under severe water stress conditions

To allow light rain to reduce the soil water stress of deep rooted crops, the root zone depletion is compared with the depletion in the top soil at each time of the simulation (Fig. 3.2c). The comparison determines which part of the soil profile is the wettest and controls the water stress (see section 3.2.2 'Soil water stress').

- **Protection at germination:**

Any inducing of early senescence due to water stress, are disregarded when the crop germinates. The protection is effective till CC is 25% above the initial canopy cover (i.e. CC > 1.25 CCo).

- **After germination:**

Once CC is above 1.25 of CCo, the protection of the germinating seedling is switched off. Under severe water stress conditions, canopy senescence will be triggered. Early canopy senescence will occur as soon as depletion (D) in the considered soil volume exceeds the upper threshold:

$$D_{sen,\,upper} = p_{sen}\ TAW \qquad \text{(Eq.3.5d)}$$

where	D_{sen}	upper threshold expressed as depletion [mm];
	p_{sen}	fraction of TAW that can be depleted from the considered soil volume before canopy senescence is triggered;
	TAW	total available soil water in the considered soil volume [mm].

Once the depletion in the considered soil volume reaches the lower limit (which is permanent wilting point):

$$D_{sen,\,lower} = TAW \qquad \text{(Eq. 3.5e)}$$

the canopy decline is at full speed. The upper and lower threshold for the soil water depletion are plotted in Figure 3.5e. Between the upper and lower threshold the rate of canopy decline (CDC), which simulates the early canopy senescence, is adjusted to the degree of water stress.

The canopy decline will be very small when water stress is limited, but increases with larger water stresses. This is simulated by adjusting the canopy decline coefficient with the water stress coefficient for senescence (Ks_{sen}). To guarantee a fast enough decline at strong depletion, the 8th power of Ks_{sen} is considered:

$$CDC_{adj} = \left(1 - Ks_{sen}^{8}\right) CDC \qquad \text{(Eq. 3.5f)}$$

where CDC reference canopy decline coefficient;
Ks_{sen} water stress coefficient for early canopy senescence.

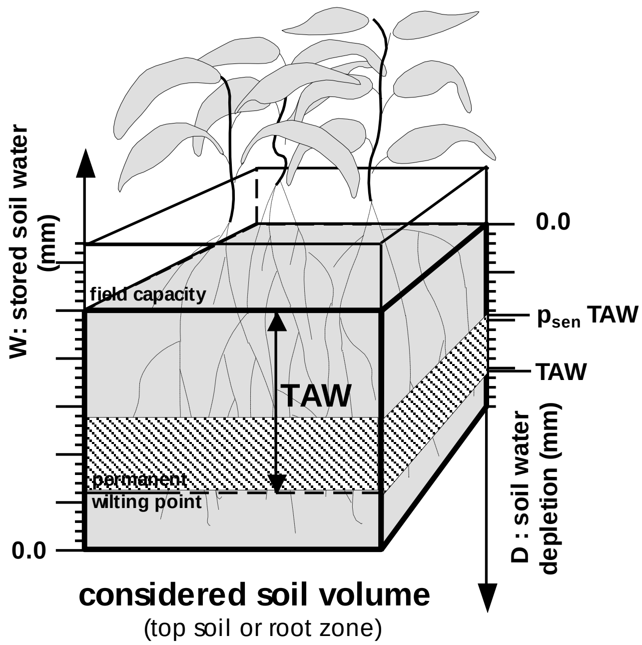


Figure 3.5e – The upper and lower threshold for soil water depletion in the considered soil volume affecting early canopy senescence

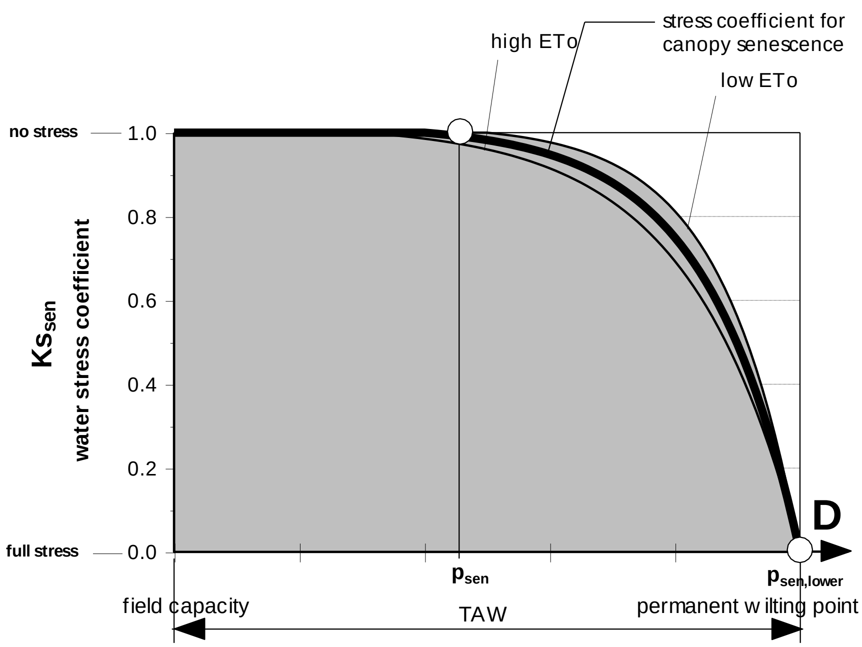


Figure 3.5f – Water stress coefficient for early canopy senescence (Ks_{sen}) for various degrees of depletion (D) in the considered soil volume

Between the upper and lower thresholds the shape of the Ks curve determines the magnitude of the stress (Fig. 3.5f). In AquaCrop the shape of the Ks curve can be selected as linear or concave (see 3.2 Stresses).

A small amount of rain or a slight expansion of the root zone in a wet subsoil, might reduce the root zone depletion above $Dr_{sen,upper}$ and de-activate as such the canopy senescence. To avoid such an overreaction of the program, p_{sen} is reduced with a few percentages (β) once early canopy senescence is triggered:

$$p_{sen,\,adj} = p_{sen} \quad \left(1 - \frac{\beta}{100}\right) \qquad \text{(Eq. 3.5g)}$$

β is a program parameter, and its value can vary between 0 % (no adjustment) to 25 %.

- **Plant recovery upon rewatering:**

Once early canopy senescence is triggered, and in the absence of rain and/or irrigation during senescence, the green canopy will continue to decline. Once CC becomes zero, the crop is permanently wilted, and can no longer recover upon rewatering. Since the moment of permanent wilting of the crop is uncertain, AquaCrop offers the option to specify a dormant period. During the dormant period it is assumed that the crop is not yet permanently wilted, and CC remains above zero to allow the simulation of canopy expansion as soon as sufficient water becomes available for plant recovery. Since the dormant period is expressed as a sum of daily ETo, its length ($L_{dormant}$) is determined by the weather conditions. Hot dry weather shortens the dormant period, while cool weather lengthens the period.

During the dormant period CC gradually decreases from $CC_{dormant}$ (fixed at 0.05 m²/m²) to CCo (Eq. 3.5g/2). If CCo is greater than 5 % soil cover, CC remains at CCo during the whole of the dormant period:

IF CCo < $CC_{dormant}$

$$CC_i = CCo + \left(\frac{1 - \sum ETo_i}{L_{dormant}}\right)\ (CC_{dormant} - CCo) \qquad \text{(Eq. 3.5g/2)}$$

where	CC_i	the green canopy cover at day i during the dormant period (m²/m²)
	CCo	canopy cover at 90% emergence or after transplanting (m²/m²)
	ΣETo_i	sum of daily ETo during the dormant period at day i (mm)
	$L_{dormant}$	length of the dormant period expressed as a sum of daily ETo (mm)

If at the end of the dormant period, the crop wasn't able to recover, CC drops to zero and the crop is considered as permanently wilted (Fig. 3.5f/2).

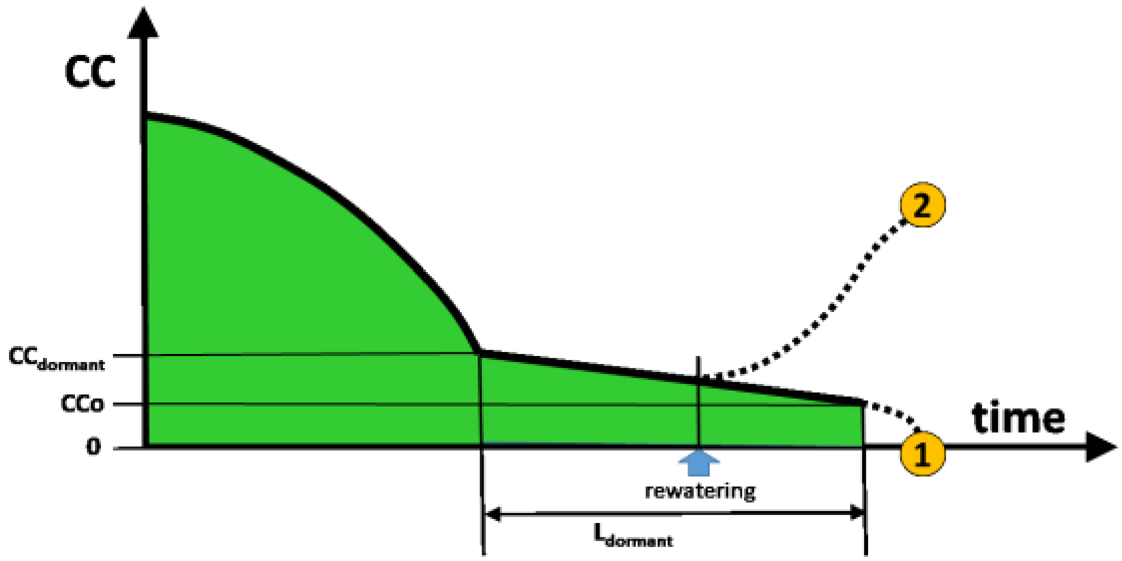


Figure 3.5f/2 – Green canopy decline during early senescence (1) in the absence of rewatering and (2) green canopy expansion when rewatering occurs during the dormant period

Once regrowth is activated, the ageing of the canopy (inducing a progressive though small reduction in crop transpiration and photosynthetic capacity) is reset to zero.

Although the plant will survive upon rewatering during the dormant period, regrowth can only occur during the period of potential vegetative growth (see 3.5.1 'Period of potential growth'). For determinant crops, once peak flowering is passed and fruits or grains begin to fill, CC can no longer increase. For indeterminant crops the canopy development stage is stretched till canopy senescence.

3.5.4 Canopy development when transpiration is inhibited

Severe water stress in the considered soil volume, salinity stress, deficient aeration conditions in the root zone, and cold stress will affect crop transpiration (see 3.10 'Crop transpiration'). When the transpiration rate plunges to zero as a result of prolonged water logging, the absence of an evaporative demand, when permanent wilting point is reached, when the soil salinity exceeds the upper thresholds, or cold stress blocks transpiration, the development of the canopy will be brought to a standstill as a result of the feedback mechanism of transpiration on canopy development.

3.5.5 Canopy development for soil fertility or soil salinity stress

The simulation of the effect of soil fertility stress and soil salinity stress are described in sections 3.14, 3.15 and 3.16.

Limited soil fertility or soil salinity stress decreases the growing capacity of the crop (CGC) as well as the maximum canopy cover (CC_x) that can be reached at mid-season. The adjustments of CGC and CC_x for soil fertility/salinity stress are given by:

$$CGC_{adj} = Ks_{\exp,f}\ CGC \qquad \text{(Eq. 3.5h)}$$

$$CC_{x,adj} = Ks_{CCx}\ CC_x \qquad \text{(Eq. 3.5i)}$$

where CGC and CC_x are the canopy growth coefficient (fraction or percentage per day) and the maximum canopy cover (fraction or percentage) in the absence of soil fertility or soil salinity stress, and $Ks_{exp,f}$ and Ks_{CCx} the stress coefficients.

For non-limiting soil fertility (i.e. soil fertility stress is zero) and in the absence of soil salinity stress the stress coefficients are 1. When the soil fertility/salinity stress is complete, crop growth is no longer possible and the Ks coefficients reach their theoretical minimum of zero. Between the upper and lower limits the Ks coefficients vary between 1 and 0 (Fig. 3.5g).

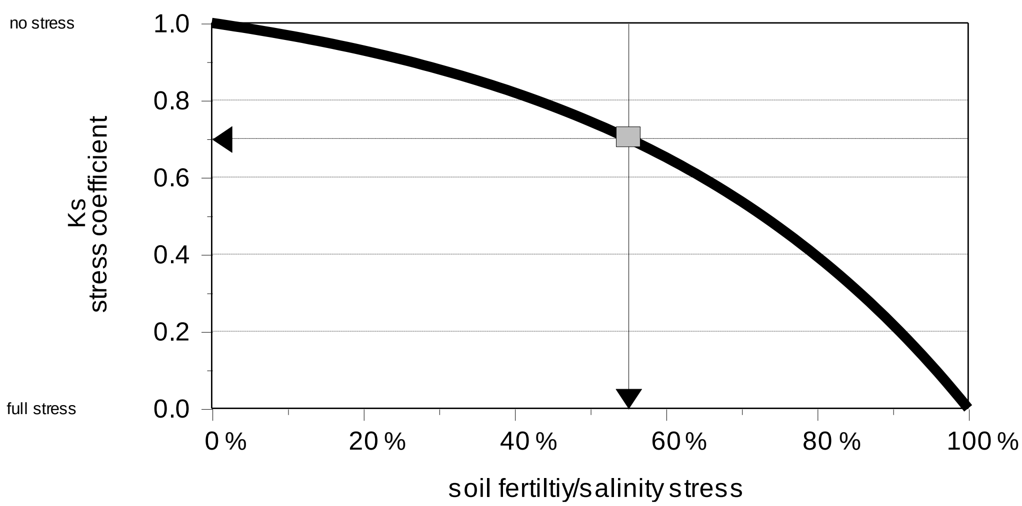


Figure 3.5g – Soil fertility stress coefficient for various soil fertility/salinity stresses (full line) with indication of the Ks and soil fertility/salinity stress used for calibration (square)

The shape of the Ks curves can be convex, linear or concave and may differ between the 2 Ks curves. The shape of each of the curves is determined at calibration by specifying a value between 1 and 0 for $Ks_{exp,f}$ and Ks_{CCx} for the particular soil fertility and soil salinity stress at which the crop response is calibrated (see Chapter 2, 'Calibration for soil fertility' and 'Calibration for soil salinity stress').

Due to the fertility/salinity stress in the soil, the canopy cover (CC) will steadily decline once CC_x is reached at mid-season (Fig. 3.5h). The average daily decline of the canopy cover is given by $f_{CDecline}$ (fraction per day). Since the decline becomes stronger when time advances, the adjustment for the Canopy Cover between the time when full canopy cover is reached ($t_{full\ canopy}$) and the start of canopy senescence at late season (t_{sen}), is simulated by:

$$CC_{adj} = CC_{x,adj} - f_{CDecline} \frac{\left(t - t_{full\,canopy}\right)^2}{\left(t_{sen} - t_{full\,canopy}\right)} \qquad \text{(Eq. 3.5j)}$$

where t is the time (days or growing degree days) after full canopy is reached.

In the late season (between the start of canopy senescence and maturity), the declines continue and is given by Eq. 3.5j. However, since during this period also the natural senescence kicks in, the green canopy decline is also described by Eq. 3.4c (see 3.4.5 'Green canopy cover decline'). The CC considered in the simulation during the late season is the smallest given by one of the two equations.

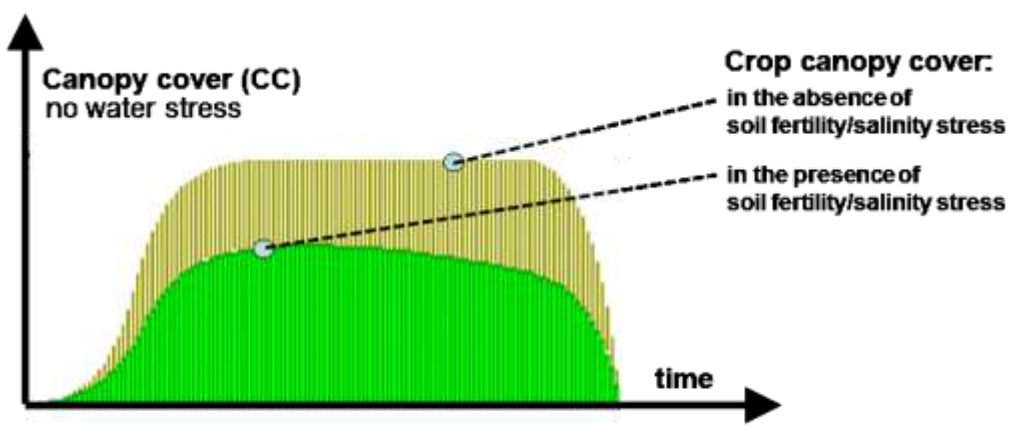


Figure 3.5h – Canopy cover in the absence (light area) and in the presence (dark area) of soil fertility/salinity stress

The calibration for the average daily decline of the canopy cover ($f_{CDecline}$) follows the same approach as for $Ks_{exp,f}$ and Ks_{CCx}. In the absence of soil fertility or soil salinity stress the decline is zero (see Chapter 2, 'Calibration for soil fertility stress' and 'Calibration for soil salinity stress'). When the stress is complete (100%), a maximum decline of 1 % per day is assumed. Between the upper and lower limits $f_{CDecline}$ varies between 0 and 1 % per day.

The values for Ks_{CCx}, $Ks_{exp,f}$ and $f_{CDecline}$ are determined by the most important stress (soil fertility or soil salinity stress) at that moment (see section 3.16 'Simulation of the combined effect of soil fertility and soil salinity stress').

3.5.6 Total canopy cover for stress conditions in weed infested fields

In AquaCrop weed infestation is expressed by the relative cover of weeds (RC), which is the ratio between the ground area covered by leaves of weeds and the total canopy cover of weeds and crop (Eq. 3.4g). It is thereby assumed:

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

In the absence of soil fertility stress and soil salinity stress, the described adjustment of the canopy growth coefficient (section 3.5.2) and early canopy senescence (section 3.5.3) under water stress conditions remain valid for weed infested fields. It is however required to replace CCo, CCx and CDC by their corresponding values in weed infested fields CCo_{TOT}, CCx_{TOT} and CDC_{TOT}.

In case of limited soil fertility or soil salinity stress, CC_{TOT} is entirely determined by the available soil nutrients or the presence of salts in the absence of water stress (Fig. 3.5i). As such the expansion of CC by f_{weed} for unlimited soil fertility and the absence of salinity stress cannot be considered. Given that weeds and crop are assumed to be equally sensitive to water, temperature, salinity and fertility stress, CC_{TOT} will be the same as the (limited) crop canopy cover under weed-free conditions (CC_{WF}). The adjustments of CC_{WF} to soil fertility and soil salinity stress are described in section 3.5.5. In case soil fertility or salinity stress limits canopy development, CCo, CCx and CDC should not be replaced by their corresponding values in weed infested fields (since f_{weed} is 1).

The crop canopy development in the weed-infested field (CC_W) can be derived at any time from CC_{TOT} (Fig. 3.5i) by considering the relative cover of weeds (RC):

$$CC_W = CC_{TOT}\ (1 - RC) \qquad \text{(Eq. 3.5k)}$$

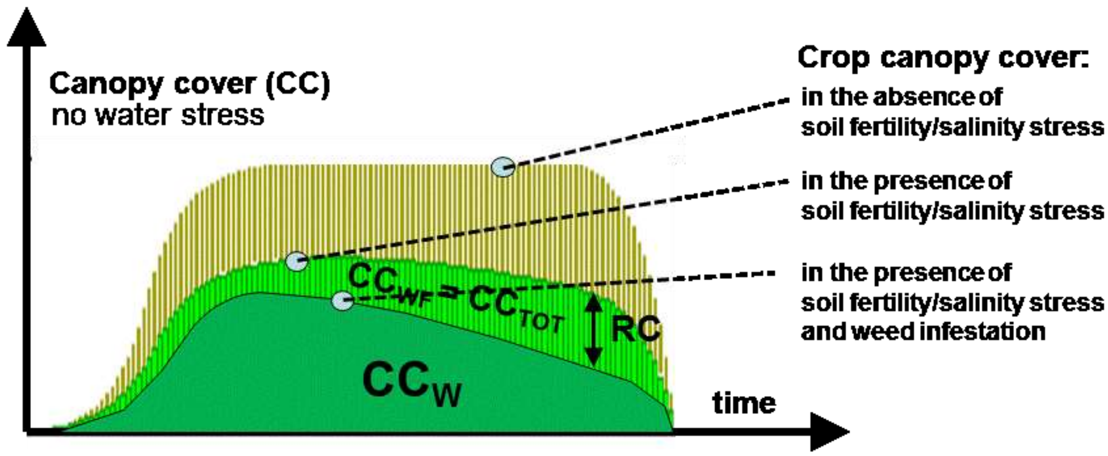


Figure 3.5i – Crop canopy cover in the absence of any stress (light area), and in the presence of soil fertility/salinity stress without and with weed infestation

3.6 Effective rooting depth

The effective rooting depth is defined as the soil depth where root proliferation is sufficient to extract most of the crop water demand. The expansion of the effective rooting depth (Z) in a well water soil is simulated by considering an exponential root deepening function till the maximum rooting depth (Z_x) is reached. Since in AquaCrop the time to reach maximum canopy cover (CC_x) is independent from the time to reach Z_x, the interdependence between root and shoot is not tight.

Since root growth is more resistant to water stress than leaf growth, root development is not affected when canopy expansion starts to be reduced.
Root development is affected:
- if the soil water stress in the root zone starts to affect crop transpiration;
- if the soil water content below the expanding root zone is too dry;
- in soil horizons with low permeability restricting root growth.

3.6.1 Effective rooting depth at planting (Z_n)

The rooting depth at planting (Z_o) is very small and corresponds with the sowing depth or the rooting depth of the transplanted seedling. The effective rooting depth at planting, Z_n, is the soil depth from which the germinating seed or the young seedling can extract water and is larger than the sowing depth. For water balance calculation, a minimum effective rooting depth of 0.2 to 0.3 meter is generally considered appropriate.

3.6.2 Expansion of the root zone in a well-watered soil

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

$$Z = Z_o + (Z_x - Z_o) \sqrt[n]{\frac{\left(t - \frac{t_0}{2}\right)}{\left(t_x - \frac{t_0}{2}\right)}} \qquad \text{(Eq. 3.6a)}$$

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

The development of the effective root zone starts when Z exceeds the minimum effective rooting depth (Z_n) and advances till the maximum effective rooting depth (Z_x) is reached (Fig. 3.6a). At any time the effective rooting depth Z is given by

$$Z_n \leq Z \leq Z_x \qquad \text{(Eq. 3.6b)}$$

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

The starting depth of the root zone expansion curve Z_o is a program parameter and expressed as a fraction of Z_n. The average expansion rate of the effective root zone can never exceed a maximum value (fixed at 5 cm/day).

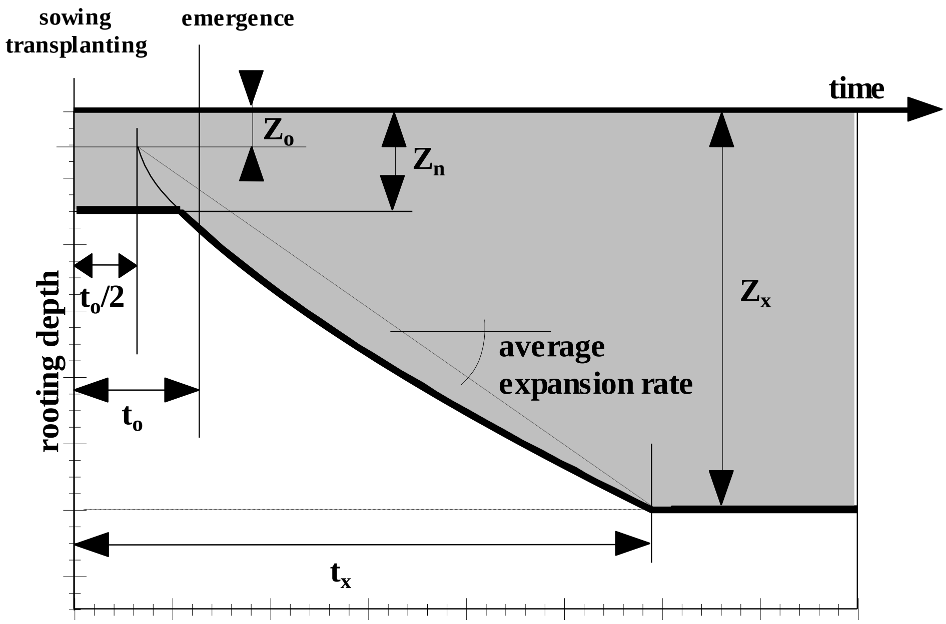


Figure 3.6a – Development of the effective rooting depth (shaded area) from sowing till the maximum effective rooting depth (Z_x) is reached

3.6.3 Rooting depth for perennial herbaceous forage crops

The rooting depth of perennial forage and pasture crops develops only in the first season (planting/sowing year). From the second season onwards, the rooting depth is constant and equal to Z_x.

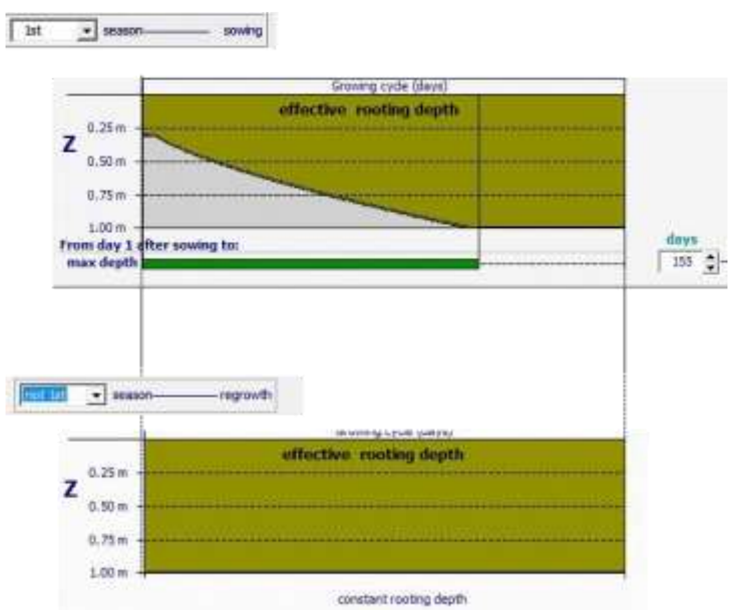


Figure 3.6a/2 – Root deepening for herbaceous forage crops in a 1st (planting/sowing year) and not a 1st season.

3.6.4 Expansion of the root zone when the crop is water stressed

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

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

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

$$dZ_{adj} = Ks_{sto}\ dZ \qquad \text{(Eq. 3.6c)}$$

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

$$dZ_{adj} = dZ\ \frac{e^{Ks_{sto}\ f_{shape}} - 1}{e^{f_{shape}} - 1} \qquad \text{(Eq. 3.6d)}$$

  Making f_{shape} (default is -6.0) more negative minimizes the effect of water stress on root zone development, whereas root zone development is slowed significant in the early period of stress development if f_{shape} is close to -1.0 (Fig. 3.6b).

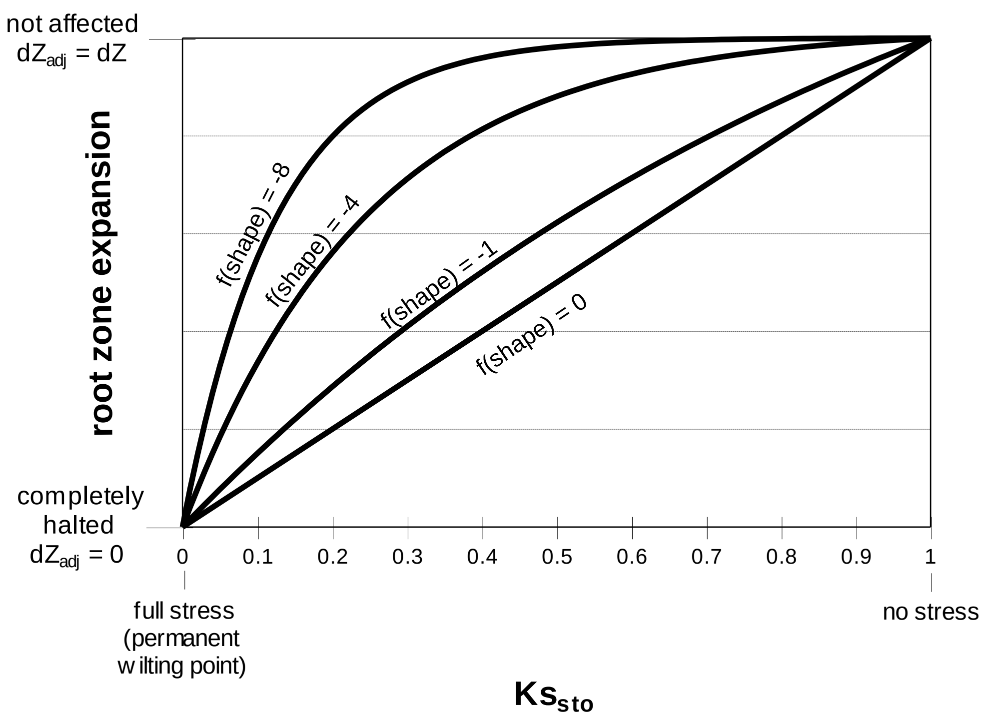


Figure 3.6b – The effect of water stress on the reduction of root zone expansion for various shape factors (f_{shape}) and water stress in the root zone (Ks_{sto})

3.6.5 Expansion of the root zone in a soil profile with restrictive horizon(s)

The effective rooting depth cannot reach its maximum value (line 1, in Fig. 3.6c) if restrictive soil horizons limit root development or when the exploitable soil depth is smaller than Z_x.

The root deepening rate is described by Eq.3.6a as long as the expanding front is in non-restrictive horizons. In a restrictive soil horizon, the expansion is slowed down (line 2b, in Fig. 3.6c) or inhibited (line 2a, in Fig 3.6c) depending on its penetrability:

$$dZ_{adj} = dZ\left(\frac{penetrability_{horion}}{100}\right) \qquad \text{(Eq. 3.6e)}$$

where dZ_{adj} and dZ are the expanding rates in respectively restrictive and non-restrictive soil horizons, and $penetrability_{horizon}$ the penetrability (expressed as a percentage) of the horizon.

Below the restrictive soil layer, the root zone expansion is normal again, and no longer restricted. However, due to the delay in expanding, the effective rooting depth can no longer reach its maximum value.

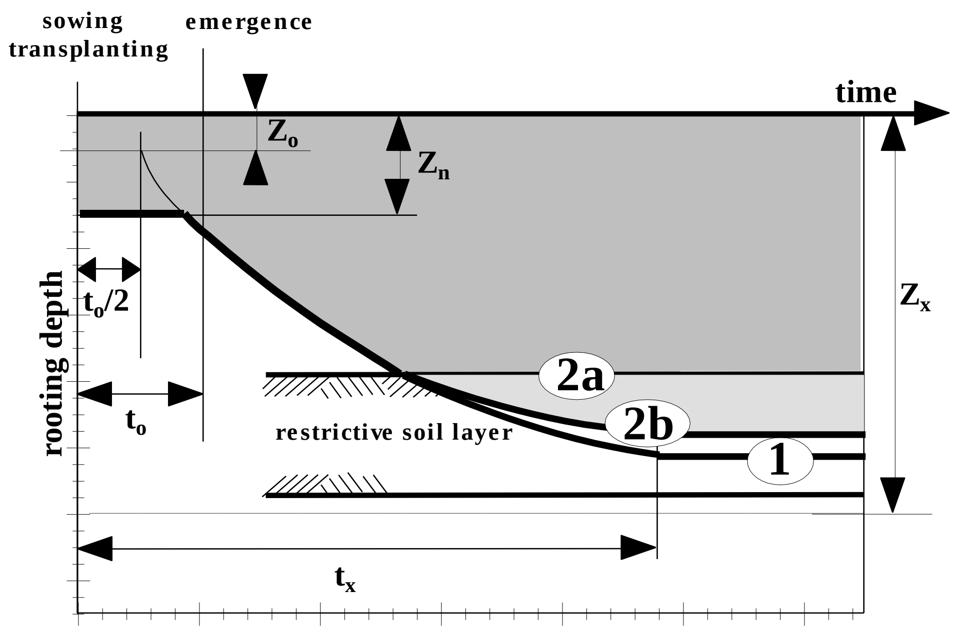


Figure 3.6c – Development of the effective rooting depth (1) in the absence and (2) in the presence of a restrictive soil layer (2a) which inhibits the expansion of the root zone (penetrability = 0 %); and (2b) which slows down the expansion of the root zone (0% < penetrability < 100%)

3.6.6 Limited expansion of the root zone in a dry subsoil

To avoid root zone expansion in a dry subsoil, an extra restriction on root zone development is implemented. If the soil water depletion at the front of root zone expansion exceeds a specific threshold ($p_{Zr,exp}$ TAW), the root deepening will slow down, and can even become inhibited if the soil water content at the front is at permanent wilting point (Fig. 3.6d). To avoid excessive parametrization and in the absence of published data, $p_{Zr,exp}$ is derived from the root zone depletion at which stomata starts to close (p_{sto}):

$$p_{Zr,\exp} = p_{sto} + \frac{1 - p_{sto}}{2} \qquad \text{(Eq. 3.6f)}$$

This makes that the root zone expansion remains unrestricted when the stomata starts to close, but also that the soil water depletion at which the expansion starts to be limited is linked with the sensitivity of the crop to water stress. Root deepening in a dry subsoil is more restrictive for sensitive crops to water stress than for more tolerant crops. The root zone expansion curve (Zr_{exp}) and the Ks_{sto} curve have the same shape factor (Fig. 3.6d). The correction for ETo of the threshold for stomatal closure (Eq. 3.2d) is however disregarded when deriving $p_{Zr,exp}$ in Eq. 3.6f.

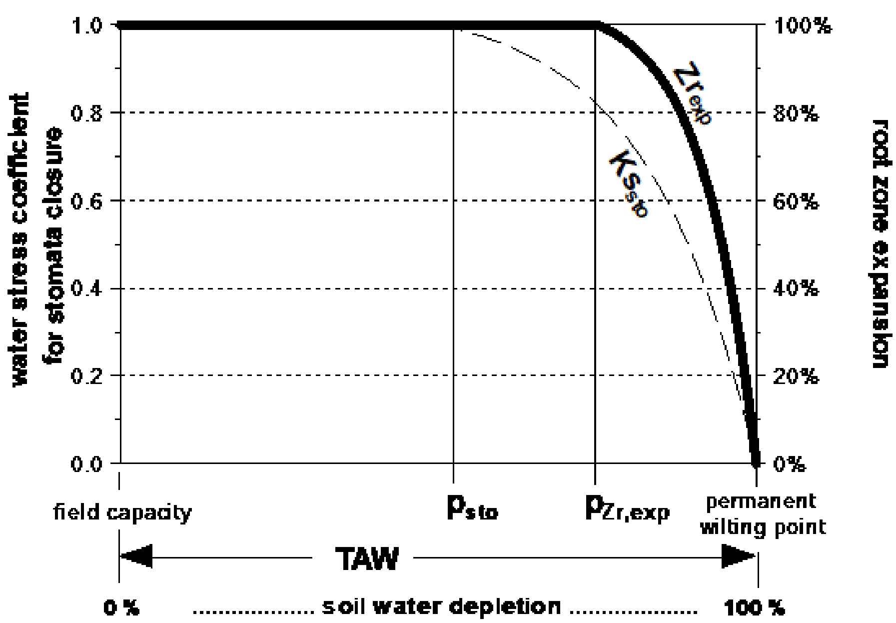


Figure 3.6d – Root zone expansion (Zr_{exp}) at the expansion front (bold line) and water stress coefficient for stomata closure, Ks_{sto} (dotted line) for various soil water depletions.

If the soil water depletion at the expansion front exceeds $p_{Zr,exp}$ TAW, the root zone deepening is slowed down. The expansion rate (Zr_{exp}) is plotted in Fig. 3.6d as a percentage of dZ (the non-restrictive expanding rate).

3.7 Soil water balance

3.7.1 Time - depth grid

To describe accurately the retention, movement and uptake of water in the soil profile throughout the growing season, AquaCrop divides both the soil profile and time into small fractions (Fig. 3.6a). As such the one-dimensional vertical water flow and root water uptake can be solved by means of a finite difference technique (Carnahan et al., 1969; Bear, 1972). A mesh of grid lines with spacing Δz and Δt is established throughout the region of interest occupied by the independent variables: soil depth (z) and time (t). The flow equation and water extraction by plant roots is solved for each node at different depths z_i and time levels t_j so that the dependent variable – the moisture content $\theta_{i,j}$ - is determined for each node of the solution mesh and for every time step.

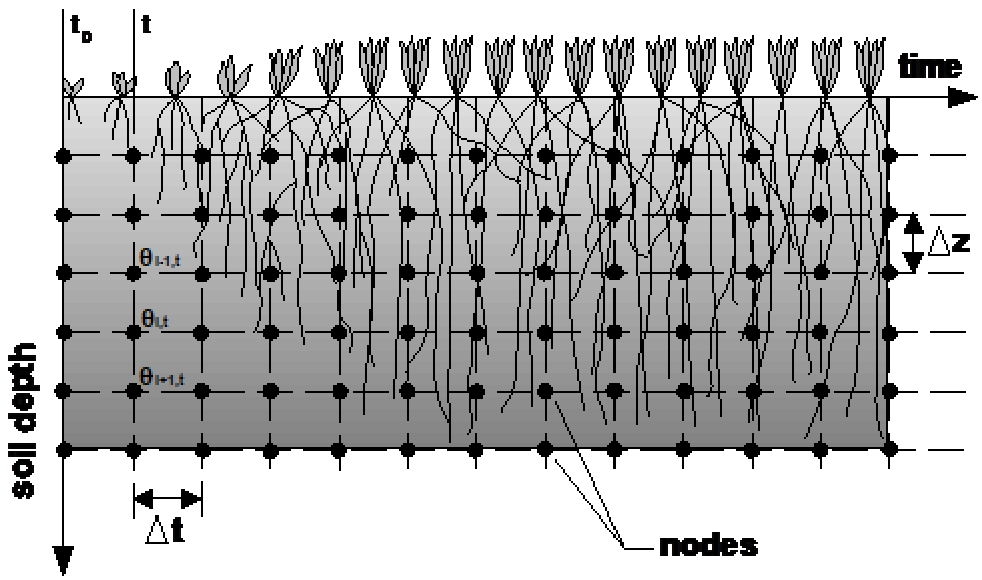


Figure 3.7a – The time(t) – depth (z) grid for the solution of the soil water balance in AquaCrop

In AquaCrop the time increment is fixed at one day and the depth increment (Δz) is by default 0.1 m. The soil profile is such divided into soil compartments (12 by default) with thickness Δz (Fig 3.7b). The hydraulic characteristics of each compartment are that of the soil horizon to which it belongs. If a crop is selected with a deep effective root zone, AquaCrop will adjust the size of the compartments (Δz) to cover the entire root zone. For deep root zones, Δz is not constant but increases exponentially with depth, so that infiltration, soil evaporation and crop transpiration from the top soil horizon can be described with sufficient detail. Program settings allow the user to adjust the number and size of the soil compartments.

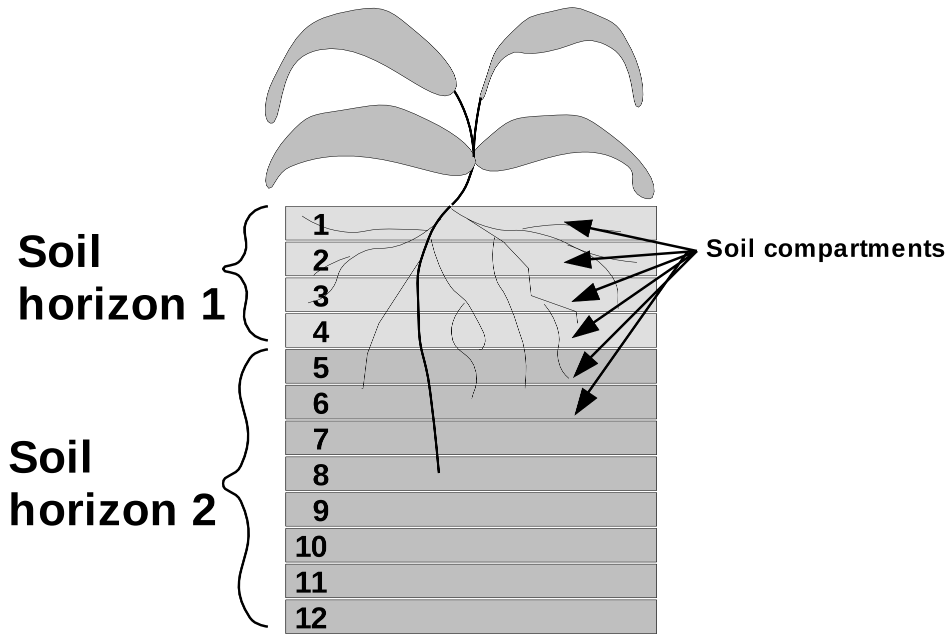


Figure 3.7b – Soil horizons and soil compartments

3.7.2 Calculation scheme

In AquaCrop, the differential flow equation is replaced by a set of finite difference equations (subroutines), written in terms of the dependent variable θ (Fig. 3.7c). The simulation starts with the drainage of the soil profile. Subsequently water infiltrates into the soil profile (after the subtraction of surface runoff), and moves upward by capillary rise from a shallow groundwater table. Finally the amount of water lost by soil evaporation and crop transpiration is calculated. In each of the described subroutines, the soil water content is updated at the end of the time step (j) and at each grid point (i), according to the calculated water content variation (Δθ). The final water content variation at the end of a time step is the result from various processes described in different subroutines.

Since the magnitude of the changes in soil water content, simulated in each of the subroutines, depends on the actual soil water content, the sequence of the calculations might theoretically have an influence on the final simulation result. The effect however will be small since the time step is restricted to one day. Further on, major changes in soil water content of the soil profile as a result of infiltration, internal redistribution of soil water and drainage, will only occur in a wet soil profile. But since in a wet soil the evaporation and transpiration are at their maximum rate, evapotranspiration is at that moment only dictated by the atmospheric water demand and crop development and hence independent of the soil water content in the soil profile. On the other hand, when the soil profile is dry, the simulated evaporation and transpiration rate depends strongly on the soil water content but at that moment soil water flow in the soil profile does not take place.

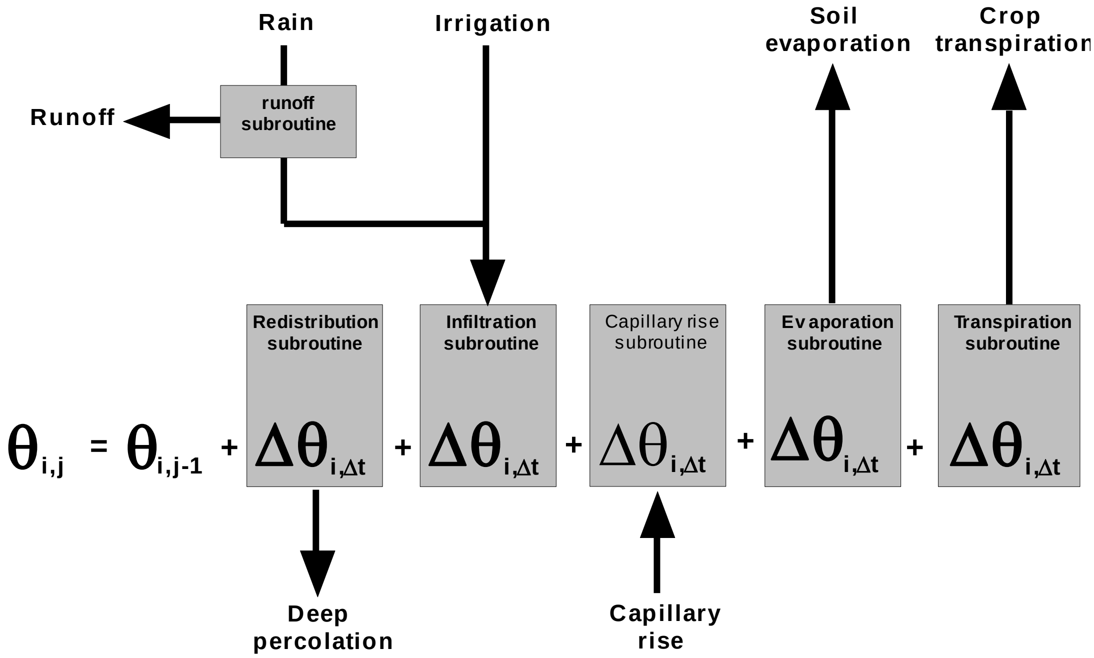


Figure 3.7c – Calculation scheme of the soil water balance in AquaCrop

3.7.3 Redistribution and drainage subroutine

- **Drainage function**

To simulate the redistribution of water into a soil layer, the drainage out of a soil profile, and the infiltration of rainfall and/or irrigation, AquaCrop makes use of a drainage function (Raes, 1982; Raes et al., 1988; Raes et al., 2006):

$$\frac{\Delta\theta_i}{\Delta t} = \tau\,(\theta_{SAT} - \theta_{FC})\,\frac{e^{\theta_i - \theta_{FC}} - 1}{e^{\theta_{sat} - \theta_{FC}} - 1} \qquad \text{(Eq. 3.7a)}$$

Where $\Delta\theta_i/\Delta t$ decrease in soil water content at depth i, during time step Δt [$m^3.m^{-3}.day^{-1}$];
τ drainage characteristic [-];
θ_i actual soil water content at depth i [$m^3.m^{-3}$];
θ_{SAT} soil water content at saturation [$m^3.m^{-3}$];
θ_{FC} soil water content at field capacity [$m^3.m^{-3}$];
Δt time step [day].

note: IF $\theta_i = \theta_{FC}$ THEN $\Delta\theta_i/\Delta t = 0$
IF $\theta_i = \theta_{SAT}$ THEN $\Delta\theta_i/\Delta t = \tau\,(\theta_{SAT} - \theta_{FC})$

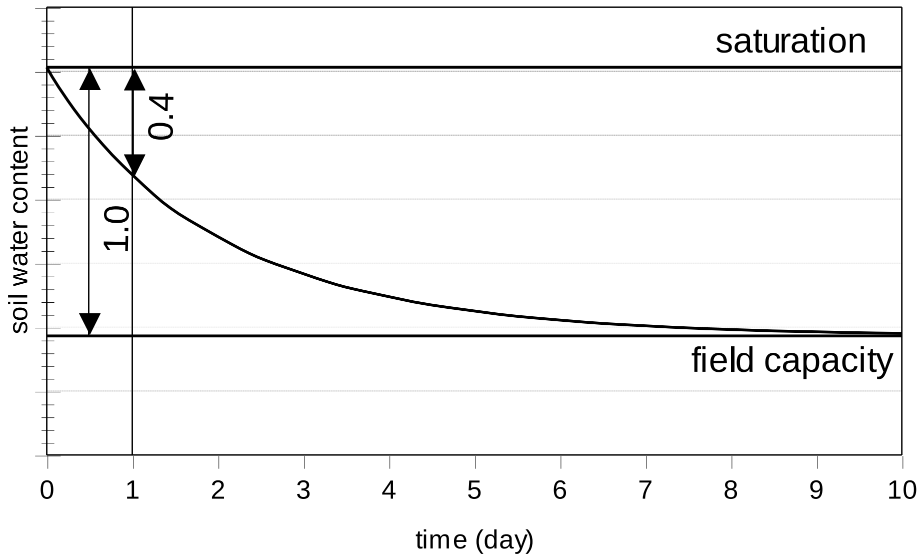


Figure 3.7d – Variation of soil water content over time in a free draining soil layer with a drainage characteristic of τ = 0.4

The drainage function describes the amount of water lost by free drainage over time between saturation and field capacity (Fig. 3.7d). The function is assumed to be exponential. When field capacity is reached further drainage of the soil is disregarded. The drainage function mimics quite realistically the infiltration and internal drainage as observed in the field (Raes, 1982; Feyen, 1987; Hess, 1999; Wiyo, 1999; Barrios Gonzales, 1999, Raes et al., 2006).

- **Drainage characteristic τ (tau)**

The drainage is described by the dimensionless drainage characteristic τ (tau). The drainage characteristic (τ) expresses the decrease in soil water content of a soil layer, originally at saturation, at the end of the first day of free drainage. It is expressed as a fraction of the total drainable amount of water, which is the water content between saturation and field capacity. In Figure 3.7d, τ is 0.4, which means that 40 % of the total drainable amount of water is lost from the fully saturated soil layer after one day of free drainage. The value of τ may vary between 1 (complete drainage after one day) and 0 (impermeable soil layer). The larger τ, the faster the soil layer will reach field capacity. A coarse textured sandy soil layer has a large τ while the τ value for a heavy clay layer is very small. In AquaCrop the close relationship (Barrios Gonzales, 1999) between the dimensionless drainage characteristics (ι) and the hydraulic conductivity at saturation (K_{sat}) is used to estimate the tau value:

$$0 \leq \tau = 0.0866\ Ksat^{0.35} \leq 1 \qquad \text{(Eq. 3.7b)}$$

where K_{sat} is given in mm/day.

- **Calculation procedure**

In a uniform soil equally wet it can be assumed that the decrease in soil water content per day ($\Delta\theta/\Delta t$) is constant throughout the draining profile. Given the actual soil water content, the corresponding drainage ability $\Delta\theta/\Delta t$ ($m^3.m^{-3}.day^{-1}$) is given by Eq. 3.7a. The amount of water DP (mm), which percolates out of the bottom of the soil profile at the end of each day, is given by:

$$DP = 1000 \quad \frac{\Delta\theta}{\Delta t} \quad \Delta z \quad \Delta t \qquad \text{(Eq. 3.7c)}$$

where θ the soil water content of the draining soil profile [$m^3.m^{-3}$];
$\Delta\theta/\Delta t$ drainage ability given by Eq. 3.6a [$m^3.m^{-3}.day^{-1}$];
Δz the thickness of the draining soil profile [m];
Δt the time step (1 day).

To simulate internal drainage in a profile composed of various compartments, not necessarily equally wet and may belong to soil horizons with different τ values, the calculation procedure considers the drainage ability ($\Delta\theta_i/\Delta t$) of the different compartments. The drainage ability for a particular soil water content between saturation and field capacity is given by Eq. 3.7a. The drainage ability is zero when the soil water content is lower than or equal to field capacity.

Given the soil water content of compartment 1, the decrease in soil water content during time step Δt is given by Eq. 3.7a. The amount of water D_1 (mm) that percolates out of the top compartment at the end of a time step is given by:

$$D_1 = 1000 \quad \frac{\Delta\theta_1}{\Delta t} \quad \Delta z_1 \quad \Delta t \qquad \text{(Eq. 3.7d)}$$

where D_1 the flux between compartment 1 and 2 [mm];
θ_1 the soil water content of the top compartment [$m^3.m^{-3}$];
Δz_1 the thickness of the top compartment [m];
Δt the time step (1 day).

Subsequently the soil water content of the top compartment is updated. The same calculations are repeated for the successive compartments. It is thereby assumed that the cumulative drainage amount $\Sigma D_i = D_1 + D_2 + \ldots$ will pass through any compartment as long as its drainage ability is greater than or equal to the drainage ability of the upperlying compartment. By comparing drainage abilities and not soil water contents, the calculation procedure is independent of the soil layer to which succeeding compartments may belong.

If a compartment is reached which drainage ability is smaller than the upperlying compartment, ΣD_i will be stored in that compartment, thereby increasing its soil water content and its drainage ability (Fig 3.7e). If the soil water content of the compartment becomes thereby as high that its drainage ability becomes equal to the drainage ability of the upperlying compartment, the excess of the cumulative drainage amount, increased with the calculated drainage amount D_i of that compartment, will be transferred to the underlying compartment (as is the case in compartment 4 and 5 of Figure 3.7e). If the entire cumulative drainage amount can be stored in a compartment without increasing its soil water content in such a way that its drainage ability becomes equal to that of the upperlying compartment (as is the case in compartment 6), only the calculated drainage amount of that compartment will be transferred to the underlying compartment. If in a compartment the soil water content remains below field capacity, its drainability is zero and no water is transferred to the underlying compartment. At the bottom of the soil profile, the remaining part of ΣD will be lost as deep percolation ($\Sigma D = DP$).

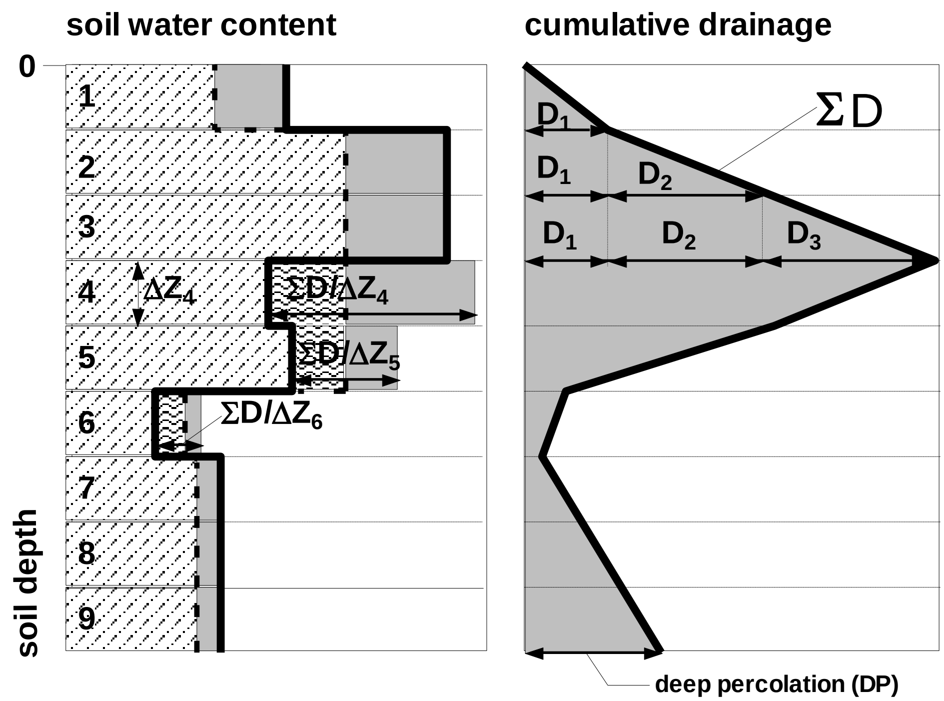


Figure 3.7e – Schematic presentation of a draining soil profile (left) with indication of the soil water content before (full line) and at the end (dotted line) of the process of internal redistribution of the water, and the calculated cumulative drainage (right)

In each compartment, the cumulative drainage amount ΣD_i that passes through should be smaller than or equal to the maximum infiltration rate of the soil layer to which the soil compartment belongs. If not so, part of the ΣD_i will be stored in that compartment, or if required in the compartments above, until the remaining part of ΣD_i equals the infiltration rate of the soil layer.

3.7.4 Runoff subroutine

In AquaCrop, the estimation of the amount of rainfall lost by surface runoff is based on the curve number method developed by the US Soil Conservation Service (USDA, 1964; Rallison, 1980; Steenhuis et al., 1995):

$$RO = \frac{[P - I_a]^2}{P + S - I_a} \qquad \text{(Eq. 3.7e)}$$

$$S = 254\left(\frac{100}{CN} - 1\right) \qquad \text{(Eq. 3.7f)}$$

where	RO	amount of water lost by surface runoff [mm];
	P	rainfall amount [mm];
	I_a	initial abstraction [mm] or the amount of water that can infiltrate before runoff occurs;
	S	potential maximum soil water retention [mm], Eq. 3.7f;
	CN	Curve Number

The initial abstraction (I_a) in Eq. 3.7e is fixed at 0.05 S. Recent research (Hawkins et al., 2002) found that this may be a more appropriate value for I_a than the previous assumed value of 0.20S in previous AquaCrop versions.

The runoff process is described by Eq. 3.7e. Rain that falls on unsaturated soil infiltrates, increasing the soil water content until the topsoil becomes saturated (P = 0.05S), after which additional rainfall becomes surface runoff. A soil with a high Curve Number (CN) will have a small potential storage (S) and may loose a large amount of rainfall as runoff.

The default Curve Numbers in AquaCrop are the average values for the four distinguished hydrologic soil groups for the 'small grain' hydrologic soil-cover complex with good hydrologic conditions as provided by USDA in the National Engineering Handbook (USDA, 2004). The same criteria used by USDA for the assignment of hydrologic soil groups (based on Ksat) are used in AquaCrop for the classification of the soils in the hydrologic soil groups (Table 3.7a).

Table 3.7a – Hydrologic soil groups, the corresponding range for the saturated hydraulic conductivity (Ksat) of the top horizon, and default CN values (assuming an initial abstraction of 5 % of S) for antecedent moisture class II (AMCII).

Hydrologic soil group	Saturated hydraulic conductivity (K_{sat}) mm/day	CN default value for AMC II
A	> 864	46
B	864 – 347	61
C	346 – 36	72
D	≤ 35	77

The user can specify a CN value different from the default, but should thereby not consider the effect of land use and cover, since these effects are considered when specifying the field management. Hence a clear distinction is made between the CN value based on soil profile characteristics (CN_{soil}: which is a soil parameter), and the adjustment of CN_{soil} as a result of field management practices (which is a field management parameter).

In AquaCrop the specified CN value as soil profile characteristic is the value that belongs to the antecedent moisture class AMC II ($CN_{AMC\ II}$). This value is considered when the soil water content in the top soil is half way between Field Capacity and Permanent Wilting Point. At run time, the specified Curve Number ($CN_{AMC\ II}$) is adjusted for the simulated wetness of the top soil layer. To adjust CN to the antecedent moisture class, relationships derived from CN values for various AMC presented by Smedema and Rycroft (1983) are used. The relationships used in AquaCrop to derive $CN_{AMC\ I}$ and $CN_{AMC\ II}$ from $CN_{AMC\ II}$ are:

$$CN_{AMC\ I} = -16.91 + 1.348\ CN_{AMC\ II} - 0.01379\ CN^2_{AMC\ II} + 0.0001172\ CN^3_{AMC\ II}$$
$$\text{with} \quad 0 \leq CN_{AMC\ I} \leq 100 \qquad \text{(Eq.3.7g)}$$

$$CN_{AMC\ III} = 2.5838 + 1.9449\ CN_{AMC\ II} - 0.014216\ CN^2_{AMC\ II} + 0.000045829\ CN^3_{AMC\ II}$$
$$\text{with} \quad 0 \leq CN_{AMC\ III} \leq 100 \qquad \text{(Eq.3.7h)}$$

The storage capacity of a soil is indeed somewhat larger (smaller CN value) if it is dry than when it is wet. By linear interpolation between the corresponding CN values at various antecedent moisture classes, CN is adjusted to the wetness of the topsoil.

The calculation of the relative wetness of the topsoil extends to a depth of 0.3 meter. In the calculation, the soil water content at the soil surface has a larger weight than the soil water content at 0.3 meter (Fig. 3.7f):

$$w_{rel} = 1 - \frac{\exp^{f\ d/dx} - 1}{\exp^{f} - 1} \qquad \text{(Eq. 3.7i)}$$

where w_{rel} relative weighing factor
- f shape factor (fixed at -4)
- d soil depth (m)
- dx the maximum depth considered as relevant for the adjustment of CN (default = 0.3 m)

Program settings allow the user to switch off the adjustment of CN for soil wetness and to adjust the default thickness of 0.3 m. Current thinking (Hawkins (personal communication) 2002) is that the AMC-I and AMC-III CN's are 'error-bands' to describe departure of surface runoff from all kind of sources, including soil moisture. There seems to be no much literature references to show real consistent impacts of prior soil water content on surface runoff on the scale proposed by USDA.

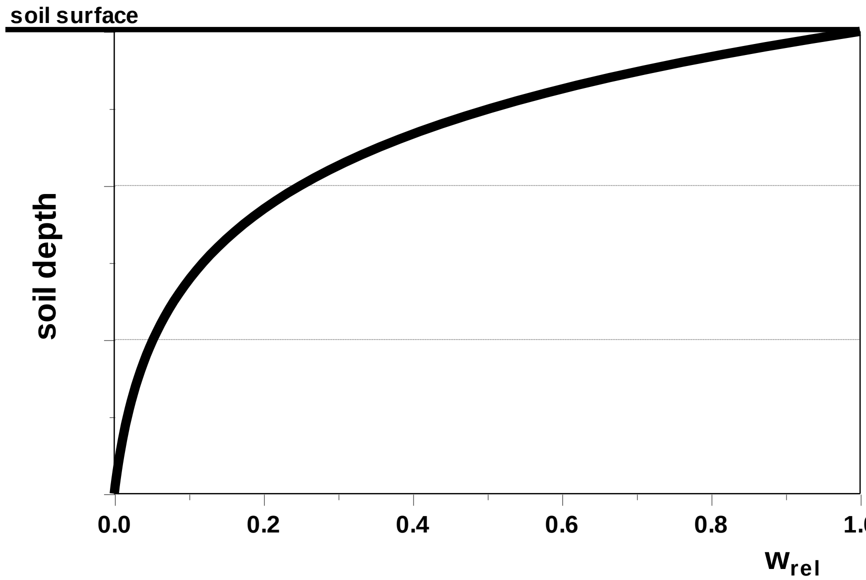


Figure 3.7f – The value for the relative weighing factor (w_{rel}) at various soil depths

For simplicity, irrigation is assumed to be fully controlled; hence the runoff subroutine (for rainfall) is bypassed for irrigation water infiltration and tailwater is assumed to be zero. If surface runoff from the field is important when irrigating, the above assumption requires that irrigation be specified as a net application amount.

The maximum amount that can infiltrate the soil, either as rainfall or irrigation, is limited by saturated hydraulic conductivity of the topsoil layer. Excess water, is considered as lost by surface runoff.

Since field management and crop type might affect surface runoff, the user can adjust CN_{soil} when specifying the effect of field surface practices affecting surface runoff. The specified CN_{soil}, can be adjusted by considering the crop type (if different from ‘small grain’), treatment and hydrologic conditions. Further-on specific field practices such as tied ridges and soil bunds might prevent soil surface runoff. In that case the runoff subroutine is bypassed. When the field is surrounded by soil bunds, water that cannot infiltrate as a result of excessive rainfall or irrigation will be stored between the bunds. The storage capacity is however limited by the height of the bunds. Water that overtops the bunds is assumed to be lost by surface runoff.

3.7.5 Infiltration subroutine

After the subtraction of surface runoff, the remaining part of the rainfall and irrigation water will infiltrate into the soil profile. In AquaCrop the amount of water that infiltrates in the soil profile is stored into succeeding compartments from the top downwards, thereby not exceeding a threshold soil water content $\theta°_i$ ($m^3.m^{-3}$). The threshold $\theta°_i$ at a particular soil depth, depends on the infiltration rate of the corresponding soil layer and on the amount of infiltrated water that is not yet stored in the soil profile. The drainage rate at $\theta°_i$, should correspond with the amount of water that still has to pass through the compartment during the time step. If the flux exceeds the maximum infiltration rate of the corresponding soil layer ($\theta°_i = \theta sat$), extra water will be stored in the compartments above, until the remaining part, that has to pass through the compartment per unit of time step, is equal to the maximum infiltration rate.

The calculation procedure is not completely independent of the thickness of the soil compartments. However, the simulation mimics quite realistic the infiltration process, by taking into account the initial wetness of the soil profile, the amount of water that infiltrates during the time step, the infiltration rate and drainage characteristics of the various soil layers of the soil profile.

3.7.6 Capillary rise

- **Capillary rise for various depths of the groundwater table**

The upward flow from a shallow groundwater table to the top soil can be described with the Darcy equation by considering the water retention curve (h-θ relationship) and the relationship between matric potential (h) and hydraulic conductivity (K). Since h-θ and K-h relationships are not available in AquaCrop, capillary rise is estimated by considering the soil type and its hydraulic characteristics.

The relationship between capillary rise and the depth of the groundwater table is given by the exponential equation:

$$CR = \exp\left(\frac{\ln(z) - b}{a}\right) \qquad \text{(Eq. 3.7j)}$$

where CR is the expected capillary rise (mm.day^{-1}), z the depth (m) of the water table below the soil surface and a and b parameters specific for the soil type and its hydraulic characteristics. Since the magnitude of capillary rise is strongly affected by the shape of the water retention curve and the K-h relationship, the a and b parameters of the equation varies with the textural class (Fig. 3.7g).

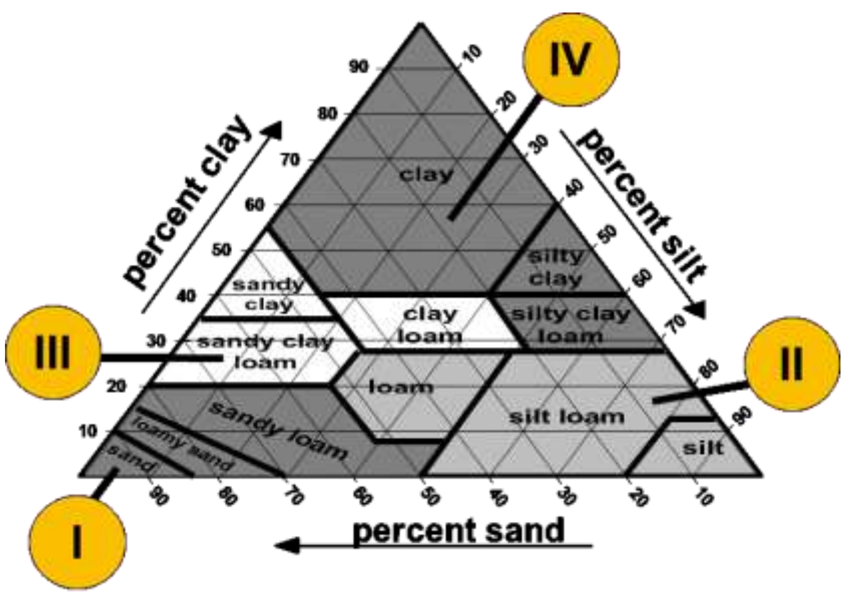


Figure 3.7g –Textural triangle with indication of the 12 different soil types and the 4 soil Classes considered for the determination of the a and b parameters of Eq. 6.1a. I. Sandy soils (dark area), II. Loamy soils (grey area), III. Sandy clayey soils (white area) and IV. Silty clayey soils (dark area)

The a and b parameters describing the capillary rise in AquaCrop were obtained in 4 successive steps:

1. Selection of typical water retention curves for the various textural classes. By considering similarities in h-θ relationships, the 12 distinguished classes were grouped into 4 Classes: I. Sandy soils, II. Loamy soils, III. Sandy clayey soils, and IV. Silty clayey soils (Fig. 3.7g). For each of the classes one representative water retention curve was selected;
2. Generation for each of the 4 classes a set of K-h relationships from the shape of the unique h-θ relationship (obtained in step 1) by considering the range of saturated hydraulic conductivities (K_{sat}) typical for each class (Tab. 3.7b);
3. Simulation of the capillary rise that can be expected for each of the 4 soil classes at various depths (z) of the water table by considering the typical water retention curve (step 1) and the different generated K-h relationships (step 2). Simulations were carried out with the UPFLOW software (Raes and De Proost, 2003);
4. From the obtained CR-z plots (step 3), a and b soil parameters were derived by Janssens (2006) for each class (by considering the saturated hydraulic conductivity (K_{sat}) as the independent variable). The coefficients of determination for the a and b equations (Eq 3.7k and 3.7l in Tab. 3.7b) were always high ($R^2 > 0.96$).

The capillary rise from a shallow groundwater table (Eq. 3.7j) for the 4 soil classes and for various depths of the groundwater table are plotted in Figure 3.7h.

Table 3.7b – Equation 3.7k and 3.7l for the 4 soil Classes with indication of the considered range for the saturated hydraulic conductivity (K_{sat}) (Janssens, 2006)

Soil Class	Range K_{sat} mm.day^{-1}	a Eq. 3.7k	b Eq. 3.7l
I. Sandy soils sand, loamy sand, sandy loam	200 to 2000	$-0.3112 - 10^{-5}\,K_{sat}$	$-1.4936 + 0.2416\,\ln(K_{sat})$
II. Loamy soils loam, silt loam, silt	100 to 750	$-0.4986 + 9\,(10^{-5})\,K_{sat}$	$-2.1320 + 0.4778\,\ln(K_{sat})$
III. Sandy clayey soils sandy clay, sandy clay loam, clay loam	5 to 150	$-0.5677 - 4\,(10^{-5})\,K_{sat}$	$-3.7189 + 0.5922\,\ln(K_{sat})$
IV. Silty clayey soils silty clay loam, silty clay, clay	1 to 150	$-0.6366 + 8\,(10^{-4})\,K_{sat}$	$-1.9165 + 0.7063\,\ln(K_{sat})$

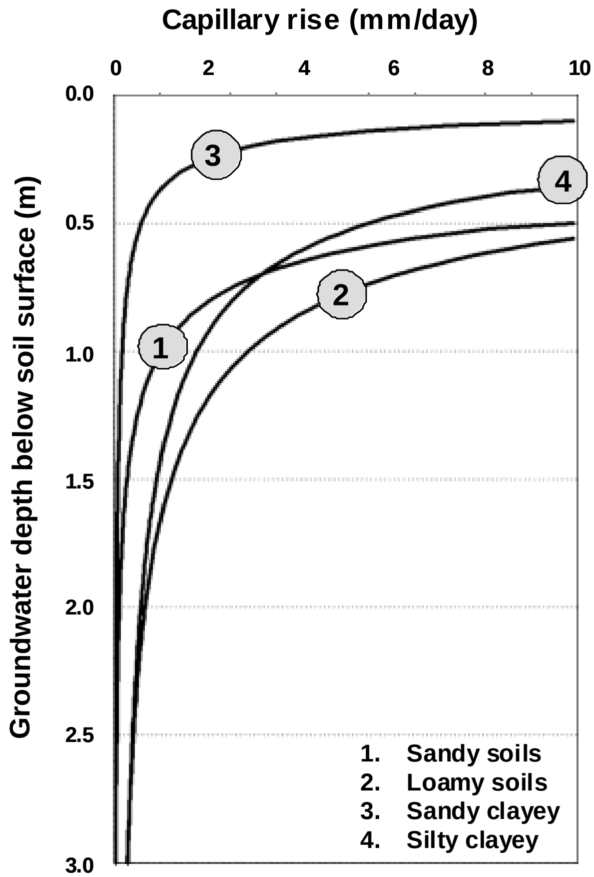


Figure 3.7h – Capillary rise to a bare soil surface, as obtained with Eq. 6.1a, for the 4 considered soil Classes and for various depths of a shallow groundwater table and by assuming a typical saturated hydraulic conductivity (Ksat) of 500 mm/day for Class I (Sandy soils), 250 mm/day for Class II (Loamy soils), 100 mm/day for Class III (Sandy clayey soils) and 25 mm/day for Class IV (Silty clayey soils)

- **Generation of the parameters for capillary rise**

The soil profile in AquaCrop can be composed of up to five different horizons, each with their own physical characteristics. The soil data for the various soil horizons consist in the soil water content at saturation (θ_{Sat}), field capacity (θ_{FC}), and permanent wilting point (θ_{PWP}), and the value for the hydraulic conductivity at soil saturation (Ksat).

To generate default values for the a and b soil parameters (Eq. 3.7j), AquaCrop determines:
- in a first step the class of the soil type for each of the soil layers. The classification is obtained by comparing the volumetric water content at saturation, field capacity and permanent wilting point of each soil layer with the expected ranges of those soil water contents in the 4 classes (Tab. 3.7c);
- in the next step, the a and b soil parameters for each soil layer with Eq. 3.7k and 3.7l (Tab. 3.7b) by considering (i) the soil class and (ii) the specified saturated hydraulic conductivity (Ksat).

Table 3.7c – Ranges considered for the soil water content at saturation, field capacity and permanent wilting point for the 4 soil classes

Soil class	Soil water content (vol %)		
	Saturation	**Field Capacity**	**Permanent Wilting Point**
I. Sandy soils	32 – 51	9 – 28	4 – 15
II. Loamy soils	42 – 55	23 – 42	6 – 20
III. Sandy clayey soils	40 – 53	25 – 45	16 – 34
IV. Silty clayey soils	49 – 58	40 – 58	20 - 42

In the ***Soil profile characteristic*** menu, the soil class and the default values are displayed. If required the user can calibrate the a and b soil parameters by considering the simulated capillary rise for various depths of the groundwater table (see Chapter 2, section 2.13 Soil profile characteristics).

- **Equilibrium at field capacity**

After the drainage of a thoroughly wetted soil profile, the soil water content will remain at Field Capacity (FC) in the absence of any soil water extraction. In the presence of a shallow groundwater table, the soil water content in the soil profile is in equilibrium with the groundwater table and varies with soil depth (Fig. 3.7i).

To simulate drainage and capillary rise correctly, AquaCrop needs to know this equilibrium state (called adjusted Field Capacity). In AquaCrop a parabolic function is used to describe the adjustment of FC in the presence of the groundwater table:

$$\theta_{FCadj,\,i} = \theta_{FC} + \Delta\theta_{FC,\,i} \qquad \text{(Eq. 3.7m)}$$

$$\text{with } \Delta\theta_{FC,i} = \left[\frac{(\theta_{Sat} - \theta_{FC})}{x^2}\right] \ (x - z_i)^2 \qquad \text{for } z_i <= x \qquad \text{(Eq. 3.7n)}$$

where θ_{FC} soil water content at FC in the absence of a groundwater table ($m^3\ m^{-3}$)
$\Delta\theta_{FC,i}$ increase in FC at height z_i above the groundwater table ($m^3\ m^{-3}$)
$\theta_{FCadj,i}$ adjusted FC at height z_i above the groundwater table ($m^3\ m^{-3}$)
θ_{sat} soil water content at saturation ($m^3\ m^{-3}$)
z_i height above the groundwater table (m)
x height above the groundwater table where FC is no longer adjusted

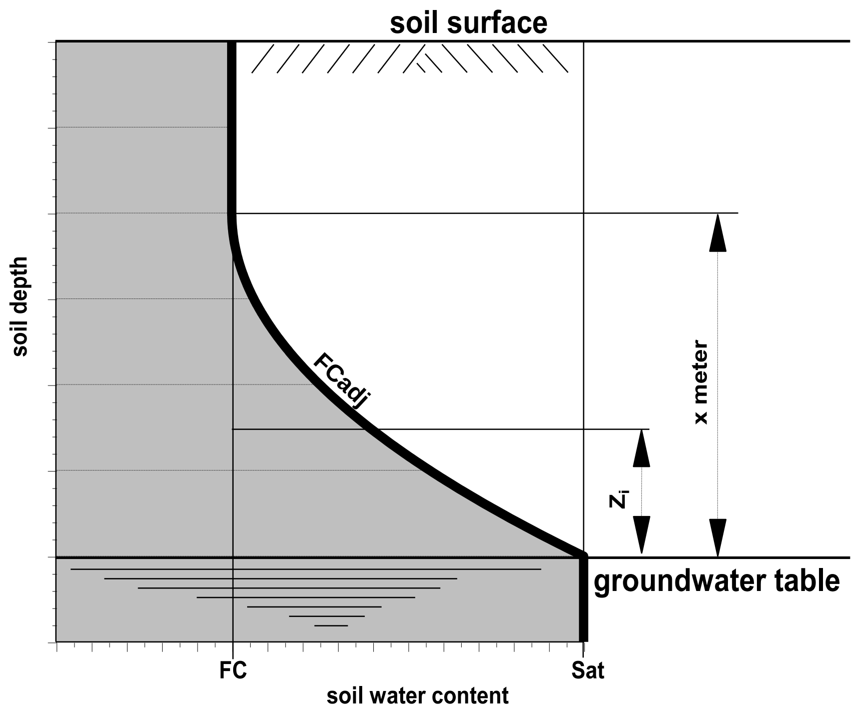


Figure 3.7i – Soil water profile in equilibrium with the groundwater table

At a height of x meter or more above the groundwater table, the adjustment of Field Capacity is neglected. At the groundwater table, $\theta_{FCadj,i}$ is equal to θ_{sat}, and at a height of x meter or more above the groundwater table (where $z_i \geq x$), $\theta_{FCadj,i}$ is equal to θ_{FC} (Fig. 3.7i).

The value for x can be derived from the soil matrix potential at Field Capacity (FC) which varies between -10 kPa (for the more sandy soils) to -20 kPa (for the more loamy and clayey soils) when expressed as energy per unit volume. This corresponds with a head (energy per unit weight) of about – 1 m water (pF 2.0) up to – 2 m (pF 2.3). By considering indicative values for the soil water content at FC of 10 vol% for the more sandy and 30 vol

% for the more loamy soils, the height (meter) where the effect of the groundwater table on FC can be neglected is given by:

$$x = \frac{10^{2+0.3\left(\frac{\theta_{FC}-10}{30-10}\right)}}{100} \quad \text{(Eq. 3.7o)}$$

where θ_{FC} the soil water content at FC (vol %) varying between 10 and 30 vol% (Tab. 3.7d).

Table 3.7d – The soil water content at Field Capacity (θ_{FC}) and the height (x) above which the effect of the groundwater table on FC can be neglected (Eq. 3.7o)

θ_{FC} (vol%)	x (meter)
$\theta_{FC} \leq 10$ vol%	1.00
15	1.19
20	1.41
25	1.68
$\theta_{FC} \geq 30$ vol%	2.00

- **Calculation procedure**

Concept

The calculation starts at the bottom compartment (n) of the soil profile, and moves step by step upwards to the upper lying compartments (i+1, i, i-1, ..) till the top compartment (1) is reached (Fig 6.4a). The calculation procedure consists of the following steps:

1. Calculation of the maximum amount of water that can be transported upward by capillary rise to the node (center) of the compartment ($CR_{max,i}$) by considering the depth of the groundwater table below the center of the soil compartment (z_i) and the characteristics of the soil layer (Eq. 3.7j);
2. Storage of water in that compartment till θ_i is equal to $\theta_{FCadj,i}$ or all the $CR_{max,i}$ has been stored. The amount of water stored in compartment i is:

   IF $\theta_i \leq \theta_{FCadj,I}$ THEN $W_{stored,i} = 1000\left(\theta_{FCadj,i} - \theta_i\right)\Delta z_i \quad \leq f_{CR,i}\ CR_{max,i}$ (Eq. 3.7p)

   ELSE $W_{stored,i} = 0$ (Eq. 3.7q)

   where Δz_i is the thickness of the compartment (m), $f_{CR,i}$ the capillary rise factor (Eq. 3.7u), and $W_{stored,i}$ the stored amount of water (mm) in the compartment. The amount of water still to store is obtained by subtraction the stored amount of water from $CR_{max,i}$

   $$W_{remain} = CR_{max,i} - W_{stored,i} \quad \text{(Eq. 3.7r)}$$

where W_{remain} is the amount of water still to store (mm). If the soil water content (θ_i) of the compartment was initially at $\theta_{FCadj,i}$ no water could have been stored and W_{remain} is equal to $CR_{max,i}$. If the stored water ($W_{stored,i}$) is equal to $CR_{max,i}$, the calculation stops since W_{remain} becomes zero;

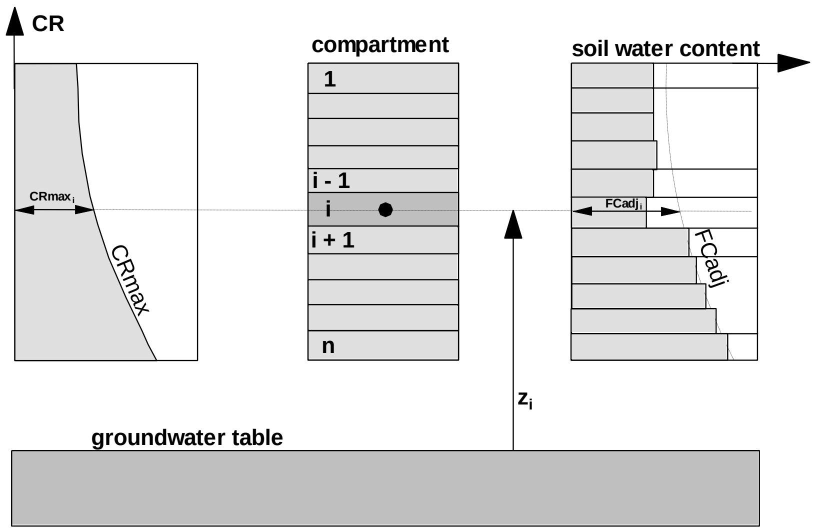


Figure 3.7j – The maximum amount of water that can be transported upward by capillary rise ($CR_{max,i}$) and the adjusted field capacity ($FC_{adj,i}$) for the node of compartment i, at a height of z_i meter above the groundwater table

3. As long as W_{remain} is not zero, the calculation continues by moving to the next upper lying compartment (i-1). The calculations restart with step 1, i.e. with the calculation of CR_{max} for that compartment ($CR_{max,i-1}$). The calculation will continue with the minimum of $CR_{max,i-1}$ and W_{remain}. This control takes care of (i) water already stored in the underlying compartments and (ii) possible changes of layers in the soil profile when moving upward (whereby the restricted capillary capacity of an underlying soil layer, limits the upward flow to the upper lying soil layers).

The calculation stops if all the water has been stored (W_{remain} becomes 0) or the soil surface is reached (i = 1). The total amount of water that has been moved upward by capillary rise to the soil profile is given by the sum of the water stored in each of the compartments:

$$CR = \sum_{i=1}^{n} W_{stored,i} \qquad \text{(Eq. 3.7s)}$$

Adjustment for soil water content

The water movement in the soil is determined by (i) a driving force (i.e. the water potential gradient) and (ii) the capacity of the soil to conduct the water (i.e. the hydraulic conductivity):

– In the absence of a water potential gradient the soil water content (θ) in the profile is at θ_{FCadj} (Fig. 3.7i). Water moves downward (drainage) if $\theta > \theta_{FCadj}$ and upwards (capillary rise) when $\theta < \theta_{FCadj}$. The larger the difference between θ and θ_{FCadj}, the stronger the water potential gradient, and the stronger the driving force for water movement.
– When most of the soil pores are filled with water as in a wet soil, the capacity of the soil to conduct the water and hence the hydraulic conductivity are large. In a soaked soil all pores are able to conduct the water and the hydraulic conductivity is at its maximum (Ksat, the saturated hydraulic conductivity). If the soil is dry, only the small pores contain water and the hydraulic conductivity is very low. In a dry soil, water can only move if the potential gradient is huge.

Upward flow affected by the potential gradient (driving force)

To move water upward from a groundwater table a water potential gradient is required. The strength of the gradient is expressed in AquaCrop by the relative wetness:

$$relative\,wetness = \frac{\theta_i - \theta_{PWP}}{\theta_{FCadj,\,i} - \theta_{PWP}} \qquad \text{(Eq. 3.7t)}$$

where θ_i is the soil water content at a height z_i above the groundwater table, and θ_{PWP} and $\theta_{FCadj,i}$ the soil water content at the Permanent Wilting Point and the adjusted Field Capacity respectively.

The restrictions for upward water movement as a result of a low potential gradient is estimated by considering a power function of the relative wetness and is expressed by a capillary rise factor ($f_{CR,i}$):

$$f_{CR,\,i} = 1 - \left(\frac{\theta_i - \theta_{PWP}}{\theta_{FCadj,\,i} - \theta_{PWP}} \right)^x \qquad \text{(Eq. 3.7u)}$$

The capillary rise factor, $f_{CR,i}$, varies with the soil water content (θ_i) and ranges between 1 and 0 (Fig. 3.7k). The capillary rise factor considers on the one hand the driving force for upward water movement and on the other hand the hydraulic conductivity.

If the top soil is dry, the potential gradient is strong and the driving force for water movement is strong as well ($f_{CR} = 1$). The wetter the soil profile, the smaller the potential gradient and the smaller the upward water movement ($f_{CR} < 1$). If the soil water content at a given height above the groundwater table is equal to $\theta_{FCadj,i}$, upward water movement is fully inhibited due to the absence of any water potential gradient. The power (x) in Equation 6.4f is a program parameter and set at 16 for testing.

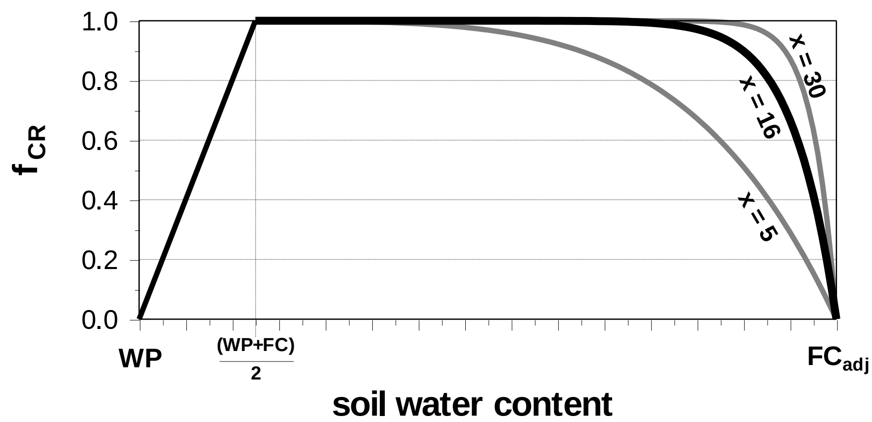


Figure 3.7k – The capillary rise factor (Eq. 3.7u) for different soil water content in the soil profile above the groundwater table and values for the power x.

The power (x) in Equation 3.7u is a program parameter which can vary between 5 and 30 (with 16 as default). With the program parameter the user can adjust the simulated capillary rise. Increasing the required soil water content gradient (by reducing x) will limit upward flow from the groundwater table, while reducing the required soil water content gradient (by increasing x) will facilitate the capillary rise to the soil profile.

The capillary rise factor affected by the hydraulic conductivity

Although the soil water potential gradient becomes very high when the top soil is very dry, upward movement of water is restricted due to the extreme low hydraulic conductivity in a dry soil. If the soil water content drops below the threshold halfway between Field Capacity and Permanent Wilting Point, f_{CR} decreases linear from 1 (at the threshold) to zero when Permanent Wilting Point is reached (Fig. 3.7k).

Capillary rise versus drainage

The calculation of upward movement from a groundwater table, which starts at the bottom compartment will stop when a compartment i is reached which soil water content is above $\theta_{FCadj,i}$. At this soil water content the compartment is draining and water cannot be stored ($f_{CR,i} = 0$). More important, as a result of the downward movement of water, water can no longer move further upwards to the upper lying compartments.

If the total soil profile is draining ($\theta_n > \theta_{FCadj,n}$), the calculation process does not start at all. As long as water moves out of the bottom compartment, capillary rise to the soil profile is inhibited. After a thorough drainage, the upward movement of water can not restart immediately since all over the soil profile, θ_i is equal to $\theta_{FCadj,i}$ and $f_{CR,i}$ is zero (Eq. 3.7u). Capillary rise is restored when sufficient water is extracted out of the soil profile by crop transpiration and/or soil evaporation and $f_{CR,i}$ becomes larger than 0 (Fig. 3.7u).

Root zone expansion

Roots of crops sensitive to water logging can not develop below the groundwater table. Hence, the maximum rooting depth (Z_x) is restricted to the depth of the groundwater table. If later in the season the water table drops, the root zone will expand till Z_x is reached.

If during the season the water table enters in the root zone, the roots under the groundwater table will become inactive and might die off. If later in the season the water table drops, it is assumed that the part of the root zone that was flooded becomes active again and that the root zone expands till Z_x is reached.

Deficient aeration conditions and reduced crop transpiration

Transpiration is hampered when the soil water content in the root zone results in deficient soil aeration. If the water content in the root zone is above the anaerobiosis point the root zone becomes water logged and transpiration is limited. This is likely to be the case if the groundwater table is very shallow and the soil water content in the root zone is close to saturation (Fig. 3.7i).

The sensitivity of the crop to water logging is specified by the soil water content (anaerobiosis point) at which the aeration of the root zone will be deficient for the crop and starts to affect crop transpiration (section 3.10 Crop transpiration). To simulate the resistance of crops to short periods of waterlogging, the full effect will only be reached after a specified number of days.

3.7.7 Processing of 10-day and monthly climatic data

- **Daily climatic data**

For each day of the simulation period, AquaCrop requires:
- the minimum (T_n) and maximum (T_x) air temperature;
- the reference evapotranspiration ETo; and
- rainfall depth.

The input may consist of daily, 10-day or monthly T_n, T_x, ETo and Rainfall data. At run time, the 10-day and monthly data are processed to derive daily minimum and maximum air temperatures, ETo and rain data.

By weighing the reference evapotranspiration rates and air temperatures in the previous, actual and next 10-day period or month, daily ETo rates, and the daily maximum and minimum air temperatures are obtained in AquaCrop. The calculation procedure is based on the interpolation procedure presented by Gommes (1983). The same interpolation procedure is applied for 10-day and monthly rainfall data but since it is highly unlikely that rainfall is homogenously distributed over all the days of the 10-day period or month, some further processing is required to determine the amount of rainfall that is (i) lost by surface runoff, (ii) stored in the top soil as effective rainfall, (iii) lost by deep percolation and (iv) by soil evaporation (Fig. 3.7f).

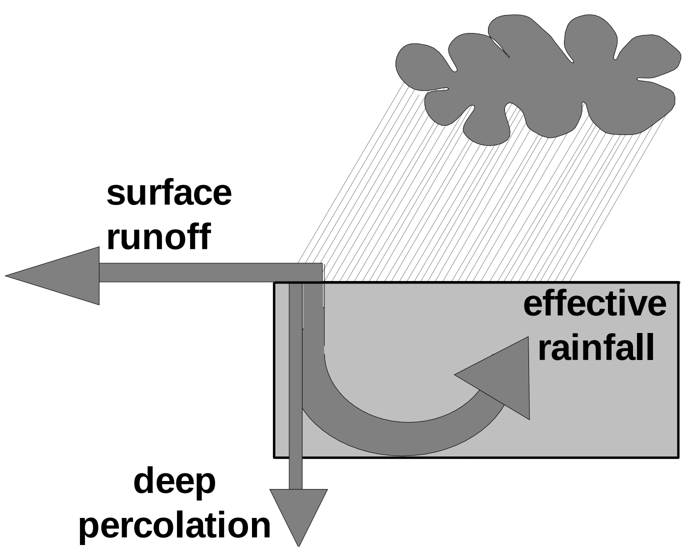


Figure 3.7l - Partitioning of rainfall in effective rainfall, surface runoff and deep percolation losses

- **Estimation of surface runoff**

To estimate surface runoff with 10-day or monthly Rainfall data, a specific number of rainy events is assumed during a 10-day period (the default is 2 showers per 10-day). By dividing the total rainfall amount for the period by the number of events in that period, the rainfall amount per shower is obtained and the surface runoff can be calculated (see 3.7.4 – Runoff subroutine). The more rainy days are considered during the 10-day period, the smaller the rainfall amount per event and the smaller the runoff will be. Because the day(s) at which it rains, are unknown the Curve Number is not corrected for soil wetness and the CN value for Antecedent Moisture Class II is used.

- **Estimation of effective rainfall and deep percolation**

Effective rainfall is that part of rainfall that is stored in the root zone and not lost by surface runoff or deep percolation (Fig. 3.7f). If the rainfall data consist of 10-day or monthly values, the rainfall distribution over the period is unknown and the amount of water lost by deep percolation cannot be determined by solving the water balance on a daily basis (time step). After the subtraction of the amount of rainfall lost by surface runoff, the effective rainfall is estimated by one or another procedure determined by the user. If the amount of rainfall that is stored in the root zone will also be effectively retained in the root zone depends on the storage capacity of the root zone at the moment of rainfall.

The following procedures are available in AquaCrop to determine the effective rainfall when 10-day or monthly rainfall data is given as input:

- 100 percent effective
- USDA-SCS procedure
- Expressed as a percentage of rainfall

100 percent effective

All rainfall is stored in the root zone. Excess water that cannot be retained, will drain out of the root zone and will be lost by deep percolation.

USDA-SCS procedure

SCS scientists analysed 50 years of rainfall records at 22 locations throughout the United Sates of America to predict effective rainfall (SCS, 1993). A daily soil water balance incorporating crop evapotranspiration, rainfall, irrigation and the storage capacity of the root zone was used to determine the effective rainfall (Tab. 3.6e). By considering the monthly crop evapotranspiration (ETc_m) and rainfall (P_m), the monthly effective rainfall (Pe_m) is obtained by the following empirical equation (USDA, 1970):

$$Pe_m = \left(0.70917\ P_m^{0.82416} - 0.11556\right)10^{0.02426\,ETc_m} \qquad \text{(Eq.3.7v)}$$

where Pe_m, P_m and ETc_m are given in inches (1 inch = 25.4 mm). In the above equation ETc_m is the sum of the soil evaporation and crop transpiration by assuming that the processes are not affected by water stress. The difference between rainfall (P_m) and the estimated effective rainfall (Pe_m) is regarded as being lost by deep percolation.

Simulations (Naesens, 2002) with rainfall data from various climatic zones indicates that the procedure predicts effective rainfall with an accuracy of +/- 20 %. The procedure is also valid for 10-day rainfall data but the accuracy decreases to +/- 40 %.

Table 3.7e – Effective rainfall (expressed as a percentage of monthly rainfall) for various levels of crop evapotranspiration and for a root zone with a RAW of 75 mm, as determined by the USDA-SCS procedure.

	Monthly crop evapotranspiration [mm/month]							
	30	**60**	**90**	**120**	**150**	**180**	**210**	**240**
Monthly Rain [mm/month]	**Effective rainfall [%]**							
10	58	62	66	71	75	81	86	92
20	63	68	72	77	82	88	94	100
30	63	67	72	77	82	88	94	100
40	62	66	71	76	81	86	92	99
50	61	65	70	74	79	85	91	97
60	60	64	68	73	78	83	89	95
70	59	63	67	72	77	82	88	93
80	58	62	66	71	76	81	86	92
90	57	61	65	70	74	80	85	91
100	56	60	64	69	73	78	84	90
120	55	59	63	67	72	77	82	87
140	54	58	61	66	70	75	80	85
160	53	56	60	64	69	74	79	84
180	52	55	59	63	68	72	77	82
200	51	55	58	62	67	71	76	81

Expressed as a percentage of rainfall

The user specifies the percentage of the 10-day/monthly rainfall that is stored in the root zone. The ineffective part of the rainfall is assumed to have drained out of the root zone and is stored immediately below the root zone.

The percentage will depend on the rainfall amount, the evapotranspiration rate and soil type. Indicative values are given in Table 3.7e. The percentage can be obtained with greater accuracy by simulating the drainage out of the root zone for those years were daily rainfall data is available (or available in a nearby representative station). As such the characteristics of the climate, cropping period, irrigation schedules and drainage characteristics of the soil can be fully considered.

- **Estimation of soil evaporation**

The calculation procedure for soil evaporation (E) assumes that the evaporation takes places in two stages (See 3.9 Soil evaporation). By distributing rainfall homogenously over all the days of the 10-day period or month, soil evaporation is likely to be over-estimated. Simulations (Mihutu, 2011) with rainfall data from various climatic zones indicated that the two stage calculation procedure over predicts E by some 10 to 30 % depending on soil type. The soil evaporation rate is adjusted by multiplying the estimated daily evaporation (E) with a reduction factor:

$$E_{adj} = \left(\sqrt[n]{\frac{REW + 1}{20}} \right) E \qquad \text{(Eq. 3.7w)}$$

where REW is the readily evaporable water (mm) and n a program parameter which may vary between 1 (strong reduction) and 10 (light reduction). Its default value is 5.

The optimal setting of the program parameter can be obtained by simulating the soil evaporation for those years were daily rainfall data is available (or available in a nearby representative station). As such the characteristics of the climate (rainfall distribution and evaporating power of the atmosphere), the degree of canopy cover and the characteristics of the soil type can be fully considered.

3.8 Salt balance

Salts enter the soil profile as solutes with the irrigation water or through capillary rise from a shallow groundwater table. It is assumed that rainfall does not contain dissolved salts. The extent to which salts accumulate in the soil depends on the irrigation water quality and quantity that infiltrates into the soil, frequency of wetting, the adequacy of leaching, the importance of soil evaporation and crop transpiration, the soil physical characteristics of the various layers of the soil profile, and the salt content and depth of the groundwater table. Salts are transported out of the soil profile (leached) by means of the drainage water.

AquaCrop uses the calculation procedure presented in BUDGET (Raes et al., 2001; Raes, 2002; Raes et al., 2006) to simulate salt movement and retention in the soil profile.

3.8.1 Movement and accumulation of salts in the soil profile

Vertical downward salt movement in a soil profile is described by assuming that salts are transferred downwards by soil water flow in macro pores. This is simulated in AquaCrop by the drainage function (see Chapter 3, section 3.7 Soil water balance). The exponential drainage function (Eq. 3.7a) describes the vertical solute movement till field capacity is reached. If the soil water content is at or below field capacity, AquaCrop assumes that all macro pores are drained and hence inactive for solute transport.

Since the solute transport in the macro pores bypass the soil water in the matrix, a diffusion process has to be considered to describe the **transfer of solutes** from macro pores to the micro pores in the soil matrix. The driving force for this horizontal diffusion process is the salt concentration gradient that exists between the water solution in the macro pores and micro pores. To avoid the building up of high salt concentrations at a particular depth, a **vertical salt diffusion** is also considered. The driving force for this vertical redistribution process is the salt concentration gradient that builds up at various soil depths in the soil profile.

Vertical upward salt movement is the result of capillary rise from a saline groundwater table and water movement in response to soil evaporation**.** The vertical upward salt movement depends on the wetness of the top of the soil profile and the salinity and depth of the groundwater table (see Chapter 3, section 3.7 Soil water balance). Due to soil evaporation water will evaporate at the soil surface while the dissolved salts remain in the top compartment.

3.8.2 Cells

To describe the movement and retention of soil water and salt in the soil profile, AquaCrop divides the soil profile in various soil compartments (12 by default) with thickness Δz (Fig. 3.7b). To simulate the convection and diffusion of salts, a soil compartment is further divided into a number of cells where salts can be stored (Fig. 3.8a).

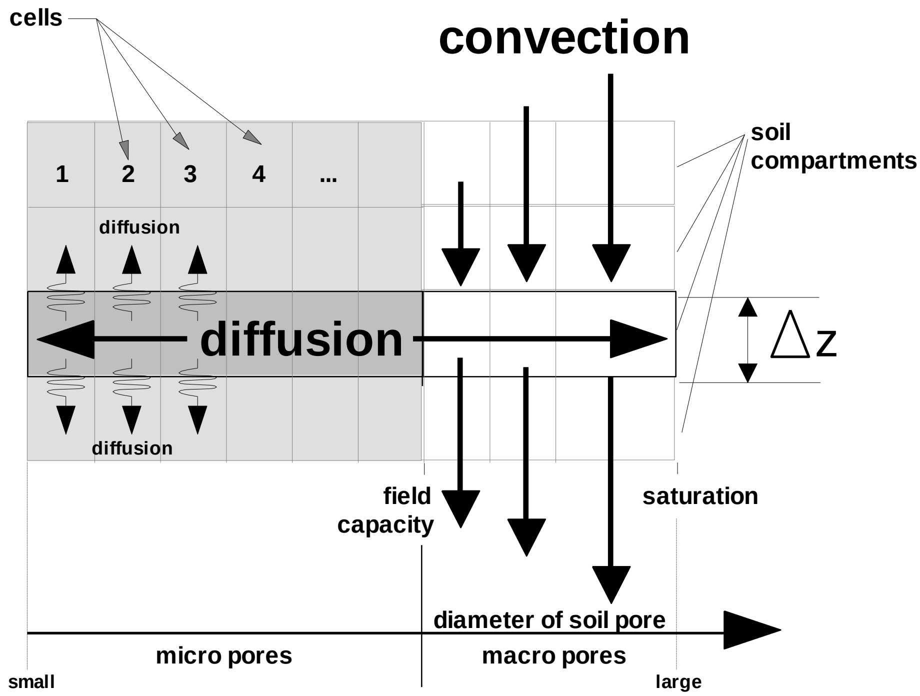


Figure 3.8a – Convection and diffusion of salts in the cells of a soil compartment

The number of cells (n), which may range from 2 to 11, depends on the soil type of the soil horizon. Since salts are strongly attached to the clay particles a clayey horizon will contain more cells than a sandy horizon. The inverse of the saturated hydraulic conductivity (Ksat) is used as an index for the clay content. The number of cells is obtained by considering the Ksat of the soil horizon to which the soil compartment belongs:

$$2 \leq \quad n = ROUND\left(1.6 + \frac{1000}{Ksat}\right) \leq 11 \qquad \text{(Eq. 3.8a)}$$

where Ksat is saturated hydraulic conductivity (mm/day) of the soil horizon. The volume of a cell, which is a fraction of the total pore volume, is given by:

$$W_{cell} = 1000 \frac{\theta_{sat}}{n} \Delta z \left(1 - \frac{Vol\%_{gravel}}{100}\right) \qquad \text{(Eq.3.8b)}$$

where W_{cell} is the volume of the cell in mm(water), θ_{sat} the soil water content at saturation (m^3/m^3) of the soil horizon, n the number of cells, Δz the thickness of the soil compartment (m), and $Vol\%_{gravel}$ the volume percentage of the gravel in the soil horizon to which the compartment belongs. A cell is in fact a representation of a volume of pores with a particular mean diameter. Cells with a low number have small diameters, while cells with a high number have large diameters (Fig. 3.8a).

Salts can be transported by diffusion horizontally and vertically from one cell to its adjacent cells if there exists a concentration gradient and if the cells are active, it is when they contain soil water. Hence, the number of active cells depends on the wetness of the soil. If the soil is dry, only cells with small pore diameters (low numbers) will accommodate water and the diffusion process will be limited. When the soil water content increases, more and more cells are active and become involved in the diffusion process. Once the soil water content is above field capacity, the macro pores are active as well and salts can now also be conducted vertically downward in the soil profile together with the movement of the soil water. If the soil is saturated all macro pores contains water and the convection rate is at its maximum.

The salt concentration in a cell can never exceed a threshold value. The threshold value is determined by the solubility of the salt (see Chapter 2: 2.13 Soil profile characteristics, 2.13.6 Program settings). If the salt concentration in a cell exceeds the threshold value, salts will precipitate and will be temporarily removed from the soil solution. Salts return to the solution as soon as the salt concentration in the cell drops below the threshold value.

3.8.3 Salt diffusion

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

$$EC_{j,t+\Delta t} = EC_{j,t} + f_{diff}\left(\frac{EC_{j,t}\,W_{cell,j} + EC_{j+1,t}\,W_{cell,j+1}}{W_{cell,j} + W_{cell,j+1}} - EC_{j,t}\right) \qquad \text{(Eq. 3.8c)}$$

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

The salt diffusion between adjacent cells does not only depend on differences in their salt concentration but also on the swiftness with which salts can be rearranged between them (f_{diff}). Between cells having large pore diameters, salts can move quite easily since the forces acting on them are relatively small. Equilibrium between the salt content in those pores is reached quickly. Due to strong adsorption forces and low hydraulic conductivity's, salt diffusion will be rather limited in the small pores and it might take quite a while before equilibrium is reached between the salt concentrations in those cells. This is simulated in AquaCrop by adjusting the diffusion process with the ease salts can diffuse. The ease of salt movement is expressed by the diffusion coefficient (f_{diff}). The coefficient varies between 1 for the macro pores (no limitation on salt diffusion) and 0 for the very smallest pores (salts can no longer diffuse between adjacent cells). Between cells representing macro pores the diffusion is entirely in response to salt concentration gradients ($f_{diff} = 1$). Between cells representing the smaller pores, salt diffusion is more limited ($f_{diff} < 1$).

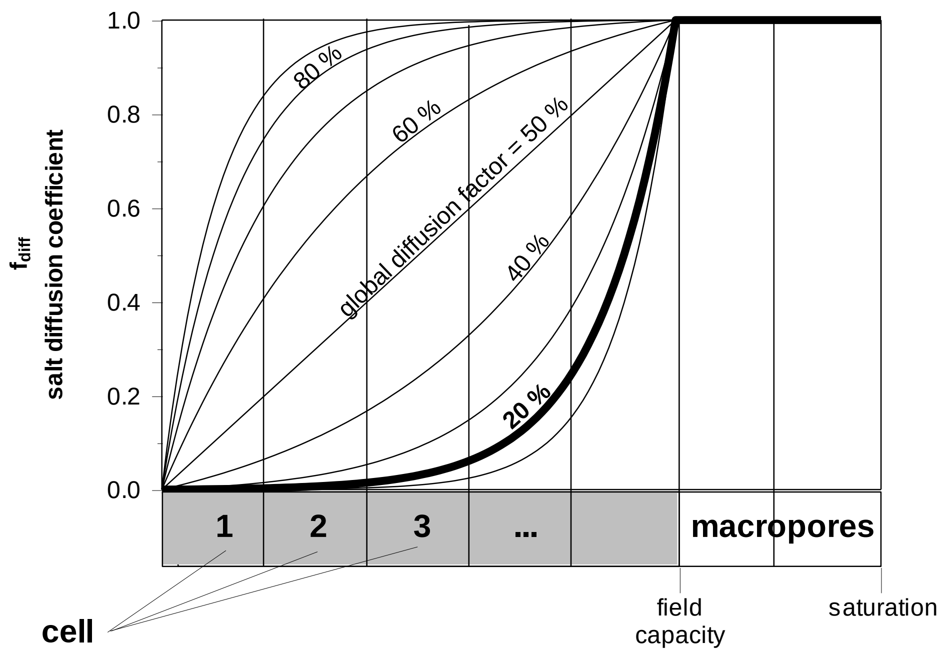
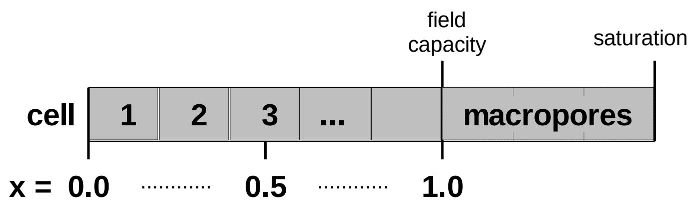


Figure 3.8b – The salt diffusion coefficient (f_{diff}) for the various cells and for various global diffusion factors

The salt diffusion coefficient for the various cells is plotted in Figure 3.8b, for various global salt diffusion factors. The global diffusion factor is a program parameter that describes the global capacity for salt diffusion and can be used to calibrate the model. Increasing or decreasing the global salt diffusion factor alters the ease for salt diffusion and increases or decreases the speed with which equilibrium is reached between the salt concentrations in the adjacent cells. The default setting for the salt diffusion factor is 20 %.

In Table 3.8a the calculation procedure (Eq. 3.8d) for f_{diff} is presented.

Table 3.8a - Equation 3.8d: Calculation procedure for the salt diffusion coefficient (f_{diff})

GDF (global diffusion factor)	< 50 %	> 50 %
x		
f_{diff}	$\frac{a\,b^{x} - a}{a\,b - a}$ (Eq. 3.8d1)	$1 - \frac{a\,b^{(1-x)} - a}{a\,b - a}$ (Eq. 3.8d2)
a	$a = 2\,\frac{GDF}{100}$ (Eq. 3.8d3)	$a = 2\left(1 - \frac{GDF}{100}\right)$ (Eq. 3.8d5)
b	$b = 10^{10\,(0.5 - GDF/100)}$ (Eq. 3.8d4)	$b = 10^{10\,(GDF/100\,-\,0.5)}$ (Eq. 3.8d6)

3.8.4 Vertical salt movement in response to soil evaporation

Soil evaporation in Stage II (falling rate stage) will bring soil water and its dissolved salts from the upper soil layer to the evaporating surface layer (see 3.9 Soil evaporation). At the soil surface, water will evaporate while the salts remain at the soil surface. If the upper soil layer is sufficiently wet, the transport of soil water will be entirely in the liquid phase and the upward salt transport can be important. When the soil dries out, water movement will be gradually replaced by vapour diffusion, resulting in a decrease of upward salt transport.

To simulate upward salt transport in response to soil evaporation, AquaCrop considers not only the amount of water that is extracted out of the soil profile by evaporation, but also the wetness of the upper soil layer (Fig. 3.8c). The relative soil water content of the upper soil layer determines the fraction of the dissolved salts that moves with the evaporating water:

$$f_{salt} = \frac{SWC_{rel}}{10}\,10^{SWC_{rel}} \qquad \text{(Eq. 3.8e)}$$

$$SWC_{rel} = \frac{\theta - \theta_{air\,dry}}{\theta_{sat} - \theta_{air\,dry}} \qquad \text{(Eq. 3.8f)}$$

where f_{salt} fraction of dissolved salts that moves with the evaporating water
SWC_{rel} relative soil water content of the upper soil layer with thickness $Z_{e,top}$
θ soil water content of the upper soil layer ($m^3.m^{-3}$)
θ_{sat} soil water content at saturation ($m^3.m^{-3}$) of the upper soil layer
$\theta_{air\ dry}$ soil water content when the upper layer is air dry ($m^3.m^{-3}$), which is taken as half of the soil water content at permanent wilting point ($\theta_{air\ dry} = \theta_{PWP}/2$)

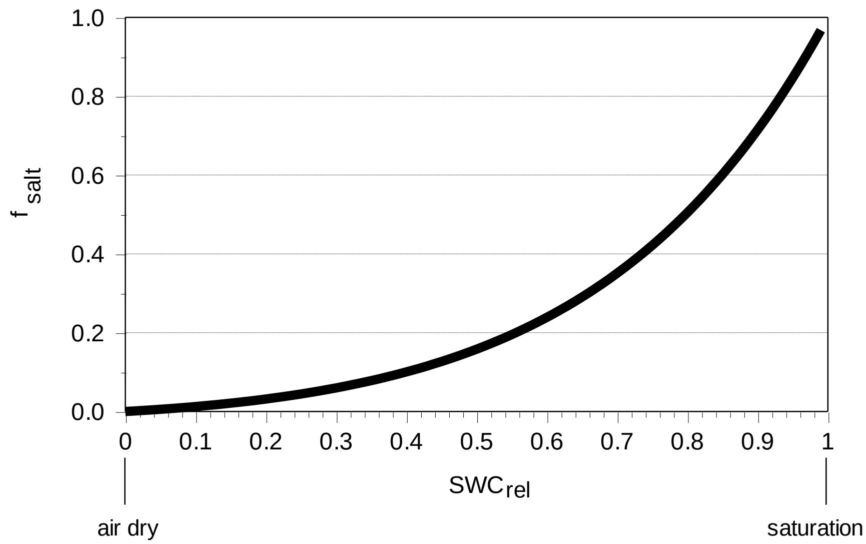


Figure 3.8c – Fraction of dissolved salts (f_{salt}) that moves with the evaporating water for various relative soil water contents (SWC_{rel}) of the upper soil layer

When the upper soil layer is sufficiently wet, soil evaporation will move an important fraction of dissolved salts with the water that is moved by the process to the evaporating soil surface layer. When the layer dries out, the fraction of the dissolved salts that can be transported upward diminishes since water is no longer entirely moved by soil water flow but also by vapour diffusion. Vertical salt movement in response to soil evaporation is no longer considered when the soil water content of the upper soil layer becomes air dry (Fig. 3.8c).

At the start of Stage II of soil evaporation, the thickness of the upper layer ($Z_{e,top}$) is set at 0.15 m (see 3.9.5 Evaporation reduction coefficient). When evaporation removes water from the upper layer $Z_{e,top}$ gradually expands to a maximum depth which is a program parameter. Its default value is 0.3 m and the range is 0.15 to 0.50m.

3.8.5 Vertical salt movement as a result of capillary rise

Salts might also accumulate in the root zone as a result of upward transport of saline water from a shallow groundwater table. The amount of salts that accumulate in the top soil depends on the magnitude of the capillary rise (see 3.7 Soil water balance), the salinity of the groundwater and leaching by excessive rainfall or irrigation.

3.8.6 Soil salinity content

The salt content of a cell is given by:

$$Salt_{cell} = 0.64\ W_{cell}\ EC_{cell} \qquad \text{(Eq. 3.8g)}$$

where $Salt_{cell}$ is the salt content expressed in grams salts per m^2 soil surface, W_{cell} (Eq. 3.8b) its volume expressed in liter per m^2 (1 mm = 1 l/m^2), and 0.64 a global conversion factor used in AquaCrop to convert deciSiemens per meter in gram salts per liter (1 dS/m = 0.64 g/l).

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

$$EC_{sw} = \frac{\sum_{j=1}^{n} Salt_{cell,j}}{0.64\left(1000\,\theta\,\Delta z\right)\left(1 - \frac{Vol\%_{gravel}}{100}\right)} \qquad \text{(Eq. 3.8h)}$$

$$ECe = \frac{\sum_{j=1}^{n} Salt_{cell,j}}{0.64\left(1000\,\theta_{sat}\ \Delta z\right)\left(1 - \frac{Vol\%_{gravel}}{100}\right)} \qquad \text{(Eq. 3.8i)}$$

where n is the number of salt cells of the soil compartment, θ the soil water content (m^3/m^3), θ_{sat} the soil water content (m^3/m^3) at saturation, Δz (m) the thickness of the compartment, and $Vol\%_{gravel}$ the volume percentage of the gravel in the soil horizon to which the compartment belongs

The effect of soil salinity on biomass production is determined by the average ECe of the soil water in the compartments of the effective rooting depth (see 3.15 'Simulation of the effect of soil salinity stress').

3.9 Soil evaporation

ET_o is the evapotranspiration rate from a grass reference surface, not short of water and is an index for the evaporating power of the atmosphere. Soil evaporation (E) is calculated by multiplying ET_o with the soil evaporation coefficient (Ke) and by considering the effect of water stress:

$$E = (Kr\ Ke)\,ET_o \qquad \text{(Eq. 3.9a)}$$

where Kr is the evaporation reduction coefficient which becomes smaller than 1, and as such reduces soil evaporation, when insufficient water is available in the soil to respond to the evaporative demand of the atmosphere. The soil evaporation coefficient Ke is proportional to the fraction of the soil surface not covered by canopy (1-CC). The proportional factor is the maximum soil evaporation coefficient (Ke_x) which integrates the effects of characteristics that distinguish soil evaporation from the evapotranspiration from the grass reference surface. The calculation procedure is presented in Fig. 3.9a.

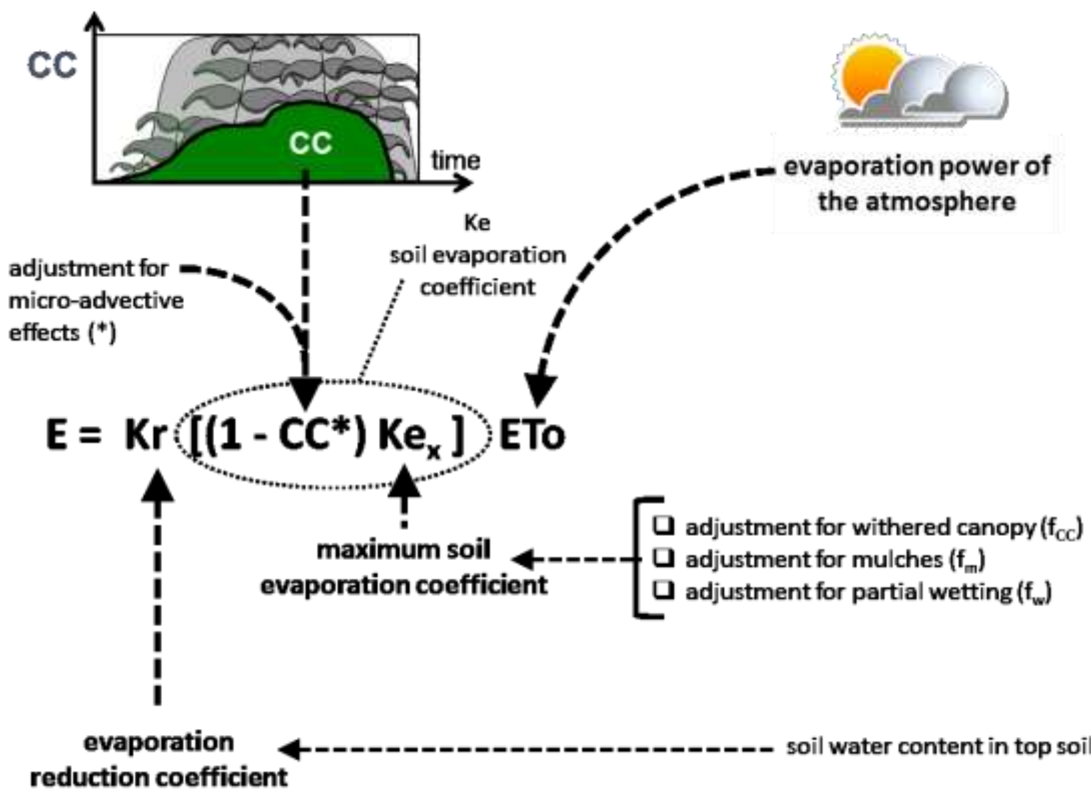


Figure 3.9a – Calculation scheme in AquaCrop for soil evaporation (E)

3.9.1 A two stage calculation method

Evaporation from soil takes place in two stages (Philip, 1957; Ritchie, 1972): an energy limiting stage (Stage I) and a falling rate stage (Stage II).

- **Stage I - energy limiting stage**

When the soil surface is wetted by rainfall or irrigation, soil evaporation switches to stage I. In this stage, water is evaporated from a thin soil surface layer ($Z_{e,surf}$) which is in direct contact with the atmosphere (Fig. 3.9b). As long as water remains in the evaporating soil surface layer, the evaporation rate is fully determined by the energy available for soil evaporation and the evaporation stays in stage I.

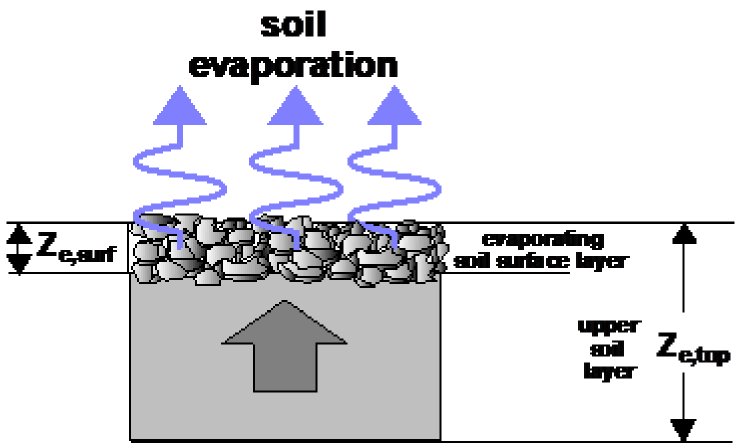


Figure 3.9b - The upward transport of water from the upper soil layer to the evaporating soil surface layer

- **Stage II - falling rate stage**

When all the water is evaporated from the evaporating soil surface layer ($Z_{e,surf}$), soil evaporation switches to stage II and water flows from the soil layer below ($Z_{e,top}$) to the surface layer. In this stage the evaporation is not only determined by the available energy but depends also on the hydraulic properties of the soil. The ability to transfer water to the evaporating soil surface layer reduces as the soil water content in the soil profile decreases. As a result the evaporation rate decreases in function of time.

3.9.2 Readily Evaporable Water (REW)

The Readily Evaporable Water, REW, expresses the maximum amount of water (mm) that can be extracted by soil evaporation from the soil surface layer in stage I. Once REW is removed from the soil, the evaporation rate switches to the falling rate stage. REW corresponds to the U value presented by Ritchie (1972). Water lost by soil evaporation in stage I comes mainly from a thin soil surface layer which is in direct contact with the air above the field (Fig. 3.9b). When the soil surface layer is sufficiently wetted by rainfall or irrigation, its soil water content is at field capacity. When the Readily Evaporable Water is removed from the surface layer, its soil water content will be in equilibrium with the atmosphere, i.e air dry; Hence REW is given by:

$$REW = 1000\left(\theta_{FC} - \theta_{air\ dry}\right) Z_{e,\ surf} \qquad \text{(Eq. 3.9b)}$$

where θ_{FC} volume water content at field capacity [m^3/m^3];
θ_{air} dry volume water content at air dry [m^3/m^3];
$Z_{e,surf}$ thickness of the evaporating soil surface layer in direct contact with the atmosphere [m].

The soil water content at air dry is estimated by applying the rule of thumb, stating that the soil water content at air dry is about half of the soil water at wilting point ($\theta_{air\ dry} \approx 0.5\ \theta_{WP}$). By assuming 40 mm for $Z_{e,surf}$, an agreement was found between REW (Eq. 3.9b) and the cumulative evaporation for the energy limiting stage (Stage I evaporation), i.e., the U value of Ritchie (1972).

3.9.3 Soil evaporation coefficient for wet soil surface (Ke)

When the surface is wet, soil evaporation is calculated by multiplying the reference evapotranspiration (ET_o) with the soil evaporation coefficient (Eq. 3.9a). The soil evaporation coefficient, Ke, considers the characteristics of the soil surface and the fraction of the soil not covered by the canopy:

$$Ke = \left(1 - CC^*\right) Ke_x \qquad \text{(Eq. 3.9.c)}$$

where ($1-CC^*$) adjusted fraction of the non-covered soil surface;
Ke_x maximum soil evaporation coefficient for fully wet and not shaded soil surface.

The maximum soil evaporation coefficient Ke_x for a wet non shaded soil surface is a program parameter. The default value is 1.10 (Allen et al., 1998) and can be adjusted by the user. When the canopy cover (CC) expands in the crop development stage, the soil evaporation coefficient Ke declines gradually (Fig. 3.9c).

In Eq. 3.9c, the fraction of the soil surface not covered by green canopy (1-CC*) is adjusted for micro-advective effects (Fig 3.9d). The adjustment for ($1-CC^*$) is based on the experimental data of Adams et al. (1976) and Villalobos and Fereres (1990):

$$(1 - CC^*) = 1 - 1.72\ CC + CC^2 - 0.30\ CC^3 \qquad \geq 0 \qquad \text{(Eq. 3.9d)}$$

The microadvection cause E to be less than just being proportional to CC. The extra energy is used for crop transpiration (see 3.10 Crop transpiration).

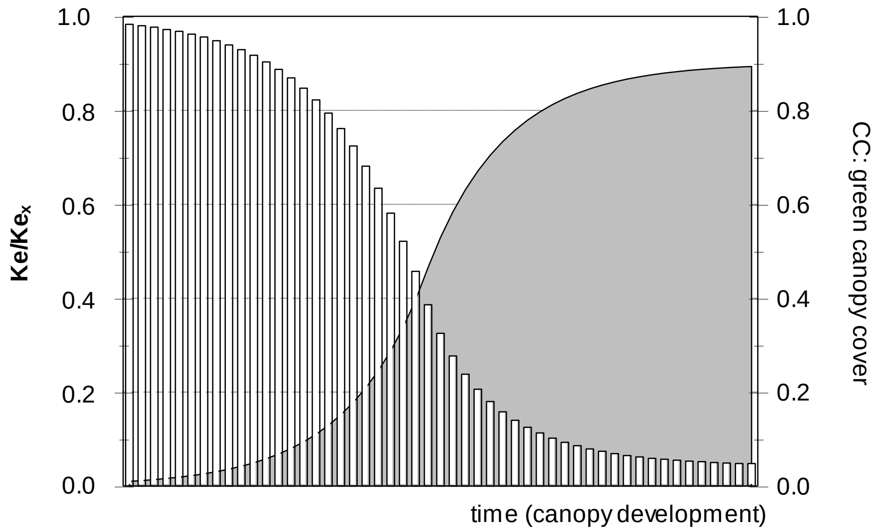


Figure 3.9c – Decline (bars) of the soil evaporation coefficient Ke with reference to the wet non shaded soil surface (Ke$_x$) in the crop development stage when the green canopy cover (shaded area) increases

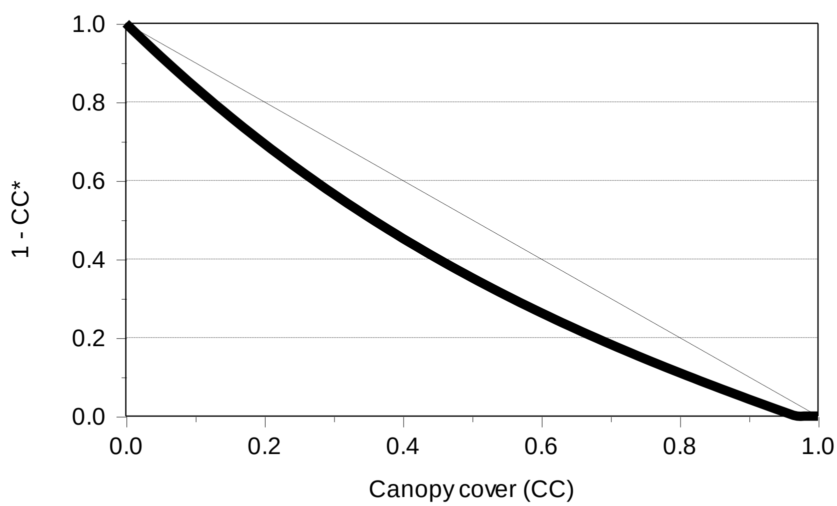


Figure 3.9d – Adjusted fraction (1-CC*) of not shaded soil surface (bold line) for various fractions of green canopy cover (CC)

3.9.4 Adjustment of Ke for withered canopy, mulches and partial wetting by irrigation

- **Sheltering effect of withered canopy cover**

The soil evaporation coefficient needs to be adjusted for the sheltering effect of withered canopy when the green canopy cover declines during periods of severe water stress or in the late season stage as dictated by phenology. The dying crop will act as a shelter which reduces soil evaporation much stronger then described by (1-CC*). Although in this stage the green canopy decreases, the soil remains well sheltered by the withered canopy even when the green canopy cover becomes zero (CC = 0) at the end of the growing cycle.

Two factors are considered for the adjustment of the soil evaporation coefficient:

- f_{cc} a coefficient expressing the sheltering effect of the dead canopy cover [0 … 1];
- CC_{top} the canopy cover prior to senescence. If the canopy cover has reached its maximum size, $CC_{top} = CC_x$

$$Ke_{adj} = \left(1 - f_{cc}\ CC_{top}\right)\left(1 - CC^*\right) Ke_x \qquad \text{(Eq. 3.9e)}$$

Notwithstanding the rule of thumb (Allen et al., 1998) to reduce the amount of soil water evaporation by about 5% for each 10 % of soil surface that is effectively covered by an organic mulch the default value for f_{cc} is 0.60 and not 0.50, because a standing crop gives better shelter against the effect of dry wind than an organic mulch that covers the soil surface. To simulate a smooth increase of evaporation in the late season stage when senescence occurs, f_{cc} increases gradually from 0 (at the start of the late-season stage) to its final value when CC is half of CC_{top}.

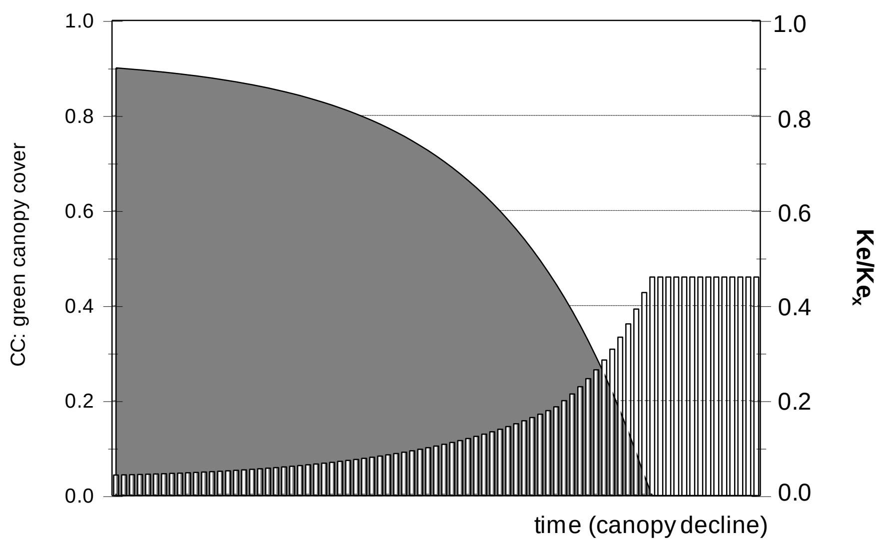


Figure 3.9e – Increase (bars) of the soil evaporation coefficient Ke adjusted for withered canopy with reference to the wet non shaded soil surface (Ke_x) in the late season stage when the green canopy cover (shaded area) decreases

The effect of the withered canopy shelter on the reduction of soil evaporation is plotted in Figure 3.9e. The effect is a program parameter which can be adjusted by the user.

- **Adjustment for mulches**

To reduce evaporation losses from the soil surface, mulches can be considered. The effect of mulches on crop evaporation is described by two factors (Allen et al., 1998):

- soil surface covered by mulch (from 0 to 100%); and
- f_m (≤ 1), the adjustment factor for the effect of mulches on soil evaporation, which varies between 0.5 for mulches of plant material and is close to 1.0 for plastic mulches (Allen et al., 1998).

The adjustment for soil evaporation consists in multiplying Ke by the correction factor:

$$Ke_{adj} = \left(1 - f_m \frac{Percent\ covered\ by\ mulch}{100}\right)\left(1 - CC^*\right) Ke_x \qquad \text{(Eq. 3.9f)}$$

The adjustment is not applied when standing water remains on the soil surface (between soil bunds).

- **Adjustment for partial wetting by irrigation**

When only a fraction of the soil surface is wetted by irrigation, Ke is multiplied by the fraction of the surface wetted (f_w) to adjust for partial wetting (Allen et al., 1998):

$$Ke_{adj} = f_w \left(1 - CC^*\right) Ke_x \qquad \text{(Eq. 3.9g)}$$

The fraction f_w is an irrigation parameter, and can be adjusted when selecting an irrigation method in the ***Irrigation Management*** Menu. The adjustment for partial wetting is not applied when:

- surface is wetted by irrigation and rain on the same day;
- surface is wetted by rain; and
- irrigation and/or rain water remains on the soil surface (between the soil bunds).

- **Adjustment for mulches and partial wetting by irrigation**

If the soil surface is covered by mulches and at the same time partial wetted by irrigation, only one of the above adjustments is valid. Ke is the minimum value obtained from Eq. 3.9f and 3.9g.

3.9.5 Evaporation reduction coefficient (Kr)

When insufficient water is available at the soil surface soil evaporation switches from Stage I (energy limiting stage) to Stage II (falling rate stage). This simulated with the introduction of an evaporation reduction coefficient (Eq. 3.9a). The evaporation reduction coefficient (Kr) varies with the amount of water available in the upper soil layer from where water is transferred to the evaporating soil surface layer. Kr is 1 if the soil is sufficiently wet and the soil evaporation is not hampered by water depletion, which is the case in Stage I. Kr decreases when the soil water depletion increases and is zero when the upper layer of the soil becomes air dry (Fig. 3.9f).

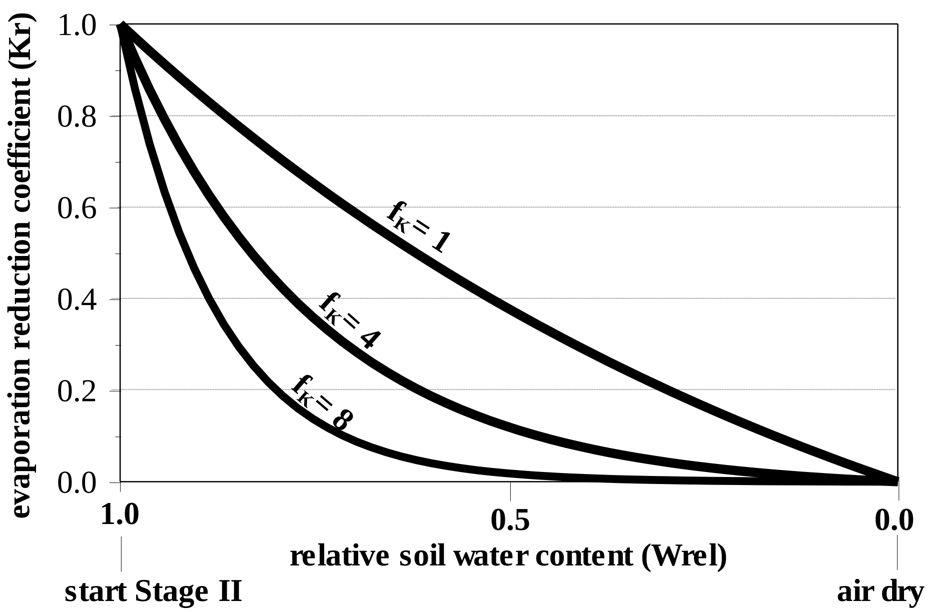


Figure 3.9f – The evaporation reduction coefficient Kr for various levels of relative soil water content and decline factors (f_K)

In stead of using the square root of time (Ritchie type of model), a mechanistic approach is used to describe the evaporation rate in the falling rate stage. With this approach not only time but also the amount of water extracted from the top soil by transpiration, groundwater contribution from a shallow water table and the weather conditions (Rain and ET_o) are considered for the determination of Kr.

To account for the sharp decline in hydraulic conductivity with decreasing soil water content, an exponential equation is used to relate Kr to the relative water content of the upper soil layer:

$$0 \leq Kr = \frac{\exp^{f_K W_{rel}} - 1}{\exp^{f_K} - 1} \leq 1 \qquad \text{(Eq. 3.9h)}$$

where f_K is a decline factor and W_{rel} the relative water content of the soil layer through which water moves to the evaporating soil surface layer (upper soil layer with thickness $Z_{e,top}$). A thickness of 0.15 m is assigned initially for $Z_{e,top}$. However, when W_{rel} drops below a threshold (set at $W_{rel} = 0.4$), $Z_{e,top}$ expands to a maximum depth which is a program parameter. Its default value is 0.3 m and the range is 0.15 to 0.50 m.

At the start of Stage II, W_{rel} begins to decline below 1 and becomes 0 when there exist no longer a hydraulic gradient i.e. when $Z_{e,top}$ is air dry (Fig. 3.9f). The decline factor f_K depends on the hydraulic properties of the soil and can be used to calibrate Kr when measurements of soil evaporation are available. The decline of Kr with decreasing W_{rel} alters by varying the value of f_K (Fig. 3.9f). When f_K takes a value of 4, a good fit was obtained between the square root of time approach (Ritchie, 1972) and the soil water content approach used by AquaCrop in the simulation of Stage II evaporation. Even after three weeks of evaporation (21 days) the cumulative amount of water lost by soil evaporation remained in the same range for both approaches and for most soil textural classes.

3.9.6 Calculation of soil evaporation (E)

- **Energy limiting stage (Stage I)**

When rainfall occurs or water is added by irrigation, the infiltrated water replenishes the soil surface layer till REW is reached. As long as readily evaporable water remains in the surface layer, E is in the energy limiting stage, and the rate of soil evaporation is the maximum rate:

$$E_{Stage\,I} = \left(1 - CC^{*}\right) Ke_x \; ET_o \qquad \text{(Eq. 3.9i)}$$

The following rules are applied:

- The maximum amount of water that can be stored in the surface layer is REW. Light wetting events do not necessarily completely replenished the soil surface;
- If the soil surface is only partly wetted by irrigation, only the wetted fraction of the surface layer is replenished;
- When the soil is flooded and water remains between soil bunds on top of the field, evaporation takes places from the water layer at the soil surface. When the water layer is completely evaporated, it is assumed that the total REW is still available in the soil surface layer and soil evaporation starts in stage I.

- **Falling rate stage (Stage II)**

When all the readily evaporable water is removed from the evaporating soil surface layer, the soil evaporation switches to the falling rate stage (Stage II). The evaporation rate is given by:

$$E_{StageII} = Kr \left(1 - CC^{*}\right) Ke_x \; ET_o \qquad \text{(Eq. 3.9j)}$$

where Kr is the dimensionless evaporation reduction coefficient.

The relative water content at which Kr is 1 (upper limit) is the soil water content of the top soil at the end of stage I. The upper limit will be close to saturation when the soil is slow draining and close to field capacity when the soil drains quickly. However, it is assumed in the model that the upper limit cannot drop below the soil water content at field capacity minus REW. As such the expected sharp drop in evaporation when the top soil is only slightly wetted by rainfall or irrigation can be simulated.

Since Kr varies strongly with W_{rel} especially at the beginning of Stage II, the routine daily time step is inadequate and had to be divided into 20 equal fractions to obtain a differential solution for Eq. 3.9j. At the end of each small time step, the water content of the soil profile is updated and Kr is estimated with Eq. 3.9h. Consequently the switch from stage I to II occurring during the day, can be simulated as well.

3.9.7 Calculation of soil evaporation (E_{TOT}) in weed infested fields

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

The soil evaporation in the weed-infested field (E_{TOT}) is given by:

$$E_{TOT} = Kr\left(1 - CC^{*}_{TOT}\right) Ke_x \; ET_o \qquad \text{(Eq. 3.9k)}$$

where Kr is the evaporation reduction coefficient (which is 1 in the energy limiting stage), Ke_x the maximum soil evaporation coefficient for fully wet and not shaded soil surface, and (1 - CC^{*}_{TOT}) the adjusted fraction of the non-covered soil surface by the canopy cover of crop and weeds.

3.10 Crop transpiration

ET_o is the evapotranspiration rate from a grass reference surface, not short of water and is an index for the evaporating power of the atmosphere. Crop transpiration (Tr) is calculated by multiplying ET_o with the crop transpiration coefficient (Kc_{Tr}) and by considering the effect of water (Ks) and cold (Ks_{Tr}) stress:

$$Tr = \left(Ks\ Ks_{Tr}\ Kc_{Tr}\right) ET_o \qquad \text{(Eq. 3.10a)}$$

where Ks is the soil water stress coefficient which becomes smaller than 1, and as such reduces crop transpiration, when insufficient water is available to respond to the evaporative demand of the atmosphere, and Ks_{Tr} is the cold stress coefficient which becomes smaller than 1 when there are not enough growing degrees in the day. The crop transpiration coefficient Kc_{Tr} is proportional with the green canopy cover (CC). The proportional factor is the maximum crop transpiration coefficient ($Kc_{Tr,x}$) which integrates the effects of characteristics that distinguish the crop transpiration from the evapotranspiration from the grass reference surface. The calculation procedure is presented in Fig. 3.10a.

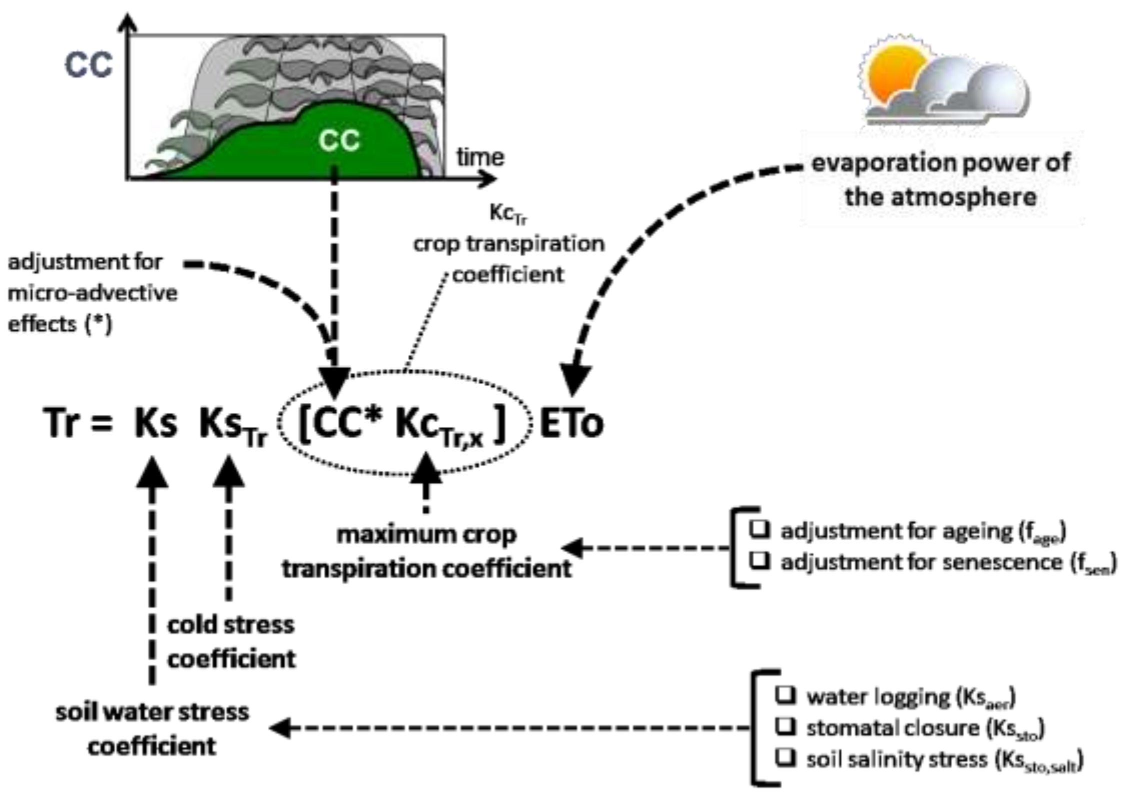


Figure 3.10a – Calculation scheme in AquaCrop for crop transpiration (Tr)

3.10.1 Crop transpiration coefficient (Kc_{Tr})

Crop transpiration is calculated by multiplying the reference evapotranspiration with the crop transpiration coefficient (Eq. 3.10a). The crop transpiration coefficient (Kc_{Tr}) considers (i) the characteristics that distinguish the crop with a complete canopy cover from the reference grass and (ii) the fraction by which the canopy covers the ground:

$$Kc_{Tr} = CC^{*}\ Kc_{Tr,x} \qquad \text{(Eq. 3.10b)}$$

where $Kc_{Tr,x}$ coefficient for maximum crop transpiration (well watered soil and complete canopy, CC = 1);

CC^{*} actual canopy cover adjusted for micro-advective effects.

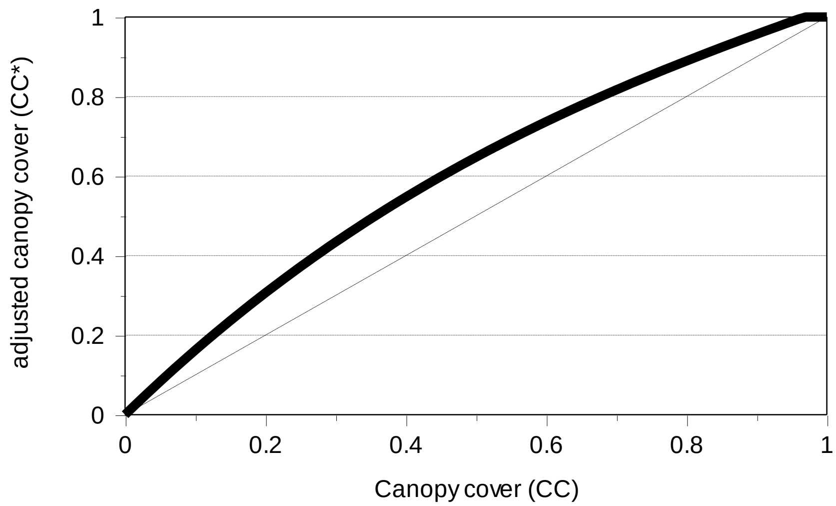


Figure 3.10b – Canopy cover (CC^{*}) adjusted for micro-advective effects (bold line) for various fractions of green canopy cover (CC)

To estimate crop transpiration, CC is increased to CC^{*} to account for interrow micro-advective and sheltering effect by partial canopy cover (Fig. 3.10b). The adjustment is based on studies of Adams et al. (1976) and Villalobos and Fereres (1990):

$$CC^{*} = 1.72\ CC - CC^{2} + 0.30\ CC^{3} \qquad \text{(Eq. 3.10c)}$$

When the canopy cover is incomplete extra energy is available for crop transpiration (Tr) and less for soil evaporation (E). The micro-advection cause Tr to be more than just being proportional to CC and E less than being proportional to (1-CC) (see 3.9 ‘Soil evaporation’).

3.10.2 Coefficient for maximum crop transpiration ($Kc_{Tr,x}$)

Due to differences in albedo, crop height, aerodynamic properties, and leaf and stomata properties, $Kc_{Tr,x}$ differs from 1. The $Kc_{Tr,x}$ coefficient is often 5-10% higher than the reference grass, and even 15-20% greater for some tall crops such as maize, sorghum or sugar cane. The $Kc_{Tr,x}$ coefficient is approximately equivalent to the basal crop coefficient at mid-season for different crops (Allen et al., 1998), but only for cases of full CC.

3.10.3 Adjustments of $Kc_{Tr,x}$ for ageing, senescence and elevated [CO_2]

- **Adjustment of $Kc_{Tr,x}$ for ageing effects**

After the time t_{CCx} required to reach CC_x under optimal conditions and before senescence, the canopy ages slowly and undergoes a progressive though small reduction in transpiration and photosynthetic capacity (Fig. 3.10c). This is simulated by applying an adjustment factor (f_{age}) that decreases $Kc_{Tr,x}$ by a constant and slight fraction (e.g., 0.3%) per day, resulting in an adjusted crop coefficient. The ageing comes in effect at t_{CCx} which is the time when CC_x (maximum canopy cover) would have been reached without water stress (i.e. at the beginning of the mid-season). A short lag phase of 5 days is assumed. After the lag phase of 5 days, $Kc_{Tr,x,adj}$ is given by:

$$Kc_{Trx,\,adj} = Kc_{Tr,x} - (t-5)\; f_{age}\; CC_x \qquad \text{(Eq. 3.10d)}$$

where t is the time in days after t_{CCx} (t is zero before and at t_{CCx}), and f_{age} is the reduction expressed as a fraction of CC_x. The f_{age} coefficient is a crop parameter, since it will require some adjustment for annual crops such as sugarcane.

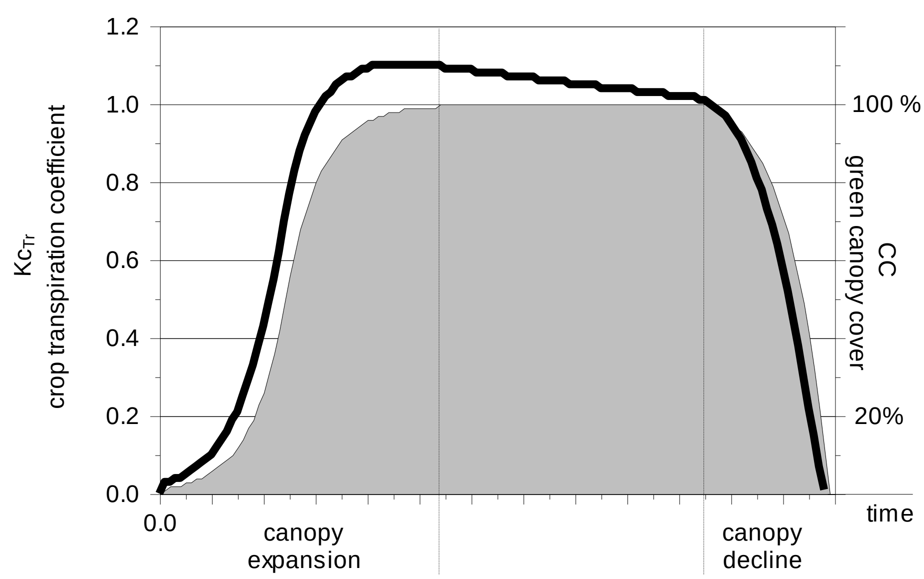


Figure 3.10c – Canopy development (shaded area) and crop transpiration coefficient Kc_{Tr} (line) throughout the crop cycle for $Kc_{Tr,x}$ = 1.1, CC_x = 100%, and f_{age} 0.16%/day

The same apply for forage and pasture crop. However, since the canopy is harvested at each cut, a new canopy has to develop which cancels the ageing. Once CC_x is reached after a cutting, the ageing kicks in again and is described by Eq. 3.10d.

- **Adjustment of $Kc_{Tr,x}$ once senescence is triggered**

When senescence is triggered, the transpiration and photosynthetic capacity of the green portion of the canopy drops more markedly with time. This is simulated by multiplying $Kc_{Trx,adj}$ (Eq. 3.10d) with another adjustment factor, f_{sen}, which declines from 1 at the start of senescence ($CC = CC_x$) to 0 when no green canopy cover remains ($CC = 0$):

$$Kc_{Trx,\,sen} = Kc_{Trx,\,adj}\left(f_{sen}\right)$$
$$with \quad f_{sen} = \left(\frac{CC}{CC_x}\right)^a \qquad \text{(Eq. 3.10e)}$$

The exponent a is a program parameter and can be used to accentuate ($a > 1$) or to minimize ($a < 1$) the drop in the transpiration/photosynthetic efficiency of the declining canopy. In the program 'a' can vary between an upper limit of 4 (very strong effect) and a lower limit of 0.1 (very limited effect). Its default value is 1. The senescence factor (f_{sen}) for various degrees of withering (CC/CC_x) and various values of the exponent 'a' is plotted in Fig. 3.10d.

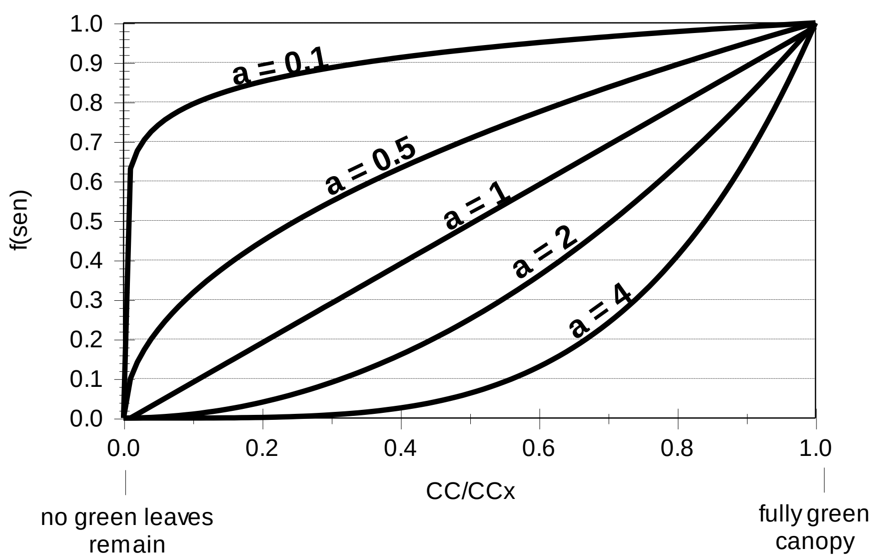


Figure 3.10d – The senescence factor (f_{sen}) for various degrees of withering (CC/CC_x) and various values of the exponent 'a'

- **Adjustment of $Kc_{Tr,x}$ for elevated [CO_2]**

The overall transpiration response to elevated [CO_2] is relatively small but significant. An average decrease of 5% in crop transpiration is considered. The decrease is a combined consequence of several effects. Elevated [CO_2] decreases crop transpiration via reductions in stomatal conductance, thus decreasing the transpiration on a leaf area basis. This mechanism reduces the cooling effect of the transpiration process, augments leaf temperature and triggers more transpiration, hence offsetting part of the transpiration reduction.

By considering the reduction of 5 %, when the [CO_2] increase from 370 to 550 ppm (analysis of FACE data), the correction of Kc for elevated [CO_2]:

$$Kc_{Trx,adj} = Kc_{Trx}\left(1 - 0.05\,\frac{[CO_2 - 369.41]}{550 - 369.41}\right) \qquad \text{(Eq. 3.10e/2)}$$

3.10.4 Soil water stress coefficient (Ks)

Crop transpiration can be affected by a shortage of water and an excess of water. This is simulated with the help of a soil water stress coefficient for stomatal closure (Ks_{sto}) and for water logging (Ks_{aer}).

To allow light rain to reduce the soil water stress of deep rooted crops, the root zone depletion is compared with the depletion in the top soil at each time of the simulation (Fig. 3.2c). The comparison determines which part of the soil profile is the wettest and controls the water stress (only for Ks_{sto}).

- **Water stress coefficient for stomatal closure (Ks_{sto})**

To simulate the result of stomatal closure induced by water stress, the coefficient for crop transpiration (Kc_{Tr}) is multiplied by the water stress coefficient for stomatal closure (Ks_{sto}):

$$Tr = Ks_{sto}\ Ks_{Tr}\ Kc_{Tr}\ ET_0 \qquad \text{(Eq. 3.10f)}$$

The Ks_{sto} coefficient describes the effect of water stress on crop transpiration (see 3.2.2: Soil water stress). When sufficient water remains in the considered soil volume (top soil or root zone), transpiration is unaffected and $Ks_{sto} = 1$. When the soil water depletion exceeds an upper threshold (p_{sto} TAW), the water extracted by the crop becomes limited ($Ks_{sto} < 1$) and the crop is under water stress (Fig. 3.10e). When the soil water content in the considered soil volume reaches its lower limit (which is permanent wilting point), the stomata are completely closed, and crop transpiration is halted ($Ks_{sto} = 0$). In AquaCrop the shape of the Ks_{sto} curve between the upper and lower threshold can be selected as linear or concave. Since the stress response curve are defined for an evaporating power of the atmosphere (ETo) of 5 mm/day, the upper threshold for water stress needs to be adjusted for ETo.

The upper threshold of soil water depletion ($D_{sto,upper}$) is given by:

$$D_{sto,upper} = p_{sto}\ TAW \qquad \text{(Eq.3.10g)}$$

where p_{sto} fraction of TAW at which stomata start to close;
TAW Total Available soil Water in the considered soil volume [mm].

At the lower threshold, which corresponds with permanent wilting point, the soil water depletion ($D_{sto,lower}$) is:

$$D_{sto,lower} = TAW \qquad \text{(Eq.3.10h)}$$

The depletion coefficient p_{sto} is the fraction of TAW that can be depleted from the considered soil volume before stomata starts to close. The p factor divides the Total Available soil Water (TAW), in two parts: water that can be extracted without stress (RAW) and water that is more difficult to extract (Fig. 3.10f).

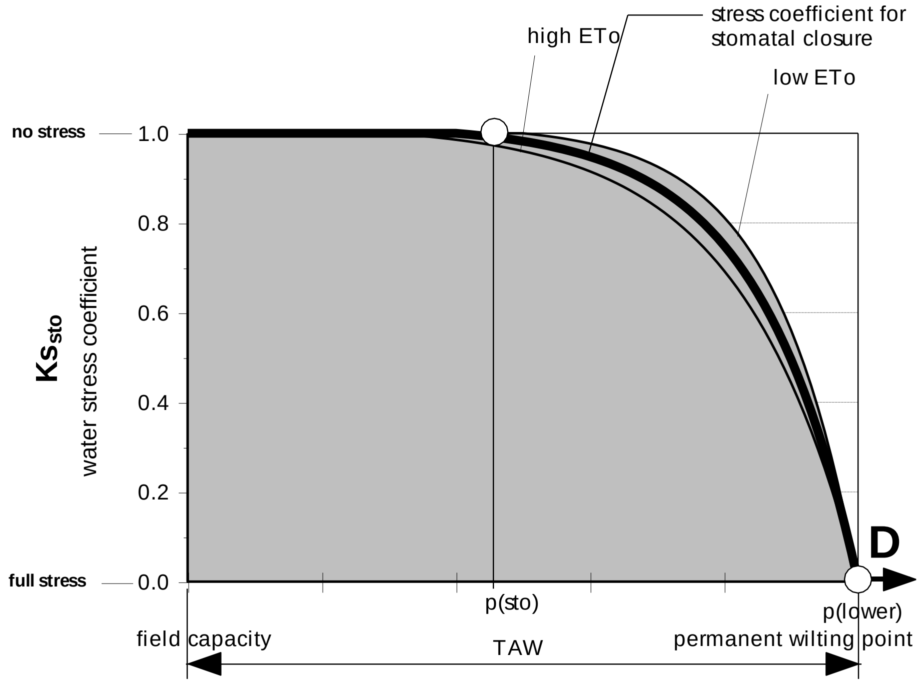


Figure 3.10e – The water stress coefficient for stomatal closure (Ks_{sto}) for various degrees of depletion (D) in he considered soil volume

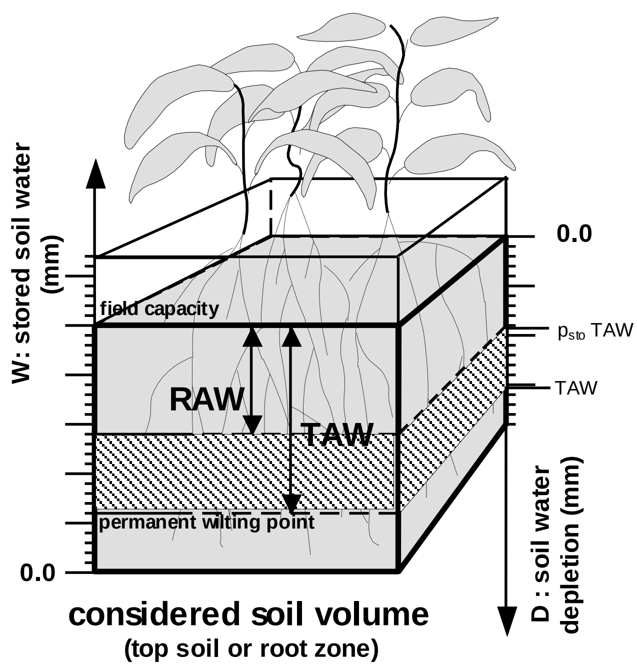


Figure 3.10f – The upper and lower threshold of soil water depletion affecting stomatal closure

- **Effect of soil salinity on the water stress coefficient for stomatal closure**

Due to osmotic forces, which lower the soil water potential, the salts in the root zone makes the water less available for the crop. This results in a decline of the biomass production.

In a well-watered saline soil, and in the absence of any other stresses than salt stress, AquaCrop obtains the relative biomass production from the 'Biomass – ECe' relationship (Fig. 3.2f). The partial closure of the stomata is specified by calibration for a particular ECe (Fig. 3.10g – effect 1).

When the soil is not well-watered, water depletion in the root zone results in an increase of the salt concentration in the remaining soil water. Although root zone depletion does not alter ECe (the indicator for soil salinity), it increases the electrical conductivity of the soil water (ECsw). The stronger the root zone depletion, the larger ECsw, and the more difficult it becomes for the crop to extract water from its root zone. This results in a stronger closure of the stomata when the soil dries out. The extra effect of ECsw on stomata closure is specified by calibration for the crop response to salinity stress (Fig. 3.10g – effect 2).

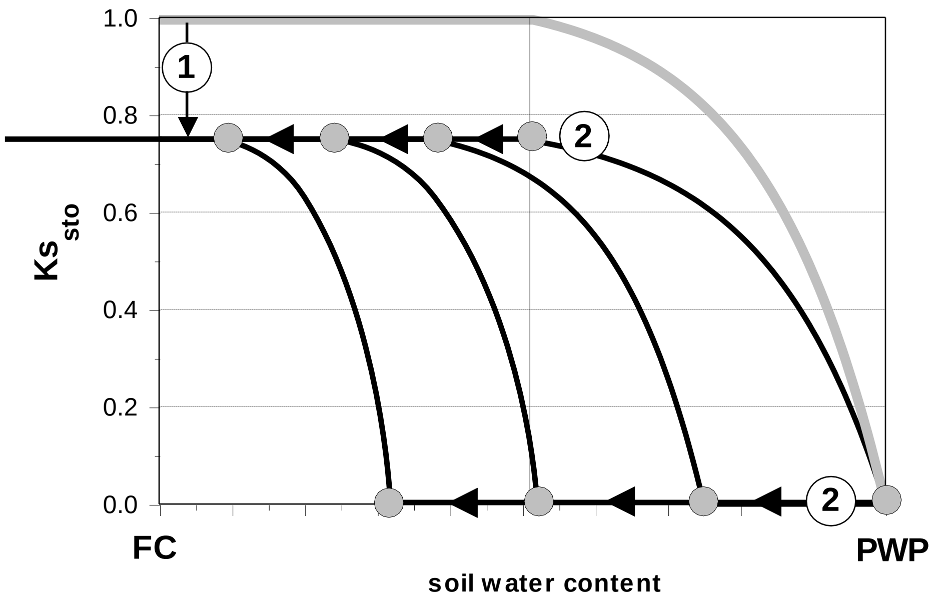


Fig. 3.10g – The soil water coefficient for stomatal closure (Ks_{sto}) without (gray line) and with (several alternative black lines) the effect of soil salinity stress. The decline of Ks_{sto} (effect 1) is linked with ECe, the shift of the upper and lower threshold (effect 2) is the effect of ECsw. The effect of ECsw on stomata closure (presented by the alternative black lines) is specified by calibration

The effect of soil salinity stress on stomatal closure is simulated by multiplying the soil water stress coefficient for stomatal closure (Ks_{sto}) with the soil salinity stress coefficient for stomatal closure ($Ks_{sto,salt}$):

$$Ks_{sto,adj} = Ks_{sto,salt}\ Ks_{sto} \qquad \text{(Eq. 3.10i)}$$

- **Water stress coefficient for deficient aeration conditions (Ks_{aer})**

Transpiration is hampered not only when the water content in the considered soil volume is limited but also when the root zone is water logged, resulting in deficient soil aeration (Fig. 3.10h). If the water content in the root zone is above the anaerobiosis point (θ_{air}) the root zone becomes water logged and transpiration is limited.

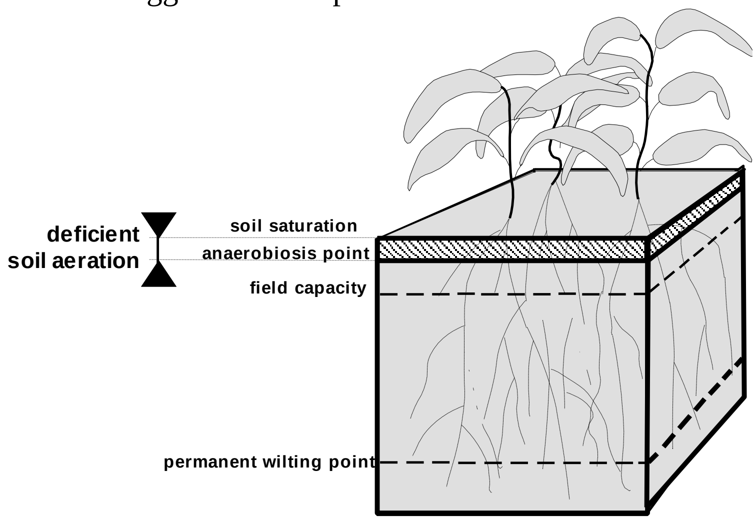


Figure 3.10h – The upper and lower threshold for the soil water content in the root zone resulting in deficient aeration conditions

The effect of water logging on crop transpiration is simulated by means of a water stress coefficient for water logging (Ks_{aer}):

$$Tr = Ks_{aer}\ Ks_{Tr}\ Kc_{Tr}\ ET_o \qquad \text{(Eq. 3.10j)}$$

Ks_{aer} varies linearly between the anaerobiosis point where Ks_{aer} is 1 and soil saturation where Ks_{aer} is zero (Fig. 3.10i).

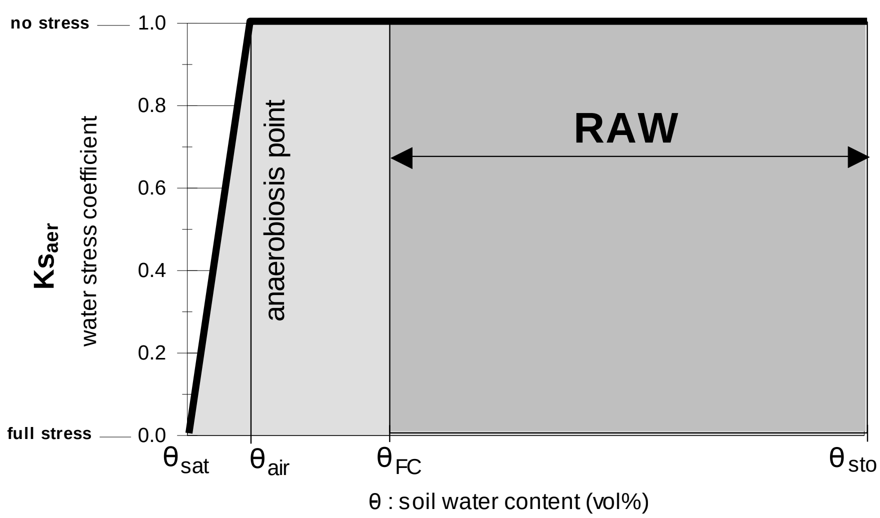


Figure 3.10i – The water stress coefficient for water logging (Ks_{aer}) for various levels of soil water content (θ)

The sensitivity of the crop to water logging is specified by the soil water content (anaerobiosis point) at which the aeration of the root zone will be deficient for the crop and starts to affect crop transpiration. The anaerobiosis point is a crop parameter. To simulate the resistance of crops to short periods of waterlogging, the full effect will only be reached after a specified number of days (which is a program parameter).

3.10.5 Cold stress coefficient (Ks_{Tr})

As for the water stress coefficient, the target crop parameter for the cold stress coefficient (Ks_{Tr}) is the crop transpiration coefficient (Kc_{Tr}). It expresses the reduction in stomatal conductance at low temperature. Daily crop transpiration (Tr) is calculated by multiplying ETo with the crop transpiration coefficient (Kc_{Tr}) and by considering the effect of water stress (Ks) and cold stress (Ks_{Tr}) on that day:

$$Tr = Ks\ Ks_{Tr}\ Kc_{Tr}\ ET_o \qquad \text{(Eq. 3.10k)}$$

Depending on the number of growing degrees generated on a day, the value of Ks_{Tr} varies between 0 (resulting in no crop transpiration on a day) and 1 (transpiration is not restricted by temperature for that day).

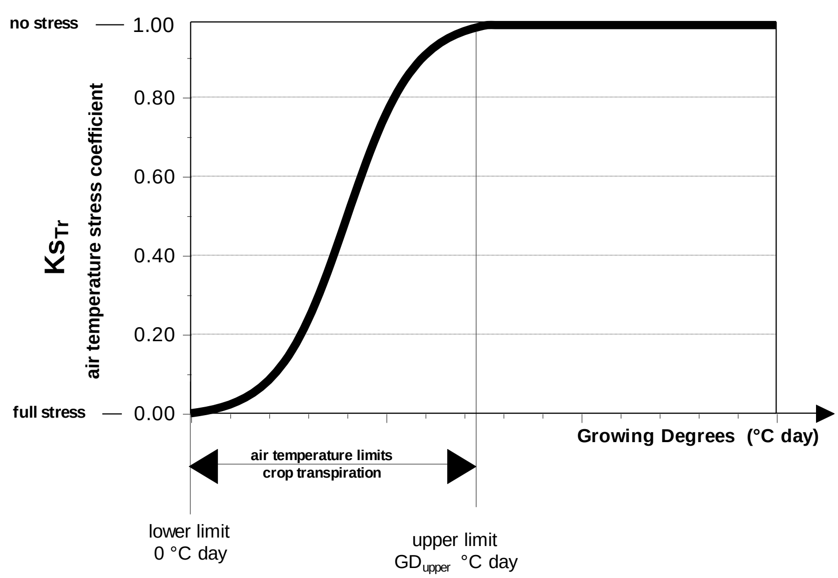


Figure 3.10j – The air temperature stress coefficient for reduction of crop transpiration (Ks_{Tr}) for various levels of growing degrees

If the growing degrees generated in a day drops below an upper threshold (GD_{upper}) the crop transpiration is limited by air temperature and Ks_b is smaller than 1 (Fig. 3.10j). In AquaCrop it is assumed that transpiration is completely halted when it becomes too cold to generate any growing degrees (Ks_{Tr} = 0 for 0 °C day). Between the lower (0°C day) and upper limit (GD_{upper}) the variation of the adjustment factor is described by a logistic function. The upper threshold (GD_{upper}) is a crop parameter, and its value can be adjusted between 0.1 and 20 °C day.

3.10.6 Calculation of crop transpiration in weed infested fields (Tr_W)

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

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

Crop transpiration in a weed infested field (Tr_W) is proportional to CC_W (Eq. 3.5k). In the calculation of Tr_W, the adjustment for micro-adjustments is based on the total canopy cover CC_{TOT}:

$$Tr_W = Ks\ Ks_{Tr}\ \left[CC_W + \left(CC^*_{TOT} - CC_{TOT}\right)\right] Kc_{Tr,x}\ ET_o \qquad \text{(Eq. 3.10l)}$$

where Ks is the water stress coefficient, Ks_{Tr} the cold stress coefficient, CCw the crop canopy cover, CC_{TOT} the total (crop and weeds) canopy cover, CC^*_{TOT} the total canopy cover adjusted for micro-advective effects, $Kc_{TR,x}$ the maximum crop transpiration coefficient, and ET_o is the evapotranspiration rate from a grass reference surface.

3.10.7 Soil water extraction

- **Calculation procedure**

The calculation procedure consists of the following steps:

1. Determination of the transpiration demand by considering the average soil water content in the considered soil volume (top soil or root zone) and as such the average total water stress in the soil volume:

$$Tr = \overline{Ks_{soil\ volume}}\ Ks_{Tr}\ Kc_{Tr}\ ET_o \qquad \text{(Eq. 3.10m)}$$

   where $\overline{Ks_{soil\ volume}}$ is the average soil water stress in the considered soil volume induced by a shortage or an excess of water and/or aeration stress. A linear relationship between the water stress coefficient ($\overline{Ks_{soil\ volume}}$) and the soil water content in the considered soil volume is assumed.

2. Determination of the amount of water that can be extracted out of the root zone at various depths, by considering the maximum root extraction rate and the water stress coefficient at the various depths (soil compartments):

$$S_i = Ks_i\ S_{x,i} \qquad \text{(Eq. 3.10n)}$$

   where
   - S_i sink term ($m^3.m^{-3}.day^{-1}$) at soil depth i;
   - Ks_i water stress factor (dimensionless) for soil water content θ_i at soil depth i;
   - $S_{x,i}$ maximum root extraction rate ($m^3.m^{-3}.day^{-1}$) at soil depth i.

   The root extraction rate or sink term, S, (Feddes et al., 1978; Hoogland et al., 1981, Belmans et al., 1983) expresses the amount of water that can be extracted by the roots at a specific depth per unit of bulk volume of soil, per unit of time ($m^3.m^{-3}.day^{-1}$). Depending on the type of water stress, Ks_i is either Ks_{sto} or Ks_{aer} in Eq. 3.10n. To determine the value of Ks_i for the given θ_i, the assigned shape of the Ks curve (linear or convex) is considered.

3. By integrating Eq. 3.10n over the different compartments of the root zone, the exact amount of water that can be extracted by transpiration is obtained:

$$Tr = \sum_{top}^{bottom} 1000\left(Ks_i\ S_{x,i}\right) dz_i \quad \leq \quad \overline{Ks_{soil\ volume}}\ Ks_{Tr}\ Kc_{Tr}\ ET_o \qquad \text{(Eq. 3.10o)}$$

   where dz_i is the thickness of the soil compartment (m). The integration starts at the top of the soil profile and is stopped when the sum is equal to the transpiration demand given by Eq. 3.10m or the bottom of the root zone is reached.

   When the maximum root extraction rate over the entire root zone (Σ $1000 S_x dz$) is too small (as a result of a limited root volume), the amount of water that can be extracted by transpiration will be smaller than the demand (Eq. 3.10m). The transpiration demand can easily be extracted out of the root zone if S_x at the various depths is sufficiently large. When S_x is large, the root zone well watered (Ks = 1) and the transpiration demand small, water will only be extracted from the top of the root zone. When the top becomes increasingly drier ($Ks_i < 1$), more and more water will need to be extracted at the lower part of the root zone.

- **Maximum root extraction rate (S_x) and the total extraction rate (Σ 1000$S_x$dz)**

In the model the maximum root extraction rate at the top of the soil profile ($S_{x,top}$) might be different from the maximum extraction rate at the bottom of the root zone ($S_{x,bottom}$). The assigned S_x values at different soil depths are proportional to the specified water extraction pattern (Fig. 3.10k). Apart from the root distribution, S_x is also determined by the total root volume. The total root volume determines the total amount of water that can be extracted out of the root zone, i.e. the total extraction rate (Σ 1000$S_x$dz).

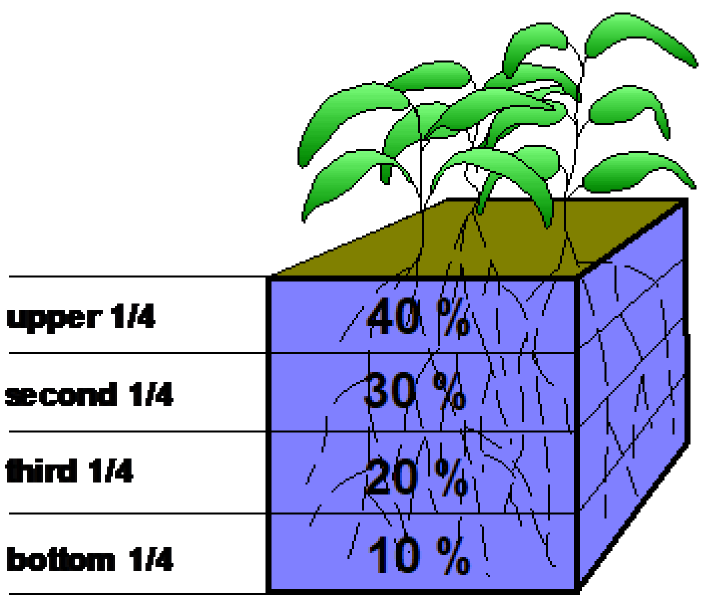


Figure 3.10k – Default extraction pattern in the root zone

The total extraction rate and the root distribution in the root zone are crop parameters which can be adjusted. The default values (which are assigned when the crop is created) are:

- for root distribution: 40, 30, 20, 10% (where the values refer to the upper, second, third and bottom quarter of the root zone as in Fig. 3.10j), and
- for total extraction rate Σ 1000$S_x$dz: A default 3 mm/day for each 0.10 m of rooting depth is considered. By making Σ $S_x$dz very small, extremely low root volume resulting in severely water stress even in a well-watered soil for normal climatic conditions can be simulated.

The maximum sink term (Sx) specifies the maximum amount of water that can be extracted by the crop roots in the time step of 1 day. It is expressed in m^3(water) per m^3(soil) per day. In AquaCrop distinction is made between the (Fig. 3.10k):

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

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

The two crop parameters determine:

- the maximum root extraction (mm/day), which is the maximum amount of water that all the roots together would be able to extract, when maximum rooting depth (Zx) is reached:

$$Ext_{Zx} = 1000\ \overline{Sx}\ Zx \qquad \text{(Eq. 3.10p)}$$

with

$$\overline{Sx} = \frac{Sx_{(top\ 1/4)} + Sx_{(bottom\ 1/4)}}{2} \qquad \text{(Eq. 3.10q)}$$

- the water extraction pattern throughout the effective root zone, which is expressed by the percentages for the upper (P_1), second (P_2), third (P_3) and bottom (P_4) quarter of the root zone:

$$P_1 = 100 \frac{Sx_{(top\,1/4)}}{4\ \overline{Sx}} \qquad \text{(Eq. 3.10r)}$$

$$P_2 = 100 \frac{Sx_{(bottom\ 1/4)} + \frac{2}{3}\left(Sx_{(top\,1/4)} - Sx_{(bottom\ 1/4)}\right)}{4\ \overline{Sx}} \qquad \text{(Eq.3.10s)}$$

$$P_3 = 100 \frac{Sx_{(bottom\,1/4)} + \frac{1}{3}\left(Sx_{(top\,1/4)} - Sx_{(bottom\ 1/4)}\right)}{4\ \overline{Sx}} \qquad \text{(Eq. 3.10t)}$$

$$P_4 = 100 \frac{Sx_{(bottom\,1/4)}}{4\ \overline{Sx}} \qquad \text{(Eq.3.10u)}$$

- **Calculation procedure for maximum root extraction and root distribution when root zone expands in growing cycle**

From the specified maximum root extraction in the top (Sx (top ¼)) and in the bottom quarter of the root zone (Sx (bottom ¼)), AquaCrop determines by trigonometry (Fig. 3.10m):

- the maximum root water extraction at the soil surface (SxTop), and
- the maximum root water extraction at the bottom of the maximum root zone (SxBottom)

SxTop and SxBottom are used throughout the simulation, to calculate at each time step, the maximum root extraction (Sx_i) at various depths Z_i in the expanding root zone (i.e. the Sx_i for the different soil compartments:

$$Sx_i = SxBottom + [SxTop - SxBottom]\frac{Zr_t - Z_i}{Zr_t} \qquad \text{(Eq. 3.10v)}$$

where Zr_t is the rooting depth at time t.

As such the specified water extraction pattern P_1, P_2, P_3 and P_4 in respectively the upper, second, third and bottom quarter of the root zone remains valid at any time, as the root zone expands during simulation.

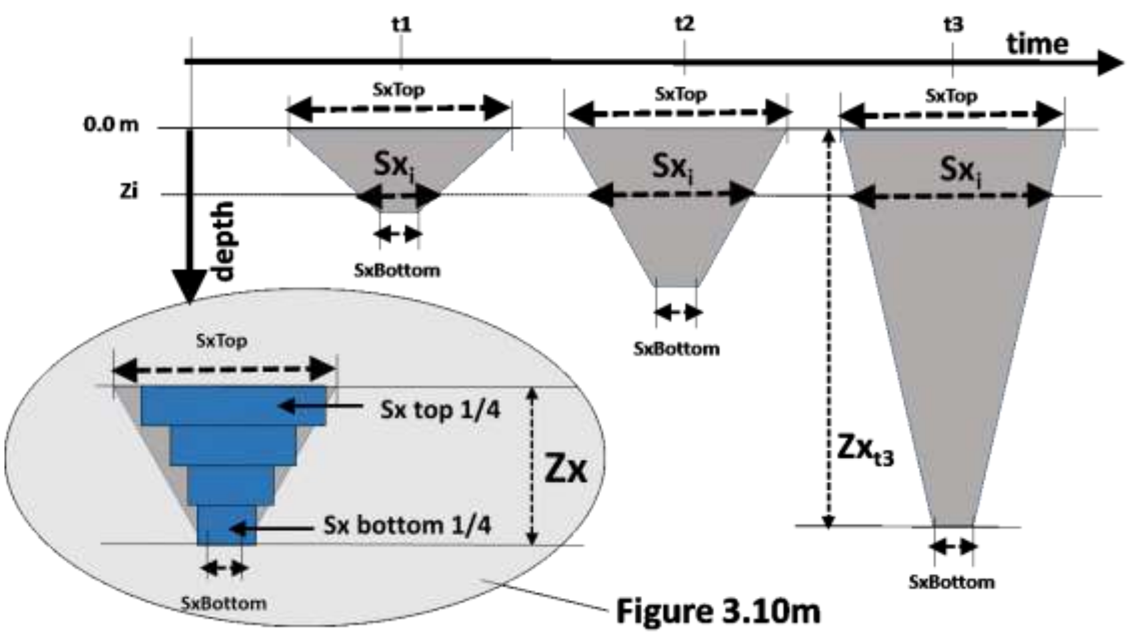


Figure 3.10m. – Specification of SxTop, SxBottom, Sx(Top ¼) and Sx(Bottom ¼)

Figure 3.10n – Root distribution or maximum root extraction (grey area) at various moments (t_1, t_2 and t_3) during the growing cycle

- **Water extraction pattern and root distribution when root zone expansion is restricted**

In AquaCrop, the root zone expansion becomes restricted (or becomes even inhibited) when:

1. water stress results in stomata closure, causing a limited CO_2 uptake, and as such limited root elongation and limited formation of new roots;
2. a restrictive soil layer is present in the root zone (which is a soil characteristic);
3. the expanding root zone reaches a dry sub soil. When the soil water content at the expansion front is below a threshold, root zone expansion slows down and will even stops when the soil water content is at permanent wilting point (the sub soil is too dry to allow root zone expansion).

If the restricted expansion of the root zone is only the result of limitations in the soil profile (conditions 2 and 3 above), new roots still continue to be formed. Since the expansion of the root zone is limited or inhibited, the new formed roots concentrate above the restrictive soil layer. This result in an increase of SxBottom and alters the root distribution (water extraction pattern) in the top soil (Fig. 3.10p).

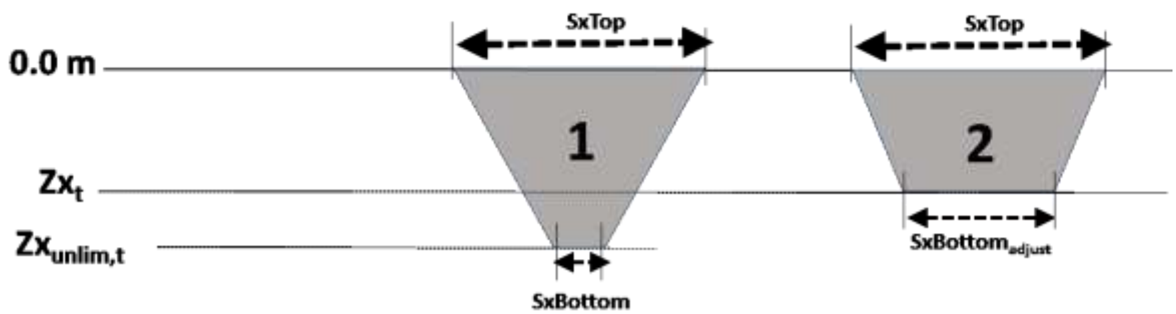


Figure 3.10p – Root distribution (water extraction pattern) at time t in a soil profile (1) without, and (2) with restrictive soil layers (too dry and/or the presence of physical or chemical restrictive soil layers).

To guarantee an identical total root density (total maximum root extraction) when a restrictive soil layer limits the root zone expansion, SxBottom is adjusted, with the correction factor, S_{cor}:

$$S_{cor} = \frac{2\left(\dfrac{Zx_{t,unlim}}{Zx_t}\right)\left(\dfrac{SxTop + SxBottom}{2}\right) - SxTop}{SxBottom} \qquad \text{(Eq. 3.10w)}$$

where Zx_t is the limited rooting depth at time t, and $Zx_{t,unlim}$ the rooting depth which could have been reached at that moment, if root deepening was unlimited.

The adjusted SxBottom is given by:

$$SxBottom_{adjust} = S_{cor}\left(\frac{\sum Tr}{\sum Tr_x}\right) SxBottom \quad \leq 0.060\ m^3.m^{-3}.day^{-1} \qquad \text{(Eq. 3.10x)}$$

where $\sum Tr$ is the sum of the actual crop transpiration, and $\sum Tr_x$ the sum of the potential crop transpiration. The ratio of the actual over the potential crop transpiration ($\sum Tr/\sum Tr_x$) in Eq. 3.10x, is a correction for the effect of the closure of the stomata which also slows down root zone expansion, but do not results in a concentration of roots at the bottom of the expanding root zone (since root formation is limited).

Eq. 3.10v, which specifies the maximum root extraction (Sx_i) at various depths Z_i in the root zone, becomes :

$$Sx_i = (Scor)\, SxBottom + \left[SxTop - (Scor)\, SxBottom\right] \frac{Zr_t - Z_i}{Zr_t} \leq 0.060\ m^3.m^{-3}.day^{-1}$$

(Eq. 3.10y)

where Zr_t is the rooting depth at time t.

The restriction of 0.060 m^3/m^3.day in Eq. 3.10x and 3.10y, refers to the limitations of the maximum root extraction.

3.10.8 Feedback mechanism of transpiration on canopy development

A feedback mechanism is added to the model to guarantee that when crop transpiration drops to zero, the canopy development is halted under all circumstances. As such leaf growth stops when the root zone is water logged (at least for crops sensitive to water logging), when it is too cold for the crop to transpire, and in the absence of any atmospheric water demand (ET_o is zero).

3.11 Dry above-ground biomass

The daily (m) and the cumulative (B) dry above-ground biomass production is obtained from the normalized biomass water productivity (WP*), and the ratio of the daily crop transpiration (Tr) over the reference evapotranspiration for that day (ETo):

$$m = WP^{*}\left(\frac{Tr}{ET_o}\right) \qquad \text{(Eq. 3.11a)}$$

$$B = WP^{*}\sum\left(\frac{Tr}{ET_o}\right) \qquad \text{(Eq. 3.11b)}$$

▪ **Crops that do not transfer assimilates to their below-ground parts (annual crops)**

The calculation scheme is presented in Fig. 3.11a/1

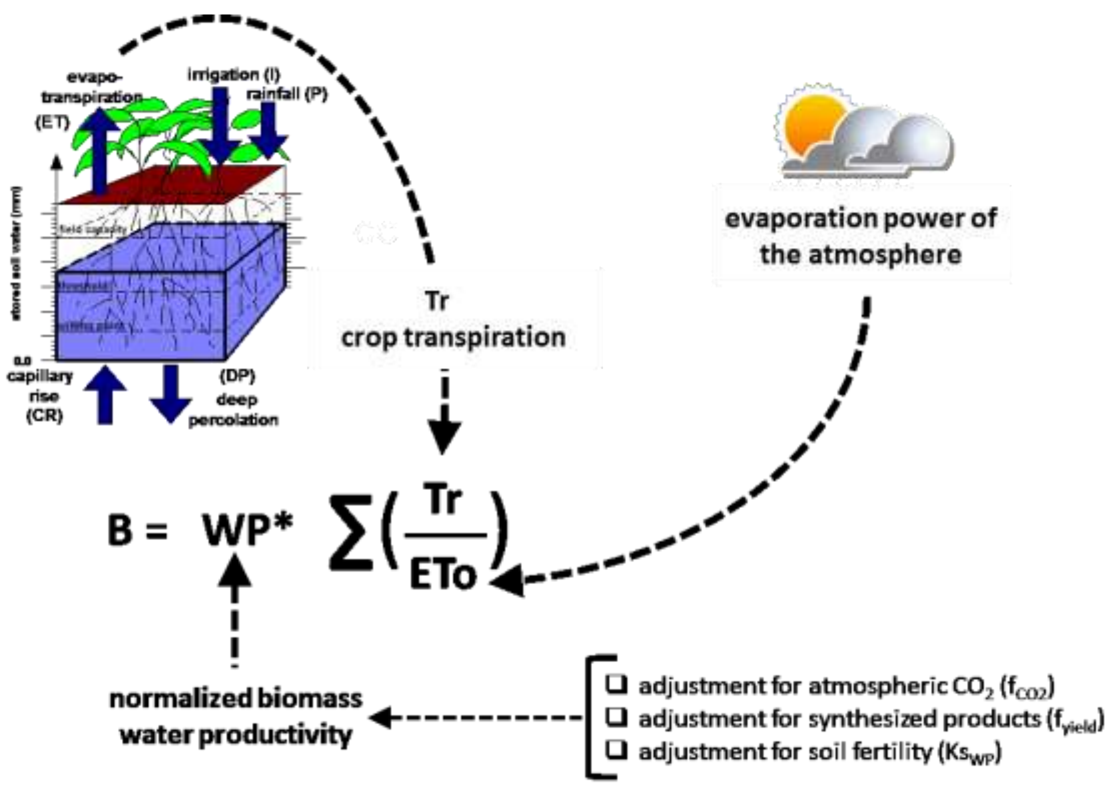


Figure 3.11a/1 – Calculation scheme in AquaCrop for dry above-ground biomass (B) for annual crops (no transfer of assimilates)

- **Crops transferring assimilates between above and below ground parts**

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

Since AquaCrop does not simulate biomass partitioning among various organs, variations in partitioning along the season are simulated by increasing or reducing WP*. The calculation scheme for the above-ground biomass is presented in Fig. 3.11a/2, with indication of the crop parameters which can be used to calibrate the transfer of assimilates:

- $L_{storage}$: the duration of the storage period;
- S: the maximum fraction of produced assimilates that are stored in the below-ground parts during the storage stage;
- M: the fraction of stored assimilates of the previous season, that are remobilized at the start of the season.

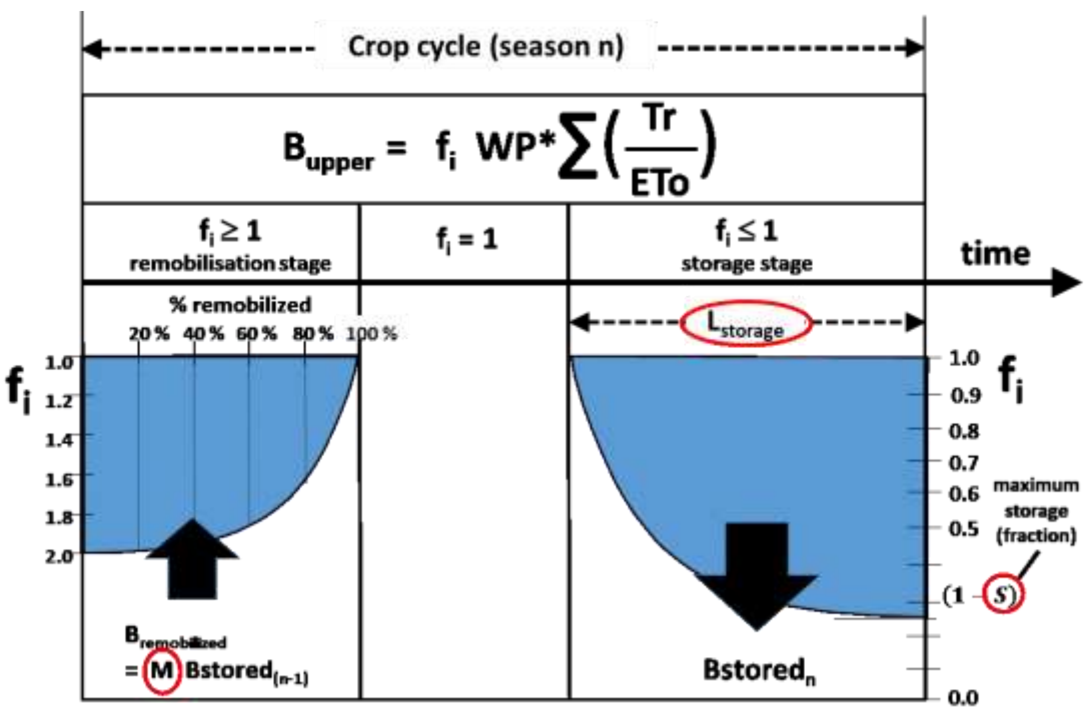


Figure 3.11a/2 – Calculation scheme in AquaCrop for dry above-ground biomass (B_{upper}) for perennial herbaceous forage crops with transfer of assimilates between the above-ground and the below-ground parts of the plant.

3.11.1 Normalized biomass water productivity (WP^*)

By considering the biomass water productivity (WP), the aboveground biomass can be derived from the simulated transpiration. The biomass water productivity expresses the above-ground dry matter (g or kg) produced per unit land area (m^2 or ha) per unit of water transpired (mm). Many experiments have shown that the relationship between biomass produced and water consumed by a given species is highly linear (Steduto et al., 2007). AquaCrop uses the normalized biomass water productivity (WP^*) for the simulation of the dry above-ground biomass (Eq. 3.11a and b). The WP is normalized for the atmospheric CO_2 concentration and for the climate. The units of biomass water productivity after the adjustment for climate are mass of above-ground dry matter (g or kg) per unit land area (m^2 or ha).

- **Normalization for atmospheric CO_2**

The normalization for CO_2 consists in considering the biomass water productivity for an atmospheric CO_2 concentration of 369.41 ppm (parts per million by volume). The reference value of 369.41 is the average atmospheric CO_2 concentration for the year 2000 measured at Mauna Loa Observatory in Hawaii (USA). The observatory was selected as the reference location because the air at the site is very pure due to its remote location in the Pacific Ocean, high altitude (3397 m.a.s.l), and great distance from major pollution sources.

- **Normalization for the climate**

The WP is normalized for climate by dividing the amount of water transpired (Tr) with the reference evapotranspiration (ET_o). Asseng and Hsiao (2000) argued that ET_o would be better than vapor pressure deficit (VPD) for normalization because the FAO Penman-Monteith equation takes into account the difference in temperature between the air and evaporation surface. Further Steduto and Albrizio (2005) demonstrated with experimental data that more consistent results were obtained when normalizing with ET_o as compared with VPD. The reference evapotranspiration ET_o is obtained from meteorological data with the help of the FAO Penman-Monteith equation (Allen et al., 1998).

- **Classes for C3 and C4 groups**

After normalization for atmospheric CO_2 concentrations and climate, recent findings indicate that crops can be grouped in classes having a similar WP^* (Fig. 3.11b). Distinction can be made between C4 crops with a WP^* of 30 - 35 g/m^2 (or 0.30 – 0.35 ton per ha) and C3 crops with a WP^* of 15 - 20 g/m^2 (or 0.15 – 0.20 ton per ha).

Some leguminous crops may have WP* values below 15 g/m^2 due to their biological nitrogen fixation process.

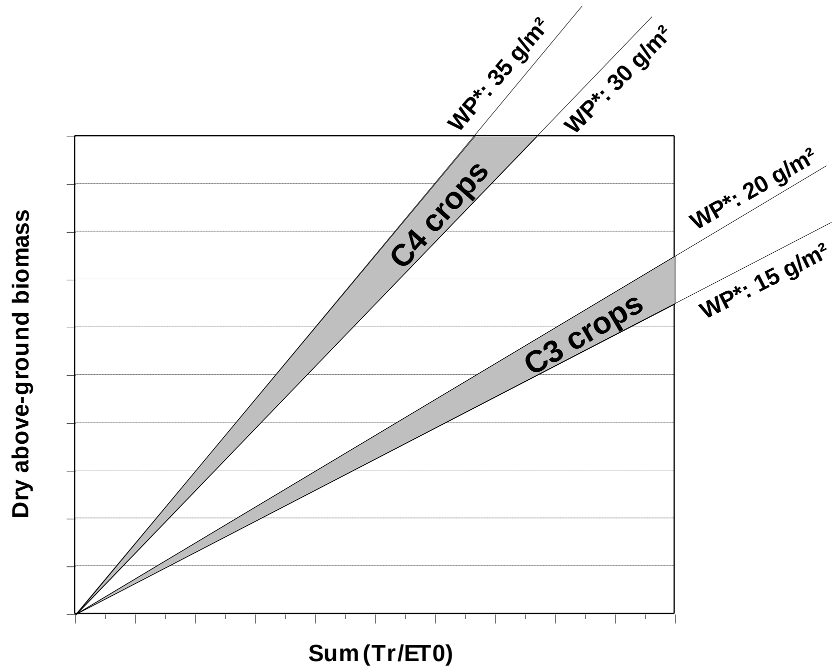


Figure 3.11b – The relationship between the dry above-ground biomass and the total amount of water transpired for C3 and C4 crops after normalization for CO_2 and climate (ET_o)

3.11.2 WP*adjusted for CO_2, products synthesized, and soil fertility

- **Adjustment of WP* for atmospheric CO_2 (f_{CO2})**

AquaCrop will adjust WP* when running a simulation for a year at which the atmospheric CO_2 concentration differs from its reference value (369.41 ppm). The adjustment is obtained by multiplying WP* with a correction coefficient:

$$WP^*_{adj} = \left[1 + f_{type}\left(f_{CO2} - 1\right)\right] WP^* \qquad \text{(Eq. 3.11c)}$$

where WP^*_{adj} WP adjusted for CO_2
f_{type} correction coefficient for crop type
f_{CO2} correction coefficient for CO_2

The coefficient between square brackets, considers the difference between the reference value and the atmospheric composition for that year (f_{CO2}) and the crop type (f_{type}).

In Figure 3.11c/1, the adjustment of WP* for various atmospheric CO_2 concentrations (Eq. 3.11c) is plotted for various crop types (f_{type}). In Table 3.11c/1 the adjustment of WP* for various atmospheric CO_2 concentrations (Eq. 3.11c) for C3 crops (f_{type} = 1) and for two different approaches of the correction coefficient for CO_2 (f_{CO2}) are listed.

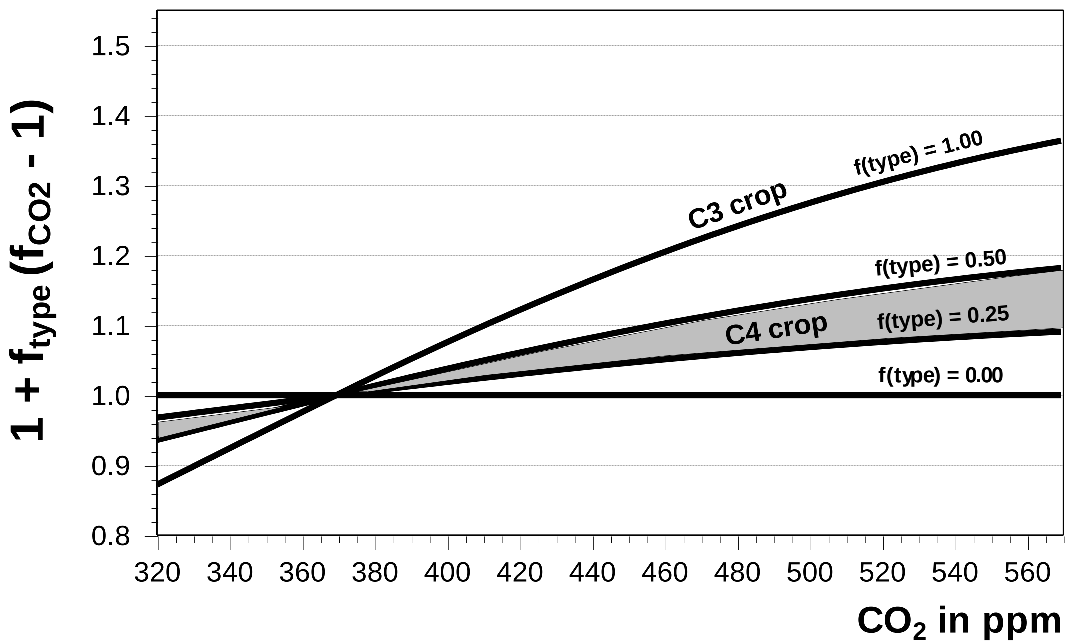


Figure 3.11c/1 – Correction for WP* as given by Eq. 3.11c (with the default f_{sink} of 0.5 for f_{CO2}) considering various atmospheric CO_2 concentration and various coefficients for crop type: f_{type} = 1.00 (WP* ≤ 20 g/m²); 0.50 (WP* = 30 g/m²); 0.25 (WP* = 35 g/m²); and 0.00 (WP* ≥ 40 g/m²).

Table 3.11c/1 – Adjustment (multiplier) for WP* (Eq. 3.11c), for various atmospheric CO_2 concentration ([CO_2]) for C3 crops (f_{type} = 1) and for two different approaches of the correction coefficient for CO_2 (f_{CO2})

Year	[CO_2]	[1 + f_{type} (f_{CO2} – 1)]	
		approach based on FACE (f_{sink} = 0)	theoretical approach (f_{sink} = 1)
-	ppm	-	-
1905	298.2	0.815	
1924	304.5	0.832	
1953	311.9	0.851	
1975	331.11	0.901	
2000	369.41	1.000 (reference)	
2015	400	1.073	1.078
2031* – 2040*	450	1.162	1.205
2052* – 2057*	500	1.214	1.330
…	550	1.230	1.453

* corresponding years depending on the assumed scenario of [CO2] elevation

Correction coefficient for crop type (f_{type})

Not many FACE experiments are conducted for C_4 crops since it is believed that this crop type hardly respond to elevated atmospheric CO_2 concentrations. The correction for crop type (f_{type}) assumes that the different response of C_3 and C_4 crops can be considered as valid.

$$0 \le f_{type} = \frac{(40 - WP^*)}{(40 - 20)} \le 1 \qquad \text{(Eq. 3.11d)}$$

The Eq. 3.11d considers the distinction between C_4 crops with a typical WP* of 30 up to 35 g/m^2 and C_3 crops with a typical WP* of 15 up to 20 g/m^2 (Fig. 3.11b)

Correction coefficient for CO_2 concentration up to 550 ppm (f_{CO2})

$$f_{CO2} = \frac{(C_{a,i} / C_{a,o})}{1 + (C_{a,i} - C_{a,o})\left[(1-w) b_{Sted} + w \left(f_{sink}\, b_{Sted} + (1 - f_{sink}) b_{FACE}\right)\right]} \qquad \text{(Eq. 3.11e/1)}$$

where
- f_{CO2} — correction coefficient for CO_2
- $C_{a,o}$ — reference atmospheric CO_2 concentration (369.41 ppm)
- $C_{a,i}$ — atmospheric CO_2 concentration for year i (ppm)
- b_{Sted} — 0.000138 (Steduto et al., 2007);
- b_{FACE} — 0.001165 (derived from FACE experiments);

	w	weighing factor;
	f_{sink}	crop sink strength coefficient.

To consider the discrepancy between the observed (FACE experiments) and theoretical adjustment (Steduto et al., 2007) of WP*, two coefficients (b_{Sted} and b_{FACE}) are considered. The weighing factor (w) makes that in Eq. 3.11e/1 b_{FACE} gradually replaces b_{Sted} starting from the reference atmospheric CO_2 concentration (Ca,o = 369.41 ppm) and becomes fully applicable for $C_{a,i}$ equal to 550 ppm:

$$0 \leq \quad w = \left(1 - \frac{\left(550 - C_{a,i}\right)}{\left(550 - C_{o,i}\right)}\right) \quad \leq 1 \qquad \text{(Eq. 3.11f)}$$

where	$C_{a,o}$	reference atmospheric CO_2 concentration (369.41 ppm);
	$C_{a,i}$	actual atmospheric CO_2 concentration (ppm) but ≤ 550 ppm

For $C_{a,i}$ smaller than or equal to $C_{a,o}$, the weighing factor is zero (w = 0), while for $C_{a,i}$ = 550 ppm, w becomes 1. The threshold of 550 ppm is selected as the representing value for the elevated [CO_2] maintained in the FACE experiments.

The crop sink strength coefficient in Eq. 3.11e/1 considers that the theoretical adjustment (with b_{Sted}) might not be entirely valid when (i) soil fertility is not properly adjusted to the higher productivity under elevated CO_2 concentration, and/or (ii) the sink capacity of the current crop variety is unable to take care of the elevated CO_2 concentration.

Table 3.11c/2 – Range of indicative values for f_{sink} for 10 crops available in the database of AquaCrop (Vanuytrecht et al., 2011)

Crop	**Class and indicative value range for f_{sink}**
Cereals	
- Maize	Low (0.0 – 0.2)
- Rice	Low (0.0 – 0.2)
- Wheat	Low (0.0 – 0.2)
- Sunflower	Low (0.0 – 0.2)
Legumes	
- Soybean	Moderate low (0.2 – 0.4)
Indeterminate crops	
- Tomato	Moderate low (0.2 – 0.4)
- Quinoa	Moderate low (0.2 – 0.4)
Woody species	
- Cotton	Moderate high (0.4 – 0.6)
Root and tuber crops	
- Potato	High (0.4 – 0.6)
- Sugar beet	High (0.4 – 0.6)

The crop sink strength coefficient (f_{sink}) can be altered according to the sink strength of the crop considered, which is determined by crop characteristics and field management. The value can be as high as one (the theoretical approach) or as low as zero (based on an analysis of crop responses in FACE environments by Vanuytrecht et al., 2011). Indicative values for f_{sink} for crops available in the AquaCrop library are presented in Table 3.11c/2.

The values of f_{sink} reported in Table 3.11c/2 should be considered as a good starting value but not as definitive. If projections of future agricultural productivity are to be made in areas where nutrient deficiency is excepted f_{sink} should be reduced. If projections are to be made for species with improved cultivars with a higher responsiveness to [CO_2] are likely to be bred (e.g. high value crops like vegetables) the values for f_{sink} can be higher than the indicative value in Table 3.11c/2.

Correction coefficient for CO_2 concentration above 550 ppm (f_{CO2})

Literature (e.g. Akita and Moss, 1973; Chapin et al., 2011; Kirschbaum, 2011; Kromdijk and Long, 2016; Yin and Struik, 2009) indicates that the response for C3 crops does not increase much beyond 700 – 900 ppm (Fig. 3.11c/2). Since the correction coefficient for CO_2 (f_{CO2}) given by Eq. 3.11e/1, does not consider such a decrease of WP* at high CO_2 concentrations (550 ppm and above), the biomass production is likely to be strongly overestimated at high CO_2 concentrations and an unrealistic effect of CO_2 fertilization on crops might be simulated with previous versions of Aquacrop. This is true for any of the selected adjustment approach (theoretical or based on FACE experiments).

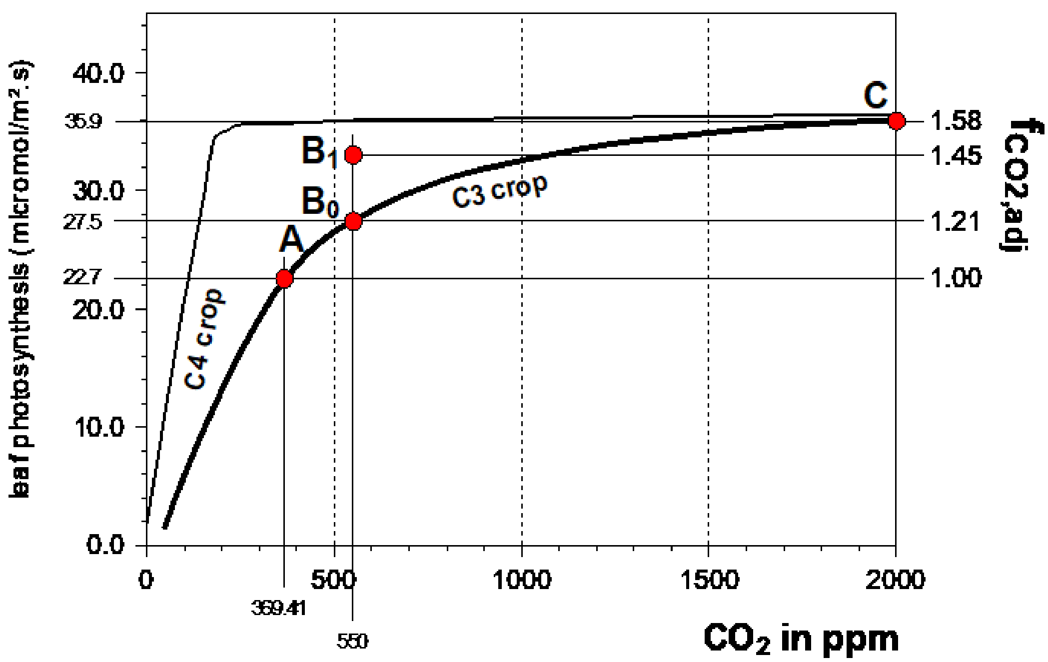


Figure 3.11c/2 – Gross leaf photosynthesis (left ordinate) for various ambient CO_2 concentrations for C3 and C4 crops (after Yin and Struik, 2009), and the derived corresponding adjusted correction coefficient for CO_2 ($f_{CO2,adj}$) at the right ordinate.

The decreasing trend in crop response to elevated CO_2 is well documented in literature (e.g. Akita and Moss, 1973; Chapin et al., 2011; Kirschbaum, 2011; Kromdijk and Long, 2016; Yin and Struik, 2009). However, the exact crop response differs between publications and might be the result of the studied crop type, and differences in the experimental set up and environmental conditions.

To avoid an unrealistic simulation of biomass production at CO_2 concentrations above 550 ppm, the correction coefficient for WP* is further adjusted. **It is stressed that it remains a purely theoretical adjustment, without any validation from field experiments.** Since it is well documented and describes the general trend, the crop response based on the research by Yin and Struik (2009), was selected to simulate the decline in rise of WP* at CO_2 concentrations above 550 ppm. With the help of the f_{sink}, the user can still vary the shape (Fig. 3.11c/3) and somewhat the corresponding response.

The adjustment for the correction coefficient for CO_2 is based on values for the gross leaf photosynthesis (Fig. 3.11c/2) given by Yin and Struik (2009). For the C3 crop, the leaf photosynthesis is:

- 22.7 µmol/m^2.s at 369.41 ppm (point A), which is the reference CO_2 concentration at the year 2000. There is no need to correct WP* (Tab. 3.11c/1) and the corresponding correction coefficient for CO_2 ($f_{CO2,adj}$) is consequently 1 (right ordinate Fig. 3.11c/2);
- 27.5 µmol/m^2.s at 550 ppm (point B_0), which is the CO_2 concentration maintained in most FACE experiments. Since the leaf photosynthesis is 21 % larger than at the reference point, $f_{CO2,adj}$ should also be 1.21 at this $C_{a,i}$. The resulting $f_{CO2,adj}$ of 1.21 corresponds well with the observed value of 1.23 derived by Vanuytrecht et al. (2011) from the FACE experiments (Eq. 3.11e/1 with f_{sink} = 0; Tab. 3.11c/1);
- 35.9 µmol/m^2.s (point C) at 2,000 ppm, which is 58 % larger than the leaf photosynthesis at the reference point. Hence at point C the $f_{CO2,adj}$ should be 1.58 (right ordinate Fig. 3.11c/2).

In Fig. 3.11c/2, the curve AB_0C (given by Yin and Struik, 2009) can also be used to specify the adjustment of WP* for CO_2 ($f_{CO2,adj}$) for the approach based on FACE experiments (when f_{sink} = 0) for high CO_2 concentrations. The corresponding value $f_{CO2,adj}$ is given at the right ordinate.

For the theoretical adjustment (Eq. 3.11e/1 with f_{sink} = 1), Eq. 3.11e/1 yields a f_{CO2} of 1.453 at 550 ppm (Tab. 3.11c/1). This corresponds with point B_1 in Fig. 3.11c/2. Hence the curve AB_1C specifies $f_{CO2,adj}$ for the theoretical adjustment (when f_{sink} = 1) for high CO_2 concentrations.

The equation for any of the curves ABC for any f_{sink} between 0 and 1 (Fig. 3.11c/3) is given by:

$$f_{CO2,adj} = 1 + 0.58\ \frac{(e^{CO2rel\ .\ fshape} - 1)}{(e^{fshape} - 1)} \qquad \text{(Eq. 3.11e/2)}$$

with $$f_{shape} = -4.61824 - 3.43831\ (f_{sink}) - 5.32587\ (f_{sink})^2 \qquad \text{(Eq . 3.11e/3)}$$

where	$f_{CO2,adj}$	adjusted correction coefficient for CO_2 concentration
	$CO2_{rel}$	$(C_{a,i} - C_{a,o}) / (2{,}000 - C_{a,o})$

$C_{a,o}$	reference atmospheric CO_2 concentration (369.41 ppm)
$C_{a,i}$	atmospheric CO_2 concentration for year i (ppm) with $369.41 \le C_{a,i} \le 2000$ ppm
f_{shape}	a shape factor which varies with f_{sink}
f_{sink}	crop sink strength coefficient

Combined correction coefficient for any CO_2 concentration (f_{CO2})

In AquaCrop, the correction for atmospheric CO_2 switches from Eq. 3.11e/1 (f_{CO2}) which is valid at low CO_2 concentrations, to Eq. 3.11e/2 ($f_{CO2,adj}$) which is valid at high CO_2 concentrations (Fig. 3.11c/3). The following rules apply:

- for $C_{a,i}$ smaller than or equal to 369.41 ppm (the reference value at year 2000), the correction for CO2 (f_{CO2}) is given by Eq. 3.11e/1;
- for $C_{a,i}$ between 369.41 and 550 ppm, the correction for CO2 ($f_{CO2,adj}$) given by Eq. 3.11e/2 is used. However the correction given by Eq. 3.11e/2 ($f_{CO2,adj}$) cannot exceeds the correction given by Eq. 3.11e/1 (f_{CO2}). Hence the restriction $f_{CO2,\,adj} \le f_{CO2}$ applies in this CO_2 range;
- for $C_{a,i}$ larger than or equal to 550 ppm (the value in most FACE experiments) but smaller than 2,000, the correction for CO2 ($f_{CO2,adj}$) is given by Eq. 3.11e/2;
- for $C_{a,i}$ larger than or equal to 2,000 ppm, the correction is at its maximum and f_{CO2} = 1.58.

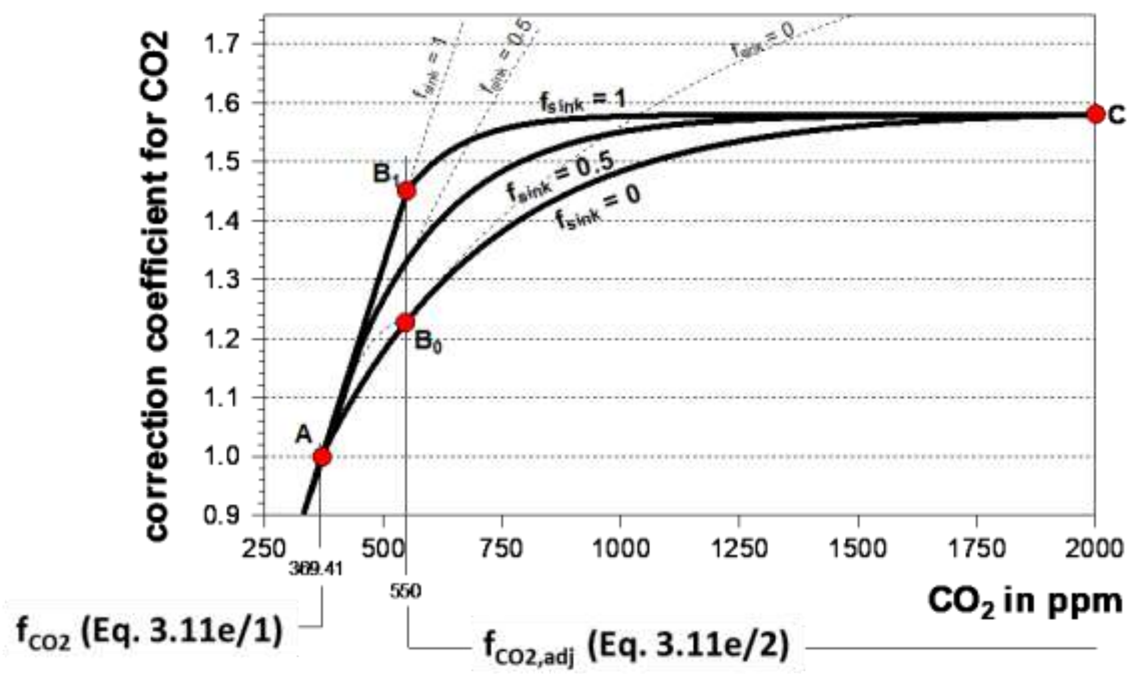


Figure 3.11c/3 – Correction coefficient for CO_2 for various atmospheric CO_2 concentrations and f_{sink} in AquaCrop, for a C3 crop type (f_{type} = 1 with WP* ≤ 20 g/m^2). The dotted lines are the f_{CO2} as given by Eq. 3.11e/1 for respectively f_{sink} = 0, 0.5 and 1. The points A, B_0, B_1, and C are identical as in Figure 3.11c/2

References

Akita S, Moss DN (1973) The Effect of an Oxygen-free Atmosphere on Net Photosynthesis and Transpiration of Barley (Hordeum vulgare L.) and Wheat (Triticum aestivum L.) Leaves. Plant Physiol 52:601–603.

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Vanuytrecht, E., D. Raes and P. Willems. 2011. Considering sink strength to model crop production under elevated atmospheric CO2. Agricultural and Forest Meteorology 151: 1753-1762.

Yin X, Struik PC (2009) C3 and C4 photosynthesis models: An overview from the perspective of crop modelling. NJAS - Wageningen Journal of Life Sciences 57:27–38.

Atmospheric CO_2 concentration for various years

Next to air temperature, ET_o and rainfall data, the CO_2 concentration is climatic input. By default AquaCrop obtains the atmospheric CO_2 concentration for a particular year from the 'MaunaLoa.CO2' file in its database which contains observed and expected concentrations at Mauna Loa Observatory. For years before 1958 (the start of observations at the Observatory) CO_2 data obtained from firn and ice samples are used. These samples were collected close to the coast of Antarctica (Etheridge et al., 1996). For future years an expected increase of 2 ppm is considered (Fig. 3.11c/4).

Years before 2000, have an atmospheric CO_2 concentration which is lower than the reference value of 369.41 ppm and hence a smaller WP ($f_{CO2} < 1$). Years after 2000 have a higher atmospheric CO_2 concentration, and hence a higher WP ($f_{CO2} > 1$).

For crop yield estimates for future years, CO2 files from four different RCP's ('RCP2-6.CO2', RCP4-5.CO2', 'RCP6-0.CO2' and 'RCP8-5.CO2') are available in the DATA subdirectory of AquaCrop. The RCPs (Representative Concentration Pathways) represent a broad range of climate outcomes. Each RCP results from different combinations of economic, technological, demographic, policy, and institutional futures. In 2021, IPCC released a new set of climate scenarios with respect to the sixth IPCC report. CO2 files for the five "Shared Socioeconomic Pathways" (SSPs) are added to the DATA subdirectory ('SSP1-1.9.CO2', 'SSP1-2.6.CO2', 'SSP2-4.5.CO2', 'SSP3-7.0.CO2' and 'SSP5-8.5.CO2'). They represent different socio-economic developments as well as different pathways of atmospheric greenhouse gas concentrations. Compared to the previous used RCPs, the new SSPs scenarios have been improved in a variety of ways (IPCC, 2021). In Figure 3.11d, the CO_2 concentrations of the new set of SSPs are plotted next to the RCPs.

For scenario analysis the user can use other 'CO2' files or own estimates as long as the structure of the CO2 files is respected (see Chapter2, section 2.23.3 'CO2 file').

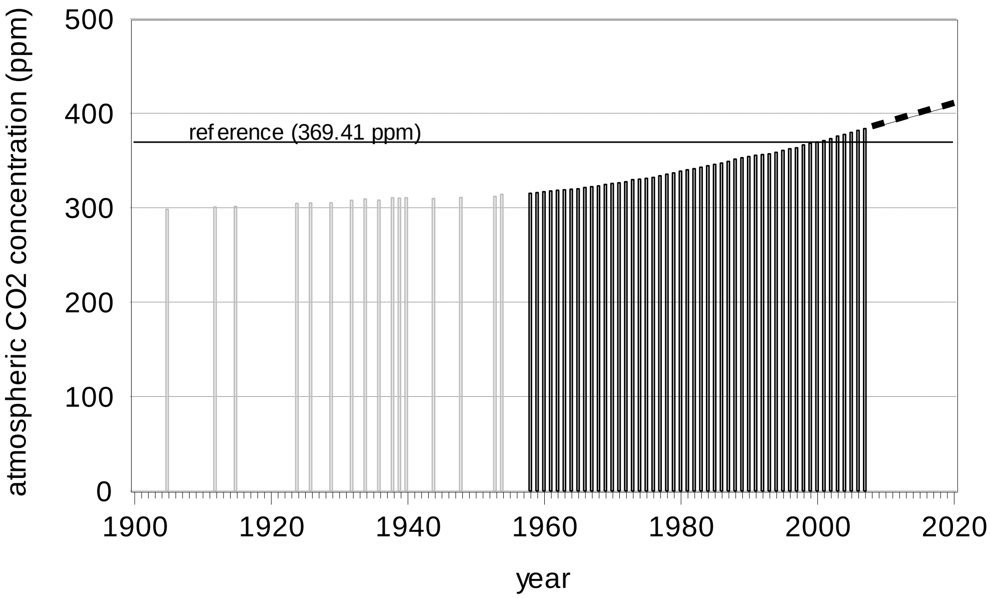


Figure 3.11c/4 – Atmospheric CO_2 concentrations derived from frin and ice samples (light bars), observed at Mauna Loa Observation (dark bars), and predicted (dotted line) by assuming a continuous rise of 2 ppm/year, with indication of the reference value

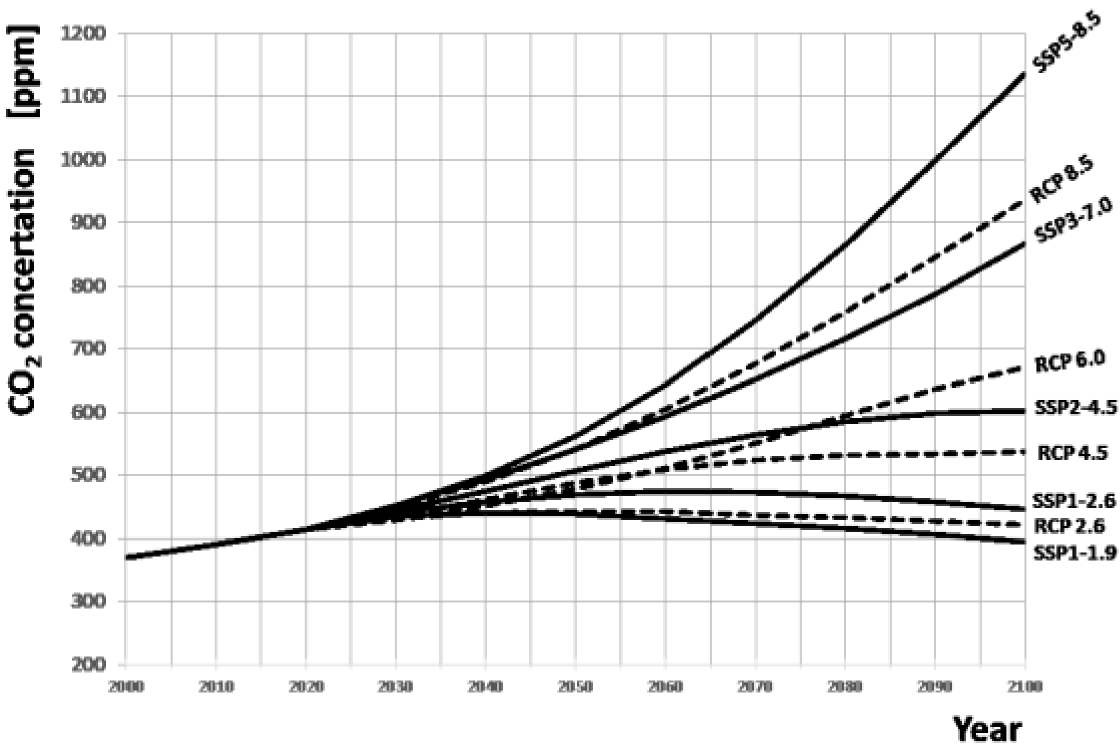


Figure 3.11d – Projected CO_2 concentrations for 5 SSPs (solid line) and 4 RCPs (dotted lines), available in the database of AquaCrop.

- **Adjustment of WP* for types of products synthesized (f_{yield})**

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 (Azam-Ali and Squire, 2002). As a consequence, the biomass water productivity during yield formation needs to be adjusted for the type of products synthesized during yield formation:

$$WP^*_{adj} = f_{yield}\, WP^* \qquad \text{(Eq. 3.11g)}$$

where WP^*_{adj} WP adjusted for type of products synthesized
f_{yield} reduction coefficient for the products synthesized ($f_{yield} <= 1$).

In the vegetative stage, the dry above-ground biomass is derived from the simulated amount of water transpired by means of WP*. During yield formation, the biomass water productivity switches gradually from WP* to WP^*_{adj} (Fig. 3.11e). For determinant crops the transition takes place during the lag phase where the increase of the Harvest Index is slow (see 3.12.3 Building up of Harvest Index). For indeterminant crops it is assumed that the biomass water productivity is fully adjusted after 1/3 of the length of the yield formation stage.

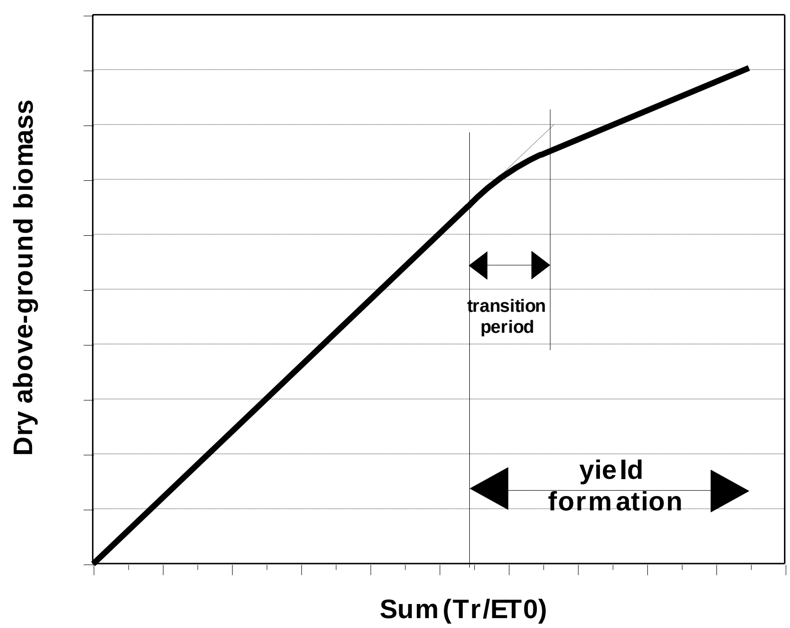


Figure 3.11e – The relationship between the dry above-ground biomass and the total amount of water transpired before and during yield formation for crops rich in lipids or proteins

- **Adjustment of WP^* for soil fertility (Ks_{WP})**

If limited soil fertility affects the biomass water productivity, the adjusted productivity is given by:

$$WP^*_{adj} = Ks_{WP}\ WP^* \qquad \text{(Eq. 3.11h)}$$

where
WP^*_{adj} WP adjusted for soil fertility
Ks_{WP} soil fertility stress coefficient for biomass water productivity ($Ks_{WP} <= 1$)

Ks_{WP} is 1 for non-limiting soil fertility. The stress coefficient decreases for increasing soil fertility stress (see 3.2. Stresses). Biomass production is no longer possible when the stress coefficient reaches the theoretical minimum of 0.

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. As long as the canopy is small, the daily biomass production will be rather similar to the daily production for non-limited soil fertility, and $Ks_{WP,i}$ at day i will be close to 1 (no fertility stress). 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. This is simulated in AquaCrop by making the stress coefficient $Ks_{WP,i}$ a function of the relative amount of biomass produced (B_{rel}). For every day in the season B_{rel} is given by the ratio between the amount of biomass produced on that day and the maximum amount of biomass that can be obtained at the end of the season for the given soil fertility level. The maximum amount refers to a production without any water stress during the season.

Since B_{rel}, after correction for temperature stress, is proportional to the relative amount of water that has been transpired, $Ks_{WP,i}$ for any day in the season is given by:

$$Ks_{WP,i} = 1 - f_{WP} \left(\frac{\sum_{j=1}^{i} \left(Tr_j / ETo_j \right)}{\sum_{j=1}^{n} \left(Tr_{x,j} / ETo_j \right)} \right)^2 \qquad \text{(Eq. 3.11i)}$$

where
$Ks_{WP,i}$ soil fertility stress coefficient for biomass water productivity at day
f_{WP} maximum reduction for WP (expressed as a fraction) for the given soil fertility level, that can be observed at the end of the season when the crop does not experience water stress ($f_{WP} = 1 – Ks_{WP}$)
$\sum(Tr_j/ETo_j)$ sum of water transpired at day i (normalized for climate)
$\sum(Tr_{x,j}/ETo_j)$ sum of water that will have been transpired at the end of the season (normalized for climate) for the given soil fertility level when the crop does not experience water stress
n number of days in the season

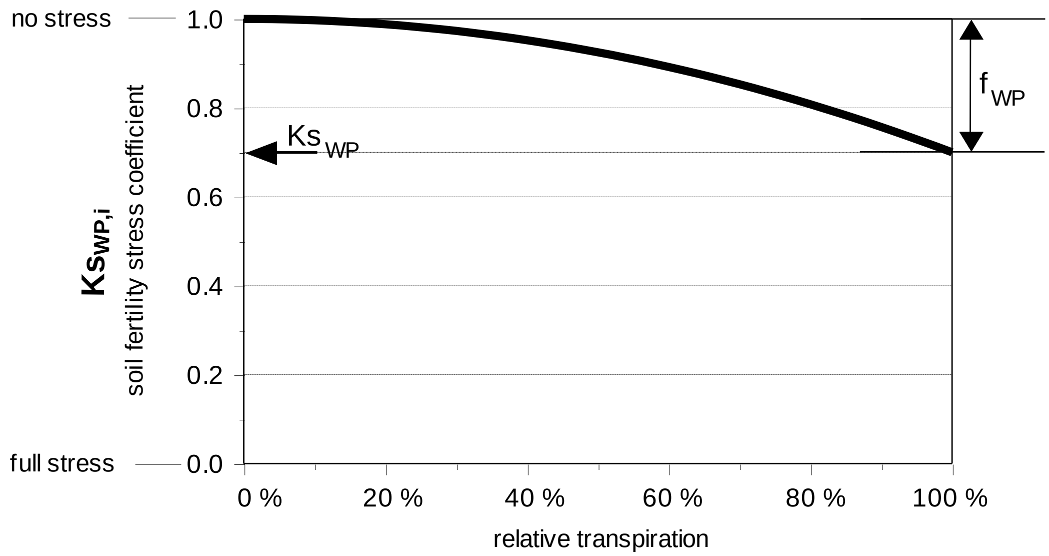


Figure 3.11f – Soil fertility stress coefficient for various degrees of relative transpiration (for a f_{WP} of 0.3 or a Ks_{WP} of 0.7)

The variation of the soil fertility stress coefficient throughout the season is plotted in Fig. 3.11f. At the start of the season $Ks_{WP,i}$ is 1 and WP^* is not adjusted. As more and more water is transpired during the season, $Ks_{WP,i}$ will gradually decline. When the crop does not experience any water stress throughout its cycle, the relative transpiration becomes 1 at the end of the season and $Ks_{WP,i=n} = Ks_{WP}$. However, if water stress hampers the canopy development and/or result in stomatal closure, the relative transpiration will remain smaller than 1 throughout the season, resulting in a smaller adjustment of WP ($Ks_{WP,i=n} > Ks_{WP,x}$).

- **WP*adjusted for CO2, products synthesized, and fertility or salinity stress**

The total adjustment of the normalized biomass water productivity for atmospheric CO_2, type of products synthesized and soil fertility/salinity stress is given by:

$$WP^*_{adj} = \left[1 + f_{type}\left(f_{CO2} - 1\right)\right] f_{yield}\ Ks_{WP,i}\ WP^* \qquad \text{(Eq. 3.11j)}$$

How strongly WP^*_{adj} differs from WP^*, depends on the deviation of the atmospheric CO_2 concentration from its 369.47 ppm reference value, the crop type, its sink strength, the growth stage (vegetative or yield formation), the type of products synthesized during yield formation, the amount of biomass produced, the soil fertility and /or soil salinity stress. For soil fertility/salinity stress, WP^*_{adj} will decline during the season as more biomass is produced and $Ks_{WP,i}$ gradually decreases.

3.11.3 Dry above-ground biomass of the crop (B_W) in weed infested fields

- **Unlimited soil fertility**

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

$$B_W = WP^* \sum \frac{Tr_W}{ET_o} \qquad \text{(Eq. 3.11k)}$$

where WP^* is the normalized biomass water productivity, and Tr_W the crop transpiration in the weed infested field.

- **Limited soil fertility**

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

$$B_W = Ks_{WP}\ WP^* \sum \frac{Tr_W}{ET_o} \qquad \text{(Eq. 3.11m)}$$

Since it is assumed that soil fertility affects both weed and crop identically, soil fertility will also be identically in a weed-stressed and in a weed-free field. But next to fertility stress, which reduces crop development, there is also weed stress, which reduces crop density.

3.11.4 Transfer of assimilates for perennial herbaceous forage crops

Reference: Raes, D., Fereres, E., García Vila, M., Curnel, Y., Knoden, D., Kale Çelik, S., Ucar, Y., Türk, M., Wellens, J. 2023. Simulation of alfalfa yield with AquaCrop. Agricultural Water Management (284), 108341.
https://doi.org/10.1016/j.agwat.2023.108341.

Perennial herbaceous forage crops transfer a considerable fraction of the assimilates to their below-ground parts after mid-season. At the start of the next season, a fraction of the stored assimilates are remobilized by transferring them from the below-ground to the above ground parts of the crop (Fig. 3.11a/2). The rest is assumed to be lost during the off-season by respiration and natural self-thinning, or remain stored in underground organs.

The transfer of assimilates is described by 3 crop parameters (Tab. 3.11n), which can be used to calibrate the process of the transfer of the assimilates.

Table 3.11n – Crop parameters describing the transfer of assimilates (Fig. 3.11a/2)

Symbol	Description	Type
$L_{storage}$	Number of days at end of season during which assimilates are stored in root system – only for perennial forage crops	Management Cultivar

S	Fraction of assimilates, transferred to the below-ground parts at last day of season – only for perennial forage crops	Management Cultivar
M	Fraction of stored assimilates, transferred to above ground parts in next season – only for perennial forage crops	Management Cultivar

- **Calibration of the process of the transfer of assimilates**

In the Transfer assimilates tab-sheet of the Production tab-sheet in the ***Crop characteristics*** menu, the seasonal transfer of the assimilates between the above and below ground parts of the crop is specified (Fig. 3.11m).

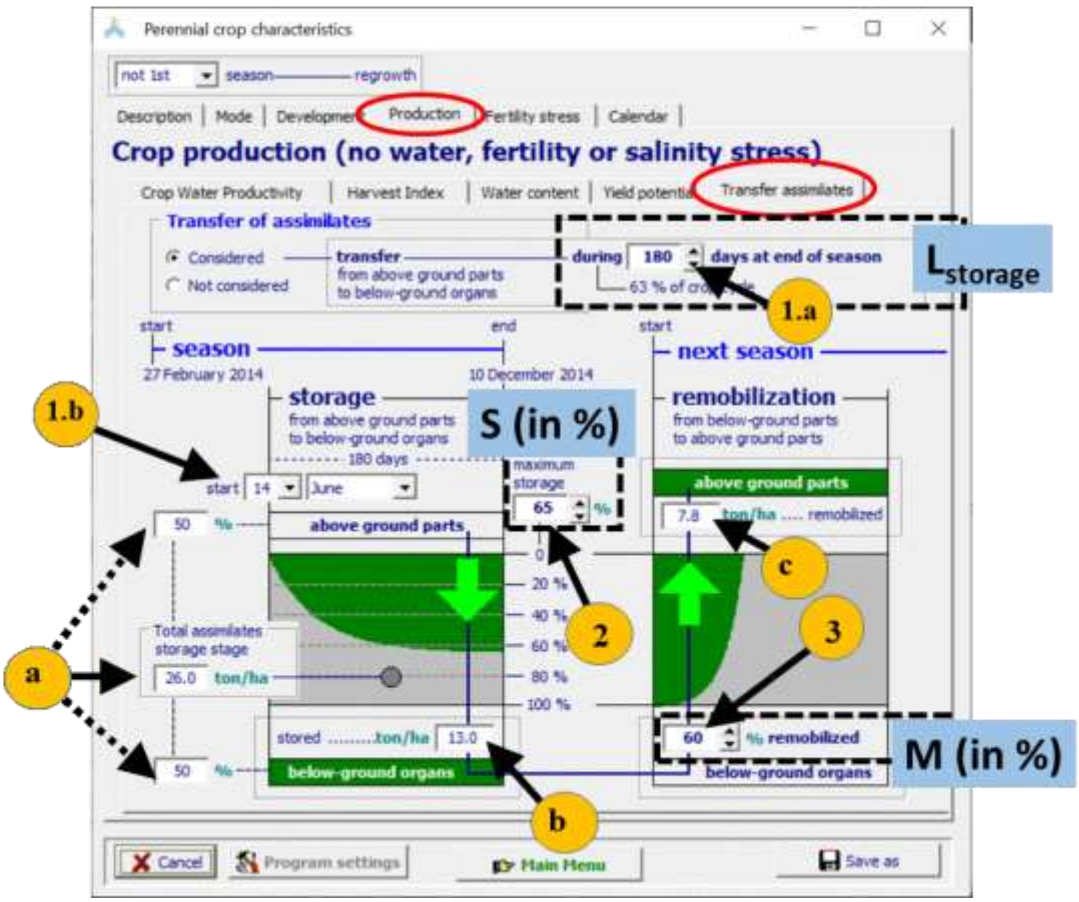


Figure 3.11m – Input (1 to 3) and information (a to c) on the transfer of assimilates in the "Transfer assimilates" tab-sheet in the *Crop characteristic*s menu

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

1. The **duration of the transfer period** in which assimilates are stored in the below-ground parts at the end of the season, by specifying (1.a) the number of days or (1.b) the starting date (day and month) of the storage stage. By knowing the total length of the crop cycle and the specified duration of the storage stage, AquaCrop obtains from the input, the time in calendar days at which the transfer starts;

2. **The fraction of produced assimilates that are stored in the below-ground parts during the storage stage**, by specifying the percentage (S in %) at the last day of the storage stage (when the storage is at its maximum);
3. **The fraction of the stored assimilates that are remobilized at the start of the next season**, by specifying the remobilization percentage (M in %)

With this information AquaCrop calculates and displays (Fig 3.11m):
a) the total mass of assimilates than can be produced without considering harvests during the storage stage in the absence of water, fertility or salinity stress, and the percentages stored in the above ground and below-ground parts;
b) the mass of assimilates that were stored to the root system;
c) the mass of assimilates that will be transferred from the below-ground to the above ground parts, at the start of the next season.

The percentage of the daily produced assimilates that is transferred to the below-ground parts gradually increases from 0 % at the start of the storage stage to a specified maximum (e.g. 65 %) at the end of the stage. For calibration purposes, AquaCrop calculates for each day of the storage stage, the total of the mass of assimilates produced (m) and the fraction (m_{sto}) that is transferred to the below-ground parts under optimal conditions (i.e. by assuming no water, fertility or salt stresses and without considering harvests):

$$m = WP^* \ (Ks\ CC^*\ Kc_{Tr,x}\ ETo)/ETo \qquad \text{(Eq. 3.11n)}$$

$$m_{sto} = fi\ \ m \qquad \text{(Eq. 3.11p)}$$

where WP* is the normalized biomass water productivity, Ks the coefficient for cold stress, CC* the canopy cover (adjusted for micro-advective effects) under optimal conditions, $Kc_{Tr,x}$ the crop transpiration coefficient for full canopy cover and ETo the reference evapotranspiration; and fi, the daily fraction of assimilates transferred, varying from 0 at the start of the storage stage to its maximum value (e.g. 0.65) at the end.

Calibration:
- By altering the length of the storage stage, the total amount of biomass produced in the storage stage ($\sum m$) can be adjusted;
- By altering the maximum percentage at the end of the storage stage, the percentage of assimilates stored ($100 \sum m_{sto}/\sum m$) can be adjusted;
- Only a fraction of the stored assimilates will be remobilized at the start of the next season. This fraction (expressed as a percentage) can be used to calibrate (increase or decrease) the remobilization of the stored assimilates at the start of the next season.

▪ **Transfer of assimilates between above and below-ground plant parts**

Perennial herbaceous forage crops allocate the carbon assimilated through photosynthesis (m_i) to above (leaves and stems) and below-ground organs (crowns and roots). Since AquaCrop does not simulate biomass partitioning among various organs, variations in partitioning along the season is simulated by increasing or reducing WP*, as it is done for the energy-rich yield products of some crops during yield formation (section 3.11.2). The above-ground biomass (B_{upper}) is simulated as:

$$B_{upper} = \sum f_i m_i = \; f_i \, WP^* \; \sum \left(\frac{Tr_i}{ETo_i} \right) \qquad \text{(Eq. 3.11q)}$$

Where f_i is a correction factor which is less than one during the period of assimilate storage in below-ground organs, and greater than one during the period of remobilization of assimilates in spring (Fig. 3.11a/2).

The net assimilate storage stage starts after mid-season when the crop transfers an important fraction of m_i to the below-ground organs. During the following spring, which corresponds to the net remobilization stage, the stored assimilates are transferred to the above-ground organs to contribute to enhanced growth. In the remobilization and storage stages, f_i is corrected for regrowth, since plants use the carbohydrate reserves for regrowth both in the spring and after each cutting (Fig. 3.11n).

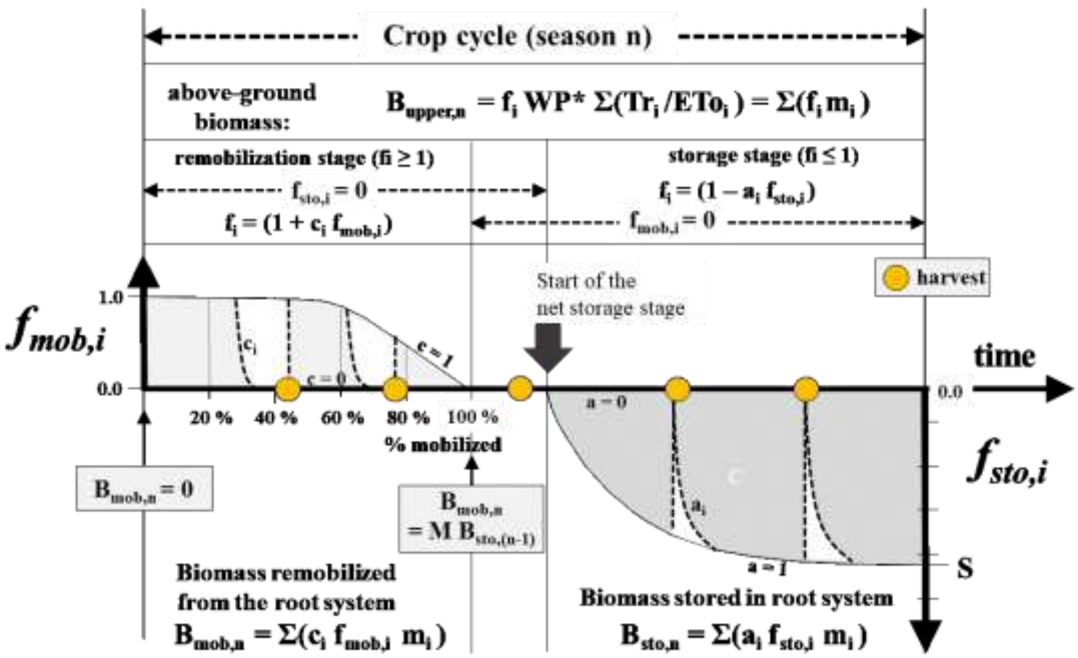


Figure 3.11n – Schematic representation of the simulation of the total above-ground biomass ($B_{upper,n}$) in the nth season, for alfalfa. During the spring (net remobilization stage), the transfer to the above-ground parts of the Mth fraction of the assimilates stored below ground in the previous season ($B_{sto,(n-1)}$), is simulated by increasing the biomass at day i (m_i) with a fraction ($c_i \, f_{mob,i}$). From mid-season (start of the net storage stage), a fraction ($a_i \, f_{sto,i}$) of m_i is stored in the below-ground parts (source Raes et al., 2023).

- **Storage of assimilates below ground (storage stage)**

At run time, AquaCrop calculates the daily amount of biomass produced (m_i) and the fraction transferred to the below-ground parts during the storage stage. The start of the storage stage is the moment derived from the specified length of the storage stage ($L_{storage}$).

Since perennial herbaceous forage crops transfer a considerable fraction of the assimilates below ground after mid-season, the daily biomass produced, m_i, is reduced by a fraction ($f_{sto,i}$) that exponentially increases from 0 at the start of the net storage stage (t = 0) to a fraction (S) of m_i at the end of the season (t = 1):

$$f_{sto,i} = \left[\frac{(exp^{-5t}-1)}{(exp^{-5}-1)}\right] S \qquad \text{(Eq. 3.11r)}$$

When the crop is harvested during the storage stage, $f_{sto,i}$ is temporarily reduced to consider the assimilates required for the regrowth of the crop canopy. This is simulated by multiplying $f_{sto,i}$ by an adjustment factor (a_i) for regrowth ($0 \le a_i \le 1$):

$$a_i = \frac{(CC_i - CC_{cut})}{(CC_x - CC_{cut})} \qquad \text{(Eq. 3.11s)}$$

where CC_{cut} is the canopy cover after harvest, and CC_i the canopy cover at day i, which increases during regrowth from CC_{cut} to the maximum canopy cover, CCx. At every harvest date, $CC_i = CC_{cut}$, a_i is zero and storage is halted (Fig. 3.11p). When CC_i reaches CCx at the end of regrowth, a_i is 1, and storage is again at maximum rate.

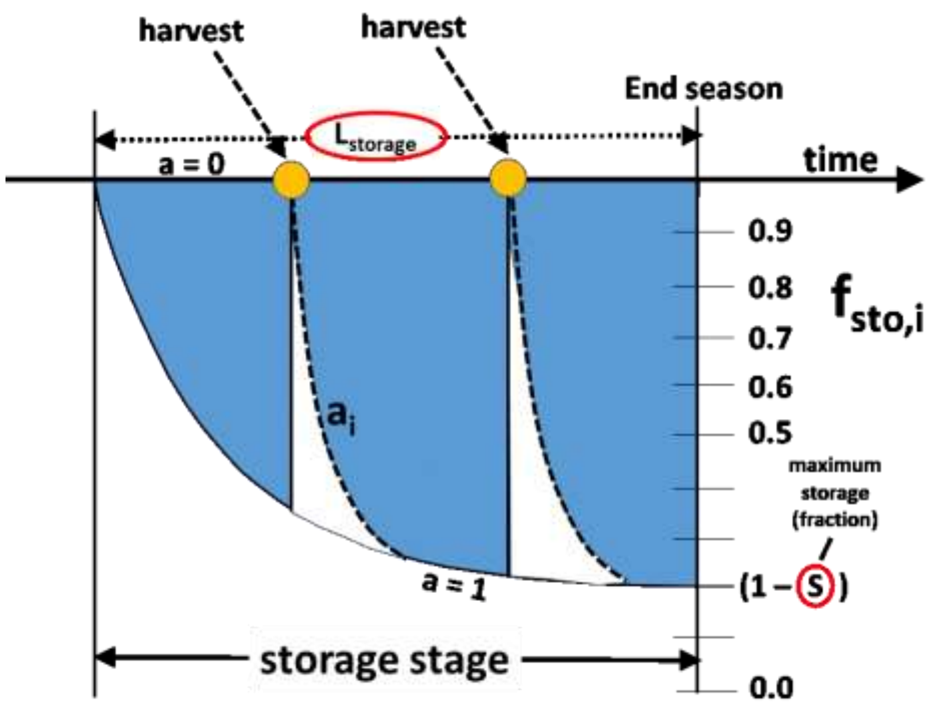


Figure 3.11p – Storage fraction ($f_{sto,i}$) that exponentially increases during the storage stage of assimilates (Eq. 3.11r). The adjustment factor a_i for regrowth (Eq. 3.11s) is zero on a day of harvest, and gradually increases to 1 during regrowth.

The mass of assimilates transferred to the root system ($m_{sto,i}$ = (1-a_i $f_{sto,i}$) m_i) might be much less than the one displayed in the ***Crop characteristics*** menu in which optimal conditions were assumed (Fig. 3.11m). When in a season, poor field management (a late harvest, low soil fertility) and limited water availability (low rainfall, insufficient irrigation, poor irrigation water quality) are encountered, the total biomass production and the fraction of assimilates stored might be very low, since:

- (unwanted) cuttings during the storage stage will results in a low CC;
- water, fertility, salinity stress during the storage stage might result in a low CC, and a (partly) closure of the stomata.

Although the percentage of assimilates transferred to the root system gradual increases (Fig. 3.11p), the daily production of the biomass at the end of the storage stage, and as such the stored fraction, might not be that important due to a reduction of the crop transpiration in the late-season as a result of the natural senescence of the crop Canopy Cover at the end of the crop cycle and/or cold stresses (Fig. 3.11q).

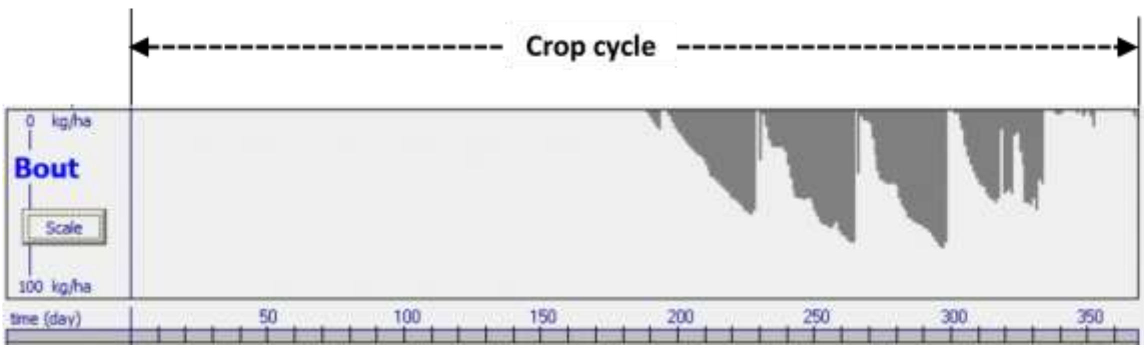


Figure 3.11q – Example of simulated stored assimilates in root system (Bout) during the storage stage

- **Remobilization of assimilates from below ground (remobilization stage)**

Not all assimilates can be recovered from storage. In AquaCrop it is assumed that of the total assimilates stored below ground in the previous season ($B_{sto,(n-1)}$), a fraction (M) is remobilized during the next season ($B_{mob,n}$). The rest is assumed to be lost by respiration and natural self-thinning, or to remain stored below ground:

$$B_{mob,n} = M\ B_{sto,(n-1)} \qquad \text{(Eq. 3.11t)}$$

Furthermore, it is assumed that at the start of the first year after sowing, only 20% of M is remobilized above ground, as many of the stored assimilates in the sowing year were required in the development and establishment of the perennial plant parts below ground (crown and root system).

To simulate the remobilization of stored assimilates at the start of the season, m_i is increased with a fraction ($f_{mob,i}$) which decreases gradually as more and more assimilates are remobilized (Fig. 3.11r):

$$f_{mob,i} = \left[\frac{(exp^{-5t}-1)}{(exp^{-5}-1)}\right] \quad \text{(Eq.3.11u)}$$

$$t = \frac{B_{mob,n} - \sum m_{mob,i}}{B_{mob,n}} \quad \text{(Eq. 3.11v)}$$

where $m_{mob,i}$ are the assimilates remobilized from the root system on day i, expressed as a fraction ($f_{mob,i}$) of m_i, and t is the relative time in the remobilization stage which gradually decreases from 1 at the start of the season to zero at the end of the remobilization stage.

When the canopy reaches 90 percent of CCx after regrowth, remobilization is no longer considered. This is simulated by multiplying $f_{mob,i}$ with an adjustment factor (c_i) for regrowth ($0 \leq c_i \leq 1$):

$$c_i = \frac{(CC_x - CC_i)}{0.1\, CC_x} \qquad \text{if } CC_i > 0.9\ CCx \quad \text{(Eq. 3.11w)}$$

At each harvest, c_i is 1 and remobilization starts at its maximum rate. It stays that way until CC has reached 90 percent of its maximum (CCx). When maximum canopy cover is reached (CC = CCx), c_i is zero and remobilization is halted until the next harvest. It is considered that remobilization and storage do not occur at the same time.

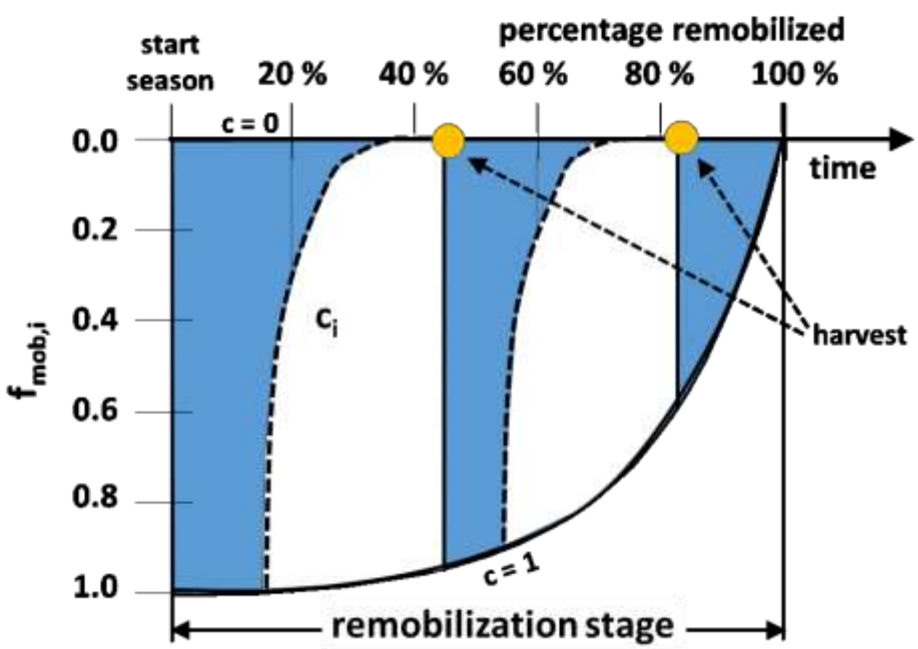


Figure 3.11r – Mobilization fraction ($f_{mob,i}$) that exponentially decreases during the mobilization stage of assimilates (Eq. 3.11u). To stimulate growth, the adjustment factor c_i is 1 as long as CC increase. When the maximum canopy cover is reached, c_i is zero and remobilization is halted (Eq. 3.11v).

AquaCrop calculates the biomass production each day (most likely to be small at the start of the season due to cold stresses and/or low CC). By already knowing the total mass of assimilates that has to be mobilized in the season (a fraction of the stored assimilates in previous season), AquaCrop will decrease gradually the multiplicator (f_i) of WP* when more and more assimilates are mobilized (Fig. 3.11s). The multiplicator will be back at 1.0, when all assimilates are mobilized.

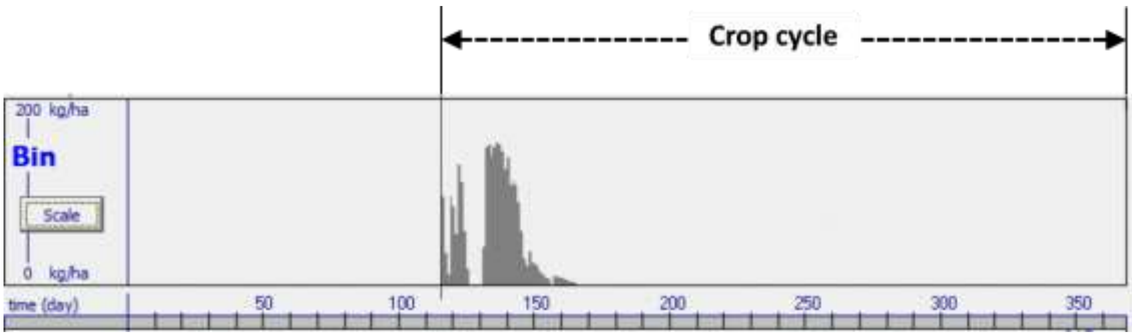


Figure 3.11s – Example of simulated mobilized assimilates from the root system (Bin) during the mobilization stage

Since remobilization and storage cannot exist at the same time, any remaining part that still needs to be remobilized at the start of the storage stage, is no longer considered and assumed to be lost.

3.12 Partition of biomass into yield part (yield formation)

The partition of biomass into dry yield part (Y) is simulated by means of a Harvest Index (HI):

$$Y_{dry} = HI\ B \qquad \text{(Eq. 3.12a)}$$

where B is the total dry above-ground biomass produced at crop maturity (Eq. 3.11b) and HI the fraction of B that is the yield part, and Y_{dry} is the dry yield. When water and/or temperature stress develops during the crop cycle, the Harvest Index is adjusted to the stresses at run time for fruit/grain producing crops and roots and tuber crops and might be different from the reference harvest index (HI_o). The adjustment can be positive or negative and depends on the timing and the extent of the stress. The calculation scheme is presented in Fig. 3.12a.

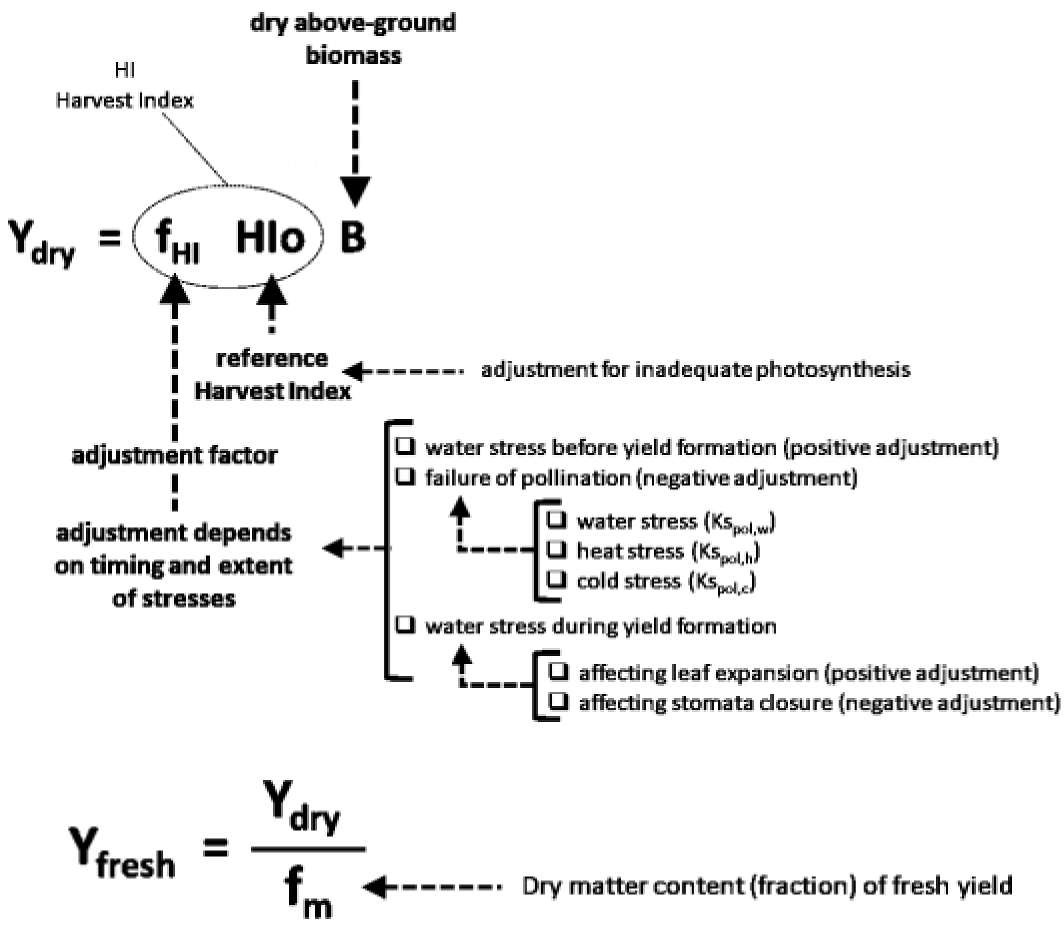


Figure 3.12a – Calculation scheme in AquaCrop for dry (Y_{dry}) and fresh yield (Y_{fresh})

3.12.1 Reference Harvest Index (HI_o)

The reference Harvest Index (HI_o) is the ratio of the dry yield mass to the total dry above-ground biomass that will be reached at maturity for non-stressed conditions. HI_o is a crop a parameter that is cultivar specific.

3.12.2 Building up of Harvest Index

The increase of HI is described by a logistic function:

$$HI_i = \frac{HI_{ini}\ HI_0}{HI_{ini} + \left(HI_0 - HI_{ini}\right) \exp^{-(HIGC)\,t}} \qquad \text{(Eq. 3.12b)}$$

where HI_i Harvest Index at day i;
HI_o specified reference Harvest Index [fraction];
HI_{ini} initial value for HI (HI_{ini} is 0.01);
HIGC growth coefficient for HI [day^{-1}];
t time [day].

The simulation of the building up of the Harvest Index differs along the crop types. Distinction is made between leafy vegetable crops (Fig. 3.12b), root/tuber crops (Fig. 3.12c), and fruit/grain producing crops (Fig. 3.12d).

- **Building up of Harvest Index for leafy vegetable crops**

After germination of leafy vegetable crops the Harvest Index builds up quickly and reaches after a short while the reference value HI_o (Fig. 3.12b). The time to reach HI_o is expressed as a fraction of the growing cycle (default is 20 %).

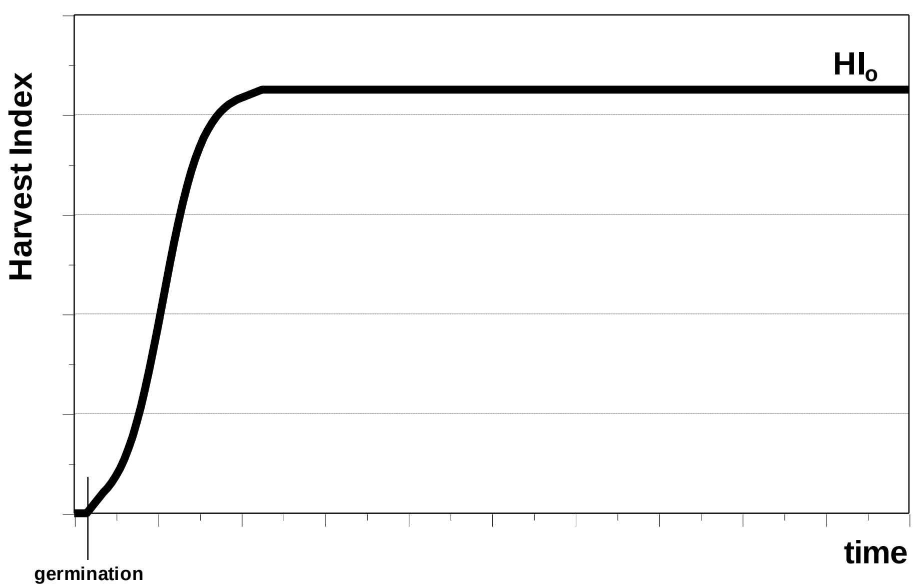


Figure 3.12b – Building up of Harvest Index along the growth cycle for leafy vegetable crops

In Eq. 3.12b, t is the time after germination. Given HI_{ini}, HI_o and the time required to obtain HI_o, the corresponding growth coefficient (HICG) for HI is derived in AquaCrop from Eq. 3.12b.

- **Building up of Harvest Index for root/tuber crops**

Just after the start of tuber formation or root enlargement the increase of the Harvest Index is described by a logistic function (Fig. 3.12c). The harvest index for any day of yield formation is given by Eq. 3.12b, where t is the time after the start of tuber formation or root enlargement. The growth coefficient (HICG) is determined with the help of the specified length of yield formation (time required to obtain HI_o). When the building up of the Harvest Index is fast, the crop might have reached its reference value (HI_o) before the end of the crop cycle.

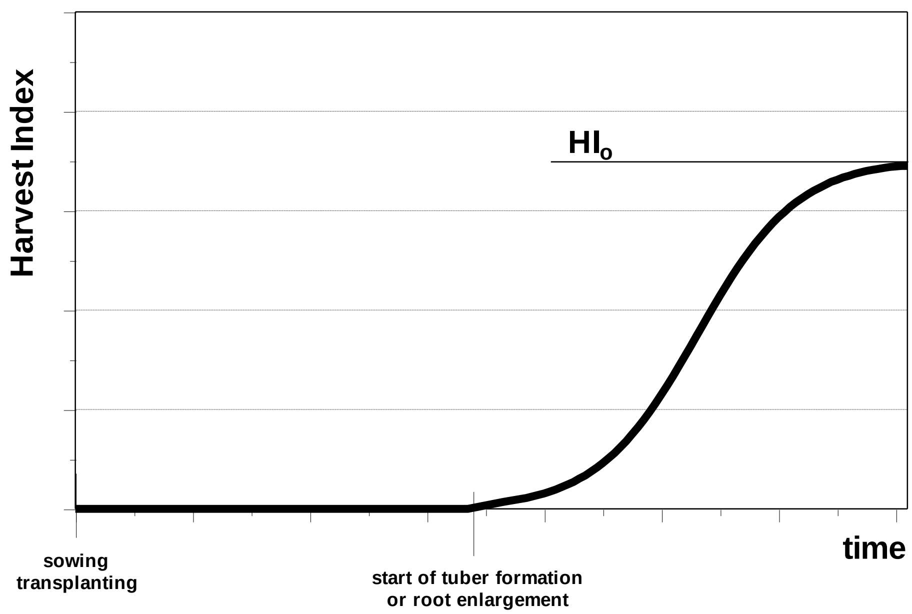


Figure 3.12c – Building up of Harvest Index for root and tuber crops

▪ **Building up of Harvest Index for fruit/grain producing crops**

Just after flowering the increase of the Harvest Index is slow (lag phase) and described by the logistic function. The harvest index for any day in the lag phase is given by Eq. 3.12b where t is the time after flowering. The growth coefficient (HICG) is determined with the help of the specified length of yield formation (time required to obtain HI_o).

Once the increase of the Harvest Index is sufficient large to reach HI_o at the end of yield formation, the lag phase is ended and the increase of HI becomes linear (Fig. 3.12d). When the building up of the Harvest Index is fast, the crop might have reached its reference value (HI_o) before the end of the crop cycle. Given the excess of potential fruits, the period of building up of HI cannot be smaller in AquaCrop than the time required to have 100% potential fruits.

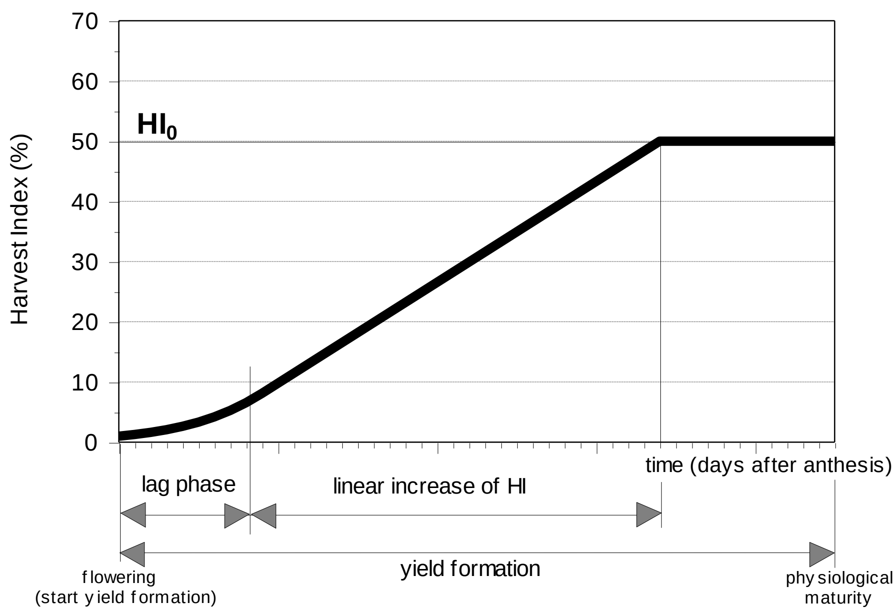


Figure 3.12d – Building up of Harvest Index from flowering till physiological maturity for fruit and grain producing crops

3.12.3 Adjustment of HI_o for inadequate photosynthesis

For root/tuber crops and fruit/grain producing crops the Harvest Index might need to be adjusted for insufficient green canopy cover. A too short grain/fruit filling stage or tuber formation stage might result in inadequate photosynthesis and a reduction of the reference Harvest Index (HI_{adj}) at run time.

During the yield formation stage, the Harvest Index for root/tuber crops and fruit/grain producing crops, gradually increases until the Reference Harvest (HIo) is reached at about the end of the crop growing cycle. However, when due to early canopy senescence, the remaining green canopy cover (CC) drops below a threshold (CC_{min}), the Harvest Index can no longer increase (Fig. 3.12e). In that case there is not enough green canopy left, so that photosynthesis becomes insufficient. This results in an adjusted HI which is smaller than HI_o. The threshold green canopy cover below which the Harvest Index can no longer increase is a program parameter.

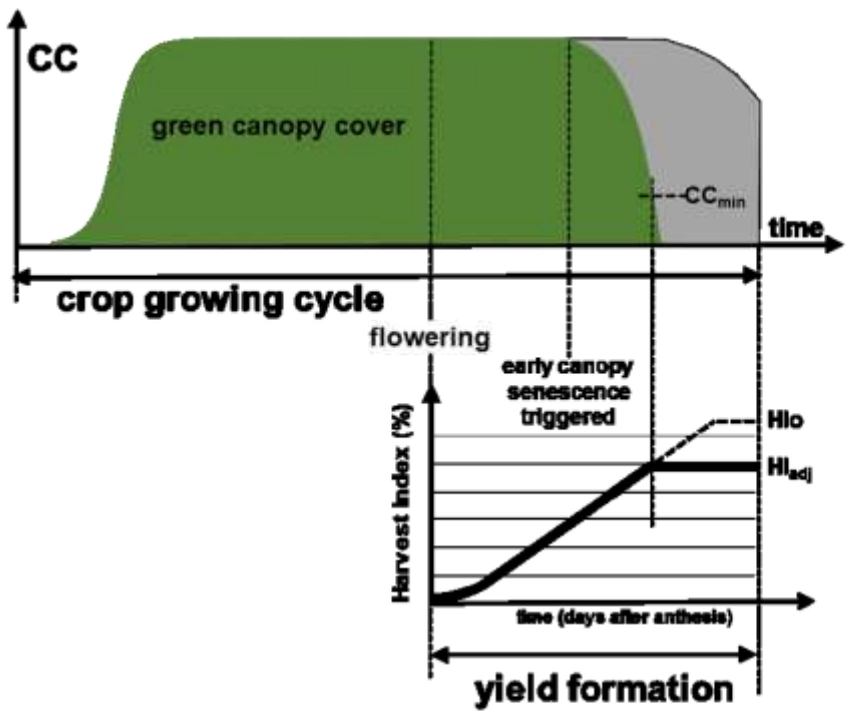


Figure 3.12e – Harvest index development (bold line) when insufficient green canopy cover remains during yield formation for crops with determinacy linked with flowering

The adjustment is limited to the case of a decline of the green canopy cover due to severe water stress, triggering an early senescence. This restriction avoids a zero HI (and no yield formation) when CC is small (as a result of stresses) at the start of yield formation (tuber formation or root enlargement for root/tuber crops or flowering for fruit/grain crops). The adjustment of HI is only valid for root/tuber crops and fruit/grain producing crops, and does not apply to leafy vegetable and forage crops.

3.12.4 Adjustment of HIo for water stress before the start of yield formation

When a fruit/grain producing or root/tuber crop has spent less energy in its vegetative growth, the Harvest Index might be higher than HI_o (Fig. 3.12f). The maximum allowable increase of HI_o as the result of water stress before flowering (ΔHI_{ante}) is specified as a percentage of HI_o.

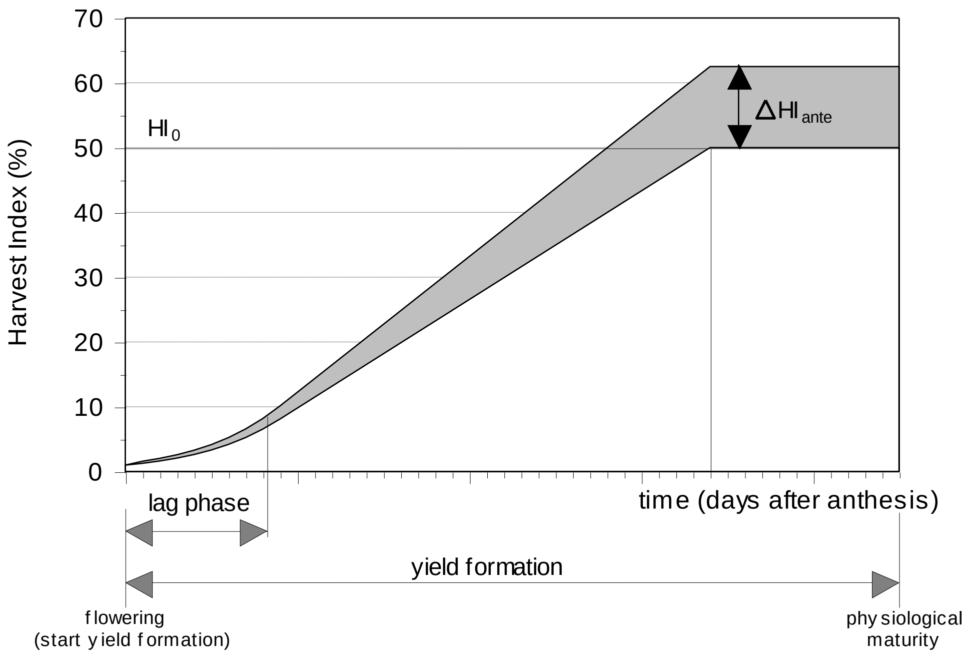


Figure 3.12f – Range (shaded area) in which the Harvest Index of fruit/grain producing or root/tuber crops can increase as a result of water stress before the start of yield formation

In AquaCrop the relative biomass is used to assess the saving in energy in the vegetative growth stage. The relative biomass (B_{rel}), determined at the start of flowering (tuber formation), is the ratio between the actual biomass (B) and the potential biomass (B_0):

$$B_{rel} = \frac{B}{B_0} \qquad \text{(Eq. 3.12c)}$$

The actual dry above-ground biomass is the biomass derived from the cumulative amount of water transpired at the moment of flowering. The potential value is the dry above-ground biomass that could have been obtained in the same period in the given environment if there was not any stress resulting in stunned growth, stomatal closure or early senescence.

HI_o might be adjusted upward if B_{rel} is smaller than 1 at the start of flowering. However, it is the magnitude of B_{rel} that determine the magnitude of the adjustment. A too high or a too low B_{rel} will result in only a slight correction or no adjustment at all (Fig. 3.12g). Hence, the adjustment is restricted to a particular range of B_{rel}. The range valid for adjustment is given by:

$$Range(B_{rel}) = \frac{\ln(\Delta HI_{ante})}{5.62} \leq 1 \qquad \text{(Eq. 3.12d)}$$

where ΔHI_{ante} allowable increase of HI_o as the result of water stress before flowering [%];

Range(B_{rel}) range of relative biomass (B_{rel}) in which HI_o can be adjusted [fraction].

In AquaCrop the range is linked to the allowable increase (in percentage) of HI_o specified by the user. The percentage is crop specific and gives the maximum possible increase of HI_o as a result of water stress before flowering. The higher the specified increase ΔHI_{ante}, the larger the range for adjustment.

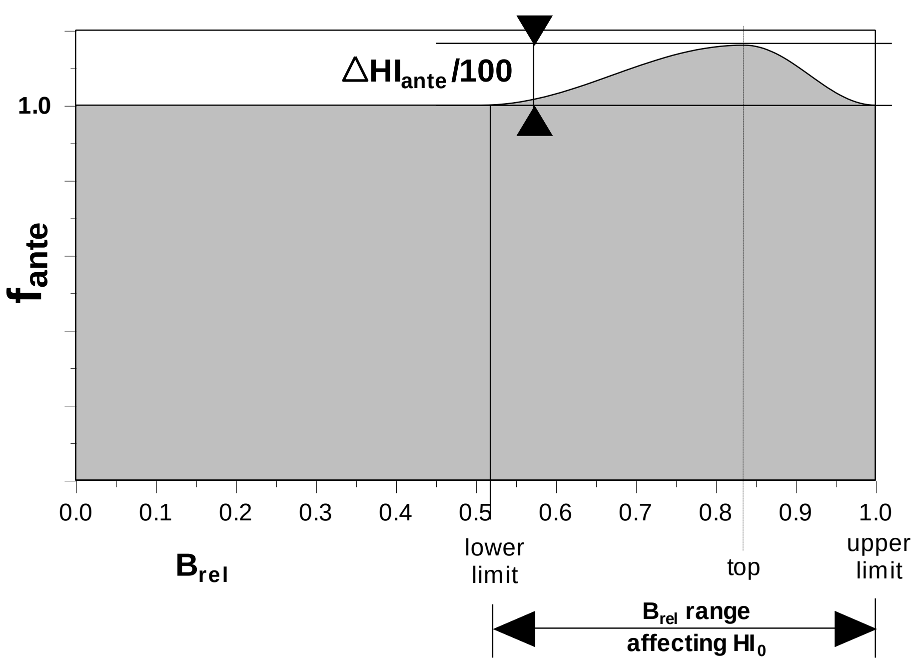


Figure 3.12g – Coefficient (f_{ante}) by which HI_o has to be multiplied to consider the effect of water stress before the start of yield formation, for various relative biomass values (B_{rel}), and a given allowable increase (ΔHI_{ante})

Within the range where HI can be adjusted, the exact correction for HI_o is given by a sine function (Fig. 3.12g):

- For B_{rel} between the lower limit and the top:

$$f_{ante} = 1 + \frac{1 + \sin\left(\left(1.5 - Ratio_{low}\right)\pi\right)}{2} \quad \frac{\Delta HI_{ante}}{100} \qquad \text{(Eq. 3.12e)}$$

where B_{rel} relative biomass at the start of flowering (Eq. 3.12c);
$B_{r,low}$ lower limit of the B_{rel} Range affecting HI_o;
$B_{r,top}$ top of B_{rel} Range affecting HI_o;
f_{ante} coefficient by which HI_o has to be multiplied to consider the effect of water stress before flowering;

$$0 \le Ratio_{low} = \frac{B_{rel} - B_{r,low}}{B_{r,top} - B_{r,low}} \le 1 \qquad \text{(Eq. 3.12f)}$$

- For B_{rel} between the top and the upper limit (B_{rel} = 1):

$$f_{ante} = 1 + \frac{1 + \sin\left(\left(0.5 + Ratio_{up}\right)\pi\right)}{2} \quad \frac{\Delta HI_{ante}}{100} \qquad \text{(Eq. 3.12g)}$$

where B_{rel} relative biomass at the start of flowering (Eq. 3.12c);
$B_{r,top}$ top of B_{rel} Range affecting HI_o;
$B_{r,up}$ upper limit of B_{rel} Range affecting HI_o;
f_{ante} coefficient by which HI_o has to be multiplied to consider the effect of water stress before flowering.

$$0 \le Ratio_{up} = \frac{B_{rel} - B_{r,top}}{B_{r,up} - B_{r,top}} \le 1 \qquad \text{(Eq. 3.12h)}$$

The response in the *Range(B_{rel})* is assumed to be asymmetric. The top is at 1/3 of $B_{r,up}$ and at 2/3 of $B_{r,low}$.

3.12.5 Adjustment of HI_o for failure of pollination (only for fruit/grain producing crops)

- **Flowering**

In AquaCrop the pattern of flowering is assumed to be asymmetric with time (Fig. 3.12h). The flowering distribution curve is given by:

$$f_k = 0.00558\ k^{0.63} - 0.000969\ k - 0.00383 \qquad \text{(Eq. 3.12i)}$$

where k is the relative time in percentage of the total flowering duration and f_k is the fraction of flowers flowering at time k.

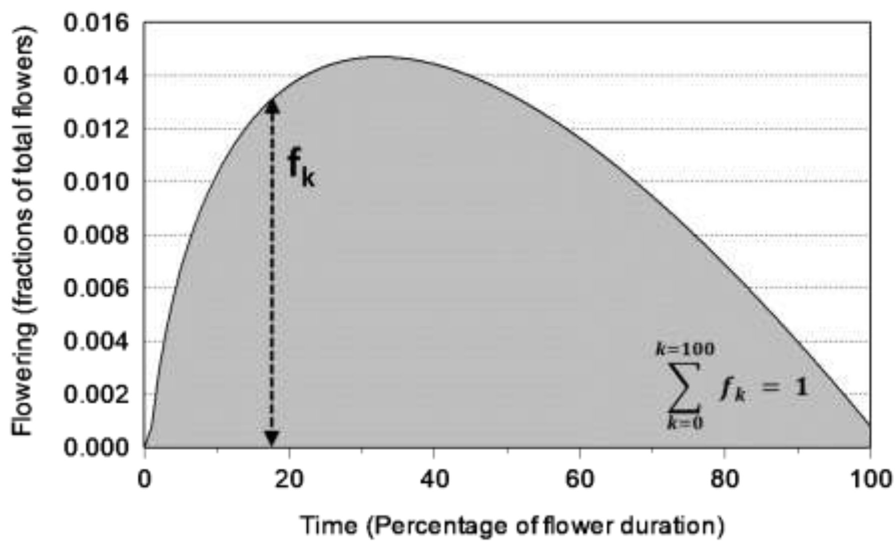


Figure 3.12h – Distribution of flowering during the flowering period

Generally a crop will produce flowers in excess. When conditions are favorable, the crop sets more fruits than needed for a good harvest. The excessive young fruits are aborted as the older fruits grow. The excess (f_{excess}) is a crop parameter.

- **Failure of pollination**

Severe water stress, cold stress, or heat stress at flowering might induce a reduction in the reference harvest index because insufficient flowers are pollinated to reach HI_o. The effect is dynamic, affecting only the population of flowers that is due to pollinate at the time of the stress, but not the younger flowers due to pollinate days later or the flowers already pollinated. To estimate HI_{adj} AquaCrop calculates for each day of the flowering period, the HI that can be reached with the number of flowers already pollinated:

$$HI_{adj} = \sum_{1}^{j}\left(Ks_j \left(1+\frac{f_{excess}}{100}\right) F_j \; HI_0 \right) \qquad \leq \; HI_0 \qquad \text{(Eq. 3.12j)}$$

where j number of days since the start of flowering (j = 1 at the start of flowering)

f_{excess} excess of the sink (percentage);

F_j fractional flowering on day j (Eq. 3.12j/2: derived from Eq. 3.12i); To be able to account for cold and heat stress at flowering, the calculation procedure works with calendar days;

Ks_j stress factor limiting pollination on day j.

$$F_j = \frac{100}{L_{flowering}} \, \overline{f_j} \qquad \text{(Eq. 3.12j/2)}$$

where $L_{flowering}$ the length of the flowering (days)

f_j average of the fraction of flowers flowering during the time step j

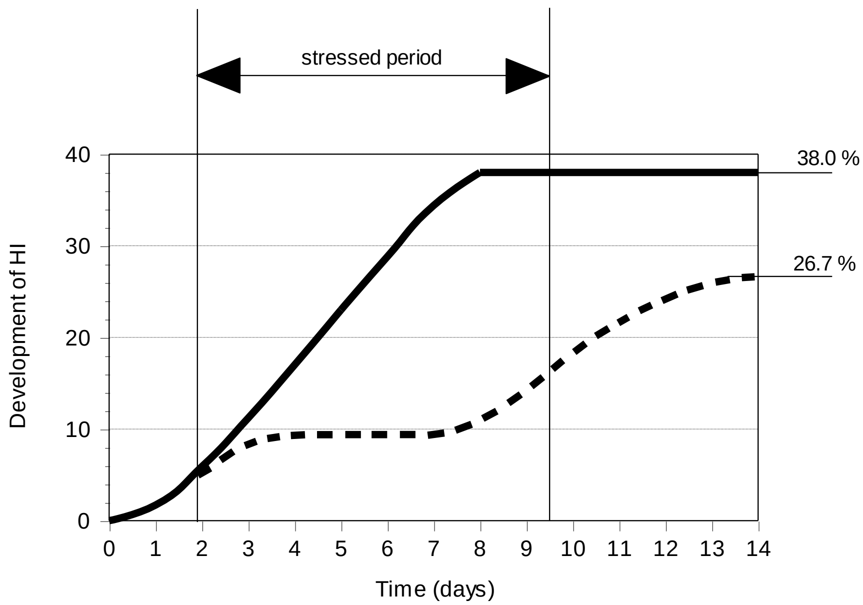


Figure 3.12i – The development of HI at flowering and the adjusted harvest indexes (HI_{adj}) for a non-stressed (full) and a stressed (dotted line) flowering period of 14 days. (HI_o = 38%, f_{excess} = 50%, and stress occurs (Ks < 1) from day 2 till day 9)

The excess of the sink made that if stress reduces pollination by a minor amount, HI_o might not be affected because the excessive young fruits are given the change to grow, instead of dropping off, if stress is ameliorated after the flowering period and canopy photosynthesis is adequate. An import stress, during several days at flowering, might result in a HI_{adj} that is smaller than the specified HI_o (Fig. 3.12i). The smaller the excess of flowers (f_{excess}) and the more severe the stress (Ks), the stronger the reduction of the reference harvest index.

Failure of pollination due to water stress ($Ks_{pol,w}$)

Severe water stress at the time of flowering, can markedly inhibit pollination and fruit setting. This is simulated by considering a soil water stress coefficient for pollination, $Ks_{pol,w}$ (see 3.2.2 Soil water stress). If the depletion in the considered soil volume (top soil or root zone) drops below a threshold (p_{pol} TAW), $Ks_{pol,w}$ becomes smaller than 1 and pollination starts to fail (Fig. 3.12j). $Ks_{pol,w}$ decreases linearly from 1 at the upper threshold (p_{pol}) to zero at the lower threshold (permanent wilting point).

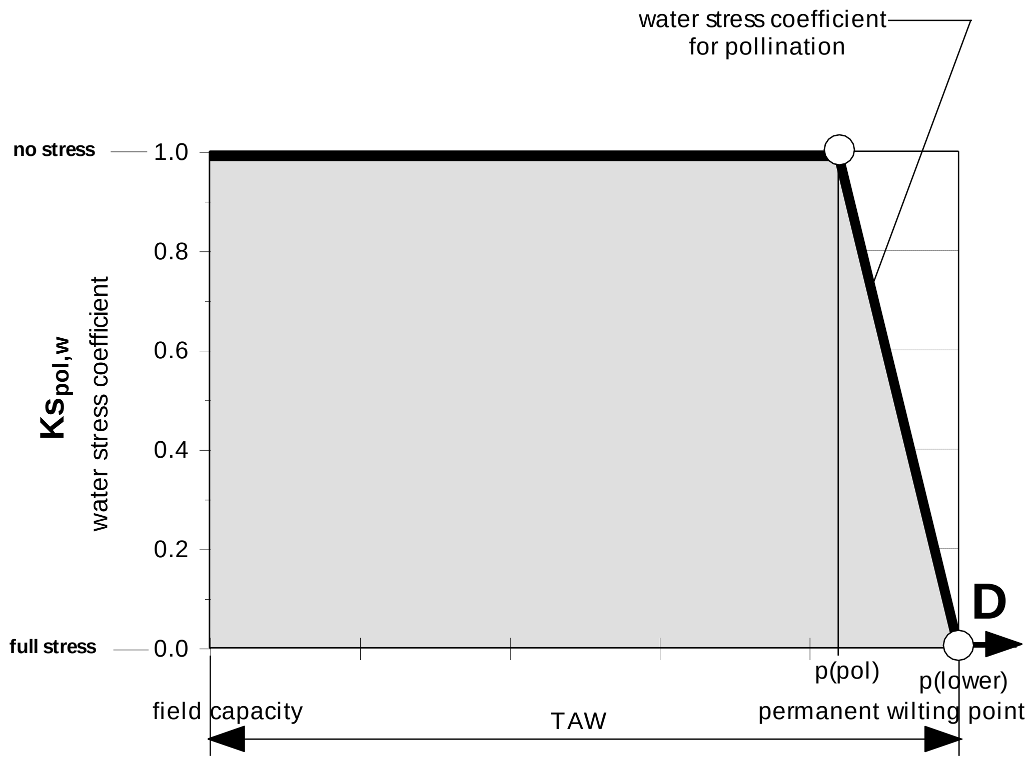


Figure 3.12j – The water stress coefficient for failure of pollination ($Ks_{pol,w}$) for various degrees of depletion (D) in the considered soil volume

Since pollination is inhibited only be severe stress, the fraction of TAW that can be depleted from the considered soil volume before pollination is affected (p_{pol}) is large. The threshold should be set lower than the threshold for the effect for stomatal closure (p_{sto}) and senescence (p_{sen}). Since by then stomata are largely closed and most of the transpiration is eliminated, the stress effect on pollination needs not to be adjusted to ET_o. Because the data on pollination failure are limited and insufficient to determine the shape of the response curve, a linear function is considered for $Ks_{pol,w}$.

Failure of pollination due to cold ($Ks_{pol,c}$) and heat stress ($Ks_{pol,h}$)

If the minimum air temperature drops below a threshold ($T_{n,cold}$) or the maximum air temperature rises above a threshold ($T_{x,heat}$), pollination might be affected. This simulated by considering a cold stress ($Ks_{pol,c}$) coefficient and heat stress ($Ks_{pol,h}$) coefficient for pollination (see 3.2.3 Air temperature stress).

When the minimum air temperature on a day drops below the specified threshold temperature ($T_{n,cold}$), the cold stress coefficient $Ks_{pol,c}$ will be smaller than 1 (Fig. 3.12k). $Ks_{pol,c}$ becomes zero at the lower threshold which is set at 5 degrees below $T_{n,cold}$. A logistic function is used as the response function between the lower temperature threshold and $T_{n,cold}$. Similarly, when the maximum air temperature rises above the specified threshold temperature ($T_{x,heat}$), the heat stress coefficient $Ks_{pol,h}$ will be smaller than 1. $Ks_{pol,h}$ becomes zero at the upper threshold which is set at 5 degrees above $T_{x,heat}$. Outside the stressed period, the air temperature stress coefficients $Ks_{pol,c}$ and $Ks_{pol,h}$ are 1.

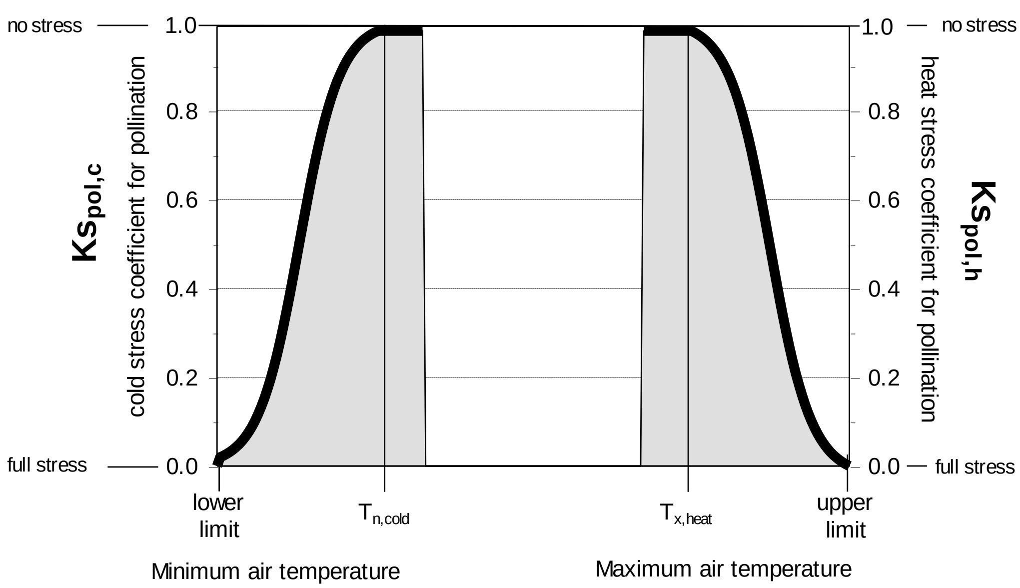


Figure 3.12k – The air temperature stress coefficients for failure of pollination due to cold ($Ks_{pol,c}$) and heat ($Ks_{pol,h}$) stress for various air temperatures

3.12.6 Adjustment of HI_o for water stress during yield formation

Water stress after flowering (fruit/grain producing crops) or after the start of tuber formation or root enlargement (root/tuber crops) might affect the reference Harvest Index (HI_o) as well. Depending on the moment when the water stress occurs and on its magnitude, the adjustment can be upwards or downwards (Fig. 3.12l).

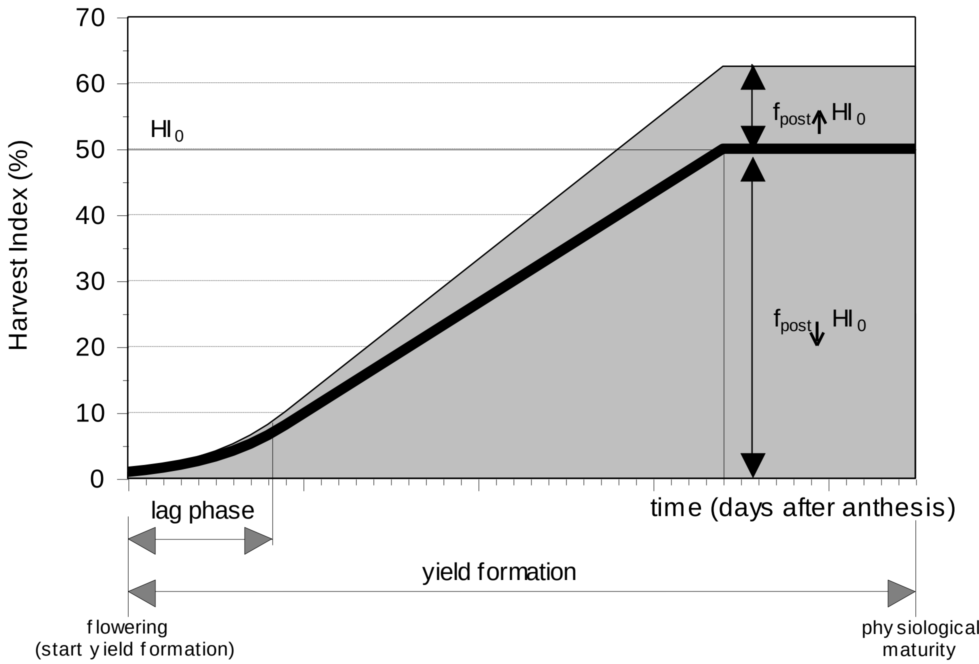


Figure 3.12l – Range (shaded area) in which the Harvest Index of fruit/grain producing or root/tuber crops can alter as a result of water stress during yield formation

- **Upward adjustment of HI_o**

As long as vegetative growth is still possible (see 3.5.2 Period of potential vegetative growth), the daily rate with which the Harvest Index increases (dHI/dt) might be adjusted if water stress affects leaf expansion. This results in an increase of dHI/dt and is given by:

$$\frac{dHI}{dt} = \left(1 + \frac{(1 - Ks_{\exp,i})}{a}\right)\left(\frac{dHI}{dt}\right)_O \qquad \text{(Eq. 3.12k)}$$

where $(dHI/dt)_o$ reference increase of the Harvest Index after flowering;
$Ks_{exp,\,i}$ value for the water stress coefficient for leaf expansion growth at day i (see 3.5.1). Ks_{exp} is 1 for no stress and 0 for full stress;
a crop parameter (the value is crop specific and can vary between 0.5 (strong effect) and 40 (very small effect).

By keeping track of the daily values for $Ks_{exp,\,i}$ during the period when vegetative growth is still possible, the positive adjustment of the Harvest Index at the end of the period is given by:

$$f_{post\uparrow} = 1 + \frac{\sum_{i=1}^{n(\exp)} \left(\frac{1 - Ks_{\exp,i}}{a} \right)}{n(\exp)} \qquad \text{(Eq. 3.12l)}$$

where n(exp) period when vegetative growth is still possible [days];
$f_{post\uparrow}$ coefficient by which HI_o has to be multiplied to consider the positive effect of water stress after flowering.

The adjustment of HI_o is plotted in Figure 3.12m for various values of 'a'. When a is 0.5 and the average root zone depletion during the potential period of vegetative growth is large ($Dr \geq p_{exp,lower}$ TAW), $f_{post\uparrow}$ might increase up to 3. This will result in a HI_o which is the triple of HI_o.

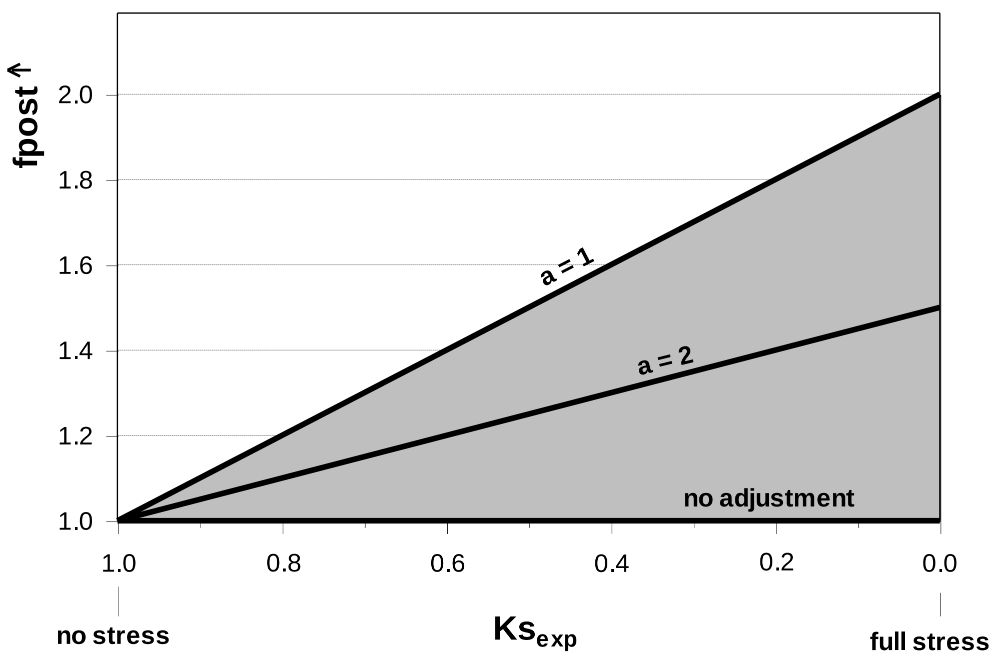


Figure 3.12m – Values for $f_{post\uparrow}$ if water stress after flowering occurs for various mean water stresses affecting leaf growth ($Ks_{exp,w}$) and 'a' values

- **Downward adjustment of HI_o**

During the total period of the building up of the Harvest Index, the daily rate with which the Harvest Index increases (dHI/dt), might be adjusted if water stress affects crop transpiration. This results in a decrease of dHI/dt, and is given by:

$$\frac{dHI}{dt} = \sqrt[10]{Ks_{sto}} \left(1 - \frac{1 - Ks_{sto,\,i}}{b}\right) \left(\frac{dHI}{dt}\right)_O \qquad \text{(Eq. 3.12m)}$$

where $(dHI/dt)_o$ reference increase of the Harvest Index after flowering;

$Ks_{sto,\,i}$ value for the water stress coefficient for stomatal closure (or for deficient aeration conditions) at day i (see 3.10.2). Ks_{sto} is 1 for no stress and 0 for full stress;

b crop parameter (the value is crop specific and can vary between 1 (strong effect) and 20 (small effect).

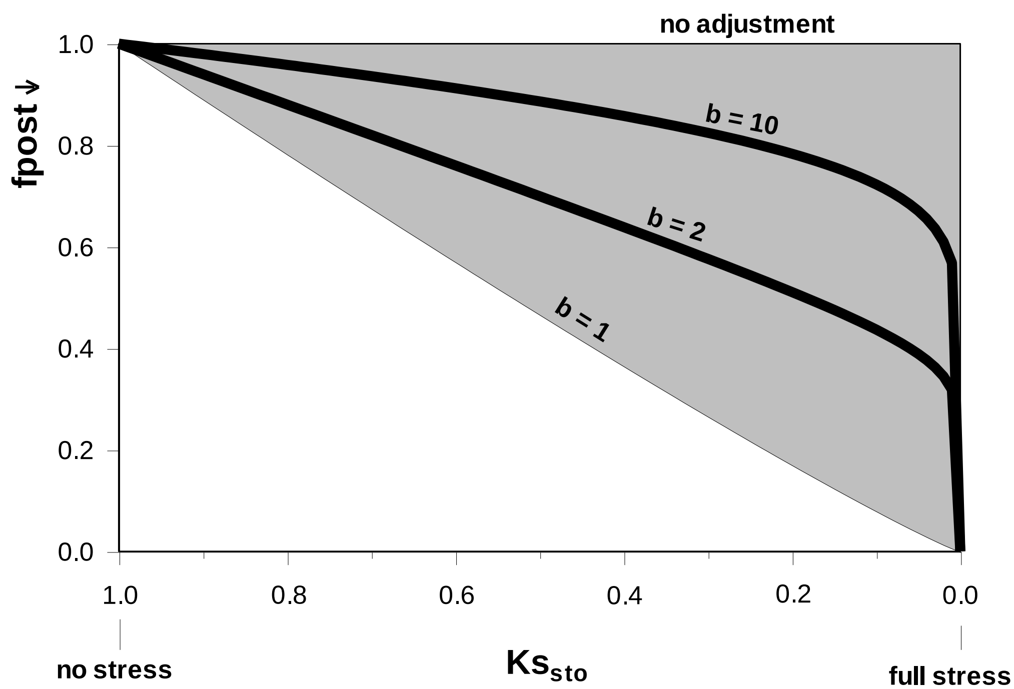


Figure 3.12n – Values for $f_{post\downarrow}$ if water stress after flowering occurs for various mean water stresses affecting crop transpiration (Ks_{sto}) and 'b' values

By keeping track of the daily values for $Ks_{sto,i}$ during the period of the building up of HI, the negative adjustment of the Harvest Index at the end of the period is given by:

$$f_{post\downarrow} = \frac{\sum_{i=1}^{n(yield)} \left(\sqrt[10]{Ks_{sto,i}} \quad \left(1 - \frac{\left(1 - Ks_{sto,i}\right)}{b} \right) \right)}{n(yield)} \qquad \text{(Eq. 3.12n)}$$

where n(yield) period for building up the Harvest Index [days];
$f_{post\downarrow}$ factor by which HI_o has to be multiplied to consider the negative effect of water stress after flowering.

The adjustment of HI_o is plotted in Figure 3.12n for various values of 'b'. The 10th root of Ks_{sto} in Eq. 3.12n makes that the effect of stomatal closure on HI_o is small when Ks_{sto} is close to 1, i.e. crop transpiration is only slightly hampered. Severe water stress might strongly reduce HI_o especially when b is small (close to 1).

- **Combined effect on HI_o**

The total adjustment for water stress after the start of yield formation on the Harvest Index is given by the product of the Eq. 3.12l and Eq. 3.12n. If the period where vegetative growth is still possible (n(exp)) is smaller than the duration of building up the Harvest Index (n(yield)), the adjustments are weighed by their relative length:

$$f_{post} = \left(\frac{w_1 \; f_{post\uparrow} + \left(w_2 - w_1\right)}{w_2} \right) f_{post\downarrow} \qquad \text{(Eq. 3.12o)}$$

where w_1 length of the period when vegetative growth is still possible [days];
w_2 length of the period of building up the harvest Index [days];
f_{post} coefficient by which HI_o has to be multiplied to consider the combined effect of water stress after flowering.

3.12.7 Total effect of water and temperature stress on the Harvest Index

The total correction of HI_o at the end of the yield formation is obtained by considering the adjustments of water stress before and after yield formation and during flowering (Fig. 3.12o).

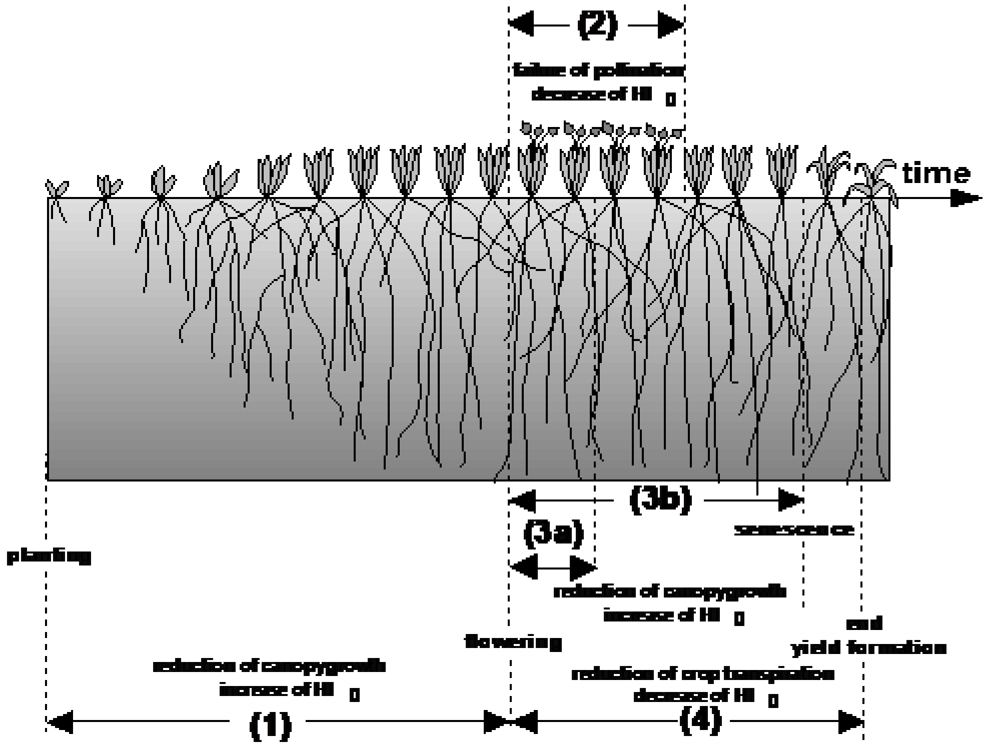


Figure 3.12o – Periods in which water stress might affect HI and its effect on HI_o. (1) before yield formation; (2) during flowering; and (4) during yield formation, with indication of (3) the period of possible vegetative growth for (a) determinant crops and (b) indeterminant crops

The total correction of HI_o at the end of the yield formation is given by:

$$HI = f_{ante}\ f_{post}\ HI_{adj} \qquad \text{(Eq. 3.12p)}$$

where
- HI — Harvest Index reached at the end of yield formation;
- f_{ante} — factor by which HI_{adj} has to be multiplied to consider the effect of water stress before flowering (Eq. 3.12e and 3.12g);
- f_{post} — factor by which HI_{adj} has to be multiplied to consider the effect of water stress after flowering (Eq. 3.12o);
- HI_{adj} — reference Harvest Index adjusted for failure of pollination and inadequate photosynthesis

The adjusted Harvest Index can range between an upper limit (larger than HI_o) and 0 (Fig. 3.12p):

- If HI is larger than HI_o, its value can however never exceed a maximum specified by the user. The allowable increase (ΔHI_{tot}) which is crop specific, is specified as a percentage of HI_o:

$$HI \leq \left(1 + \frac{\Delta HI_{tot}}{100}\right) HI_0 \qquad \text{(Eq. 3.12q)}$$

- As a result of water stress at and after flowering, HI might be smaller than HI_o. If the water stress during yield formation is very severe and results in a crop transpiration rate far below its potential value, HI might become very small. HI will be zero (resulting in no yield) if the average water content in the root zone is at wilting point during yield formation.

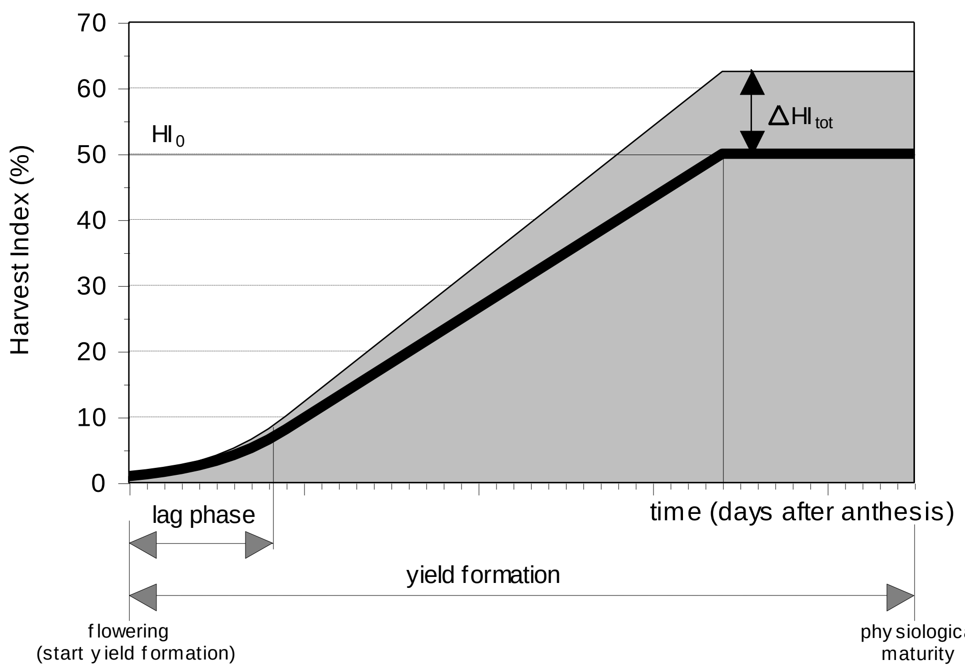


Figure 3.12p – Range (shaded area) in which the Harvest Index can increase or decrease as a result of water stress before and after the start of yield formation

3.12.8 Crop dry yield (Y_W) in weed infested fields

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

$$Y_W = HI\ B_W \qquad \text{(Eq. 3.12r)}$$

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

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

3.12.9 Dry and Fresh yield

In AquaCrop biomass (B) and crop yield (Y) are expressed as the mass of dry matter per unit of surface (ton/ha). The dry yield (Y_{dry}) is a fraction (f_m) of the fresh yield (Y_{fresh}). The fraction f_m, expresses the dry matter content of the fresh yield:

$$Y_{dry} = f_m\ Y_{fresh} \qquad \text{(Eq. 3.12s)}$$

The dry matter content is not a conservative crop parameter.

3.12.10 ET or Yield water productivity (WP_{ET})

In AquaCrop distinction is made between biomass water productivity (WP) and yield or ET water productivity (WP_{ET}):

- WP refers to the amount of biomass that can be obtained with a certain quantity of water transpired (see section 3.11 'Dry above-ground biomass');
- WP_{ET} is the ratio between crop yield and evapotranspiration. It is expressed as kg yield per m^3 of water evapotranspired. Yield (instead of biomass) is used since it is often the output in which one is most interested in. Evapotranspiration (ET) instead of crop transpiration is used since soil evaporation needs to be considered as well at field level, since water will evaporate from the crop and soil surface each time the soil is wetted by rainfall or irrigation (Fig. 3.12s).

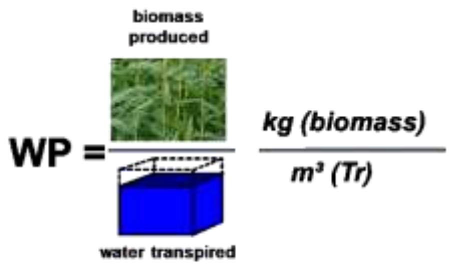
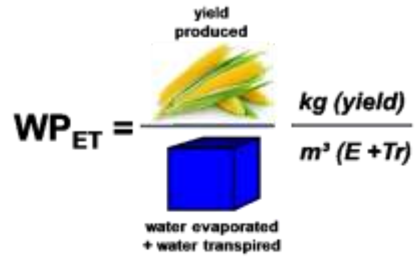
Biomass water productivity A constant relationship between biomass production and transpiration	**Yield or ET water productivity** A performance indicator of the crop system
	

Figure 3.12s – The biomass water productivity (WP) vs yield or ET water productivity (WP_{ET})

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

$$WP_{ET} = \frac{Y_w}{\left(E_{TOT} + Tr_{TOT}\right)} \qquad \text{(Eq. 3.12t)}$$

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

WP_{ET}, which is an output of AquaCrop when running simulations, 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 consumed (ET) can be maximized. This type of performance indicator is useful under conditions of scarcity of water resources.

One way to increase WP_{ET}, and as such the production of more marketable yield per unit of water evapo-transpired in the field, consists in reducing soil evaporation (which is in the denominator of the equation). Reducing soil evaporation, which is a non-productive consumption of water, can be achieved by mulches or by switching from traditional irrigation methods to drip irrigation, which only partially wets the soil surface. By running AquaCrop with and without the interventions, the increase in WP_{ET} can be quantified.

AquaCrop can also be used to quantify the effect of other irrigation, field and crop management strategies on WP_{ET} (more crop per drop) in water-scarce regions. Examples of strategies that can be analysed by AquaCrop are the effect of selecting a more suitable crop and/or cultivar for the region, altering the time for seeding/planting, adjusting the planting density to the rainfall and soil fertility, introducing deficit irrigation, limiting surface run-off of valuable rainwater from the field, improving weed management, etc.

3.13 Schematic outline of the model operation

The model operation as explained in this chapter is schematic depicted in Figure 3.13.

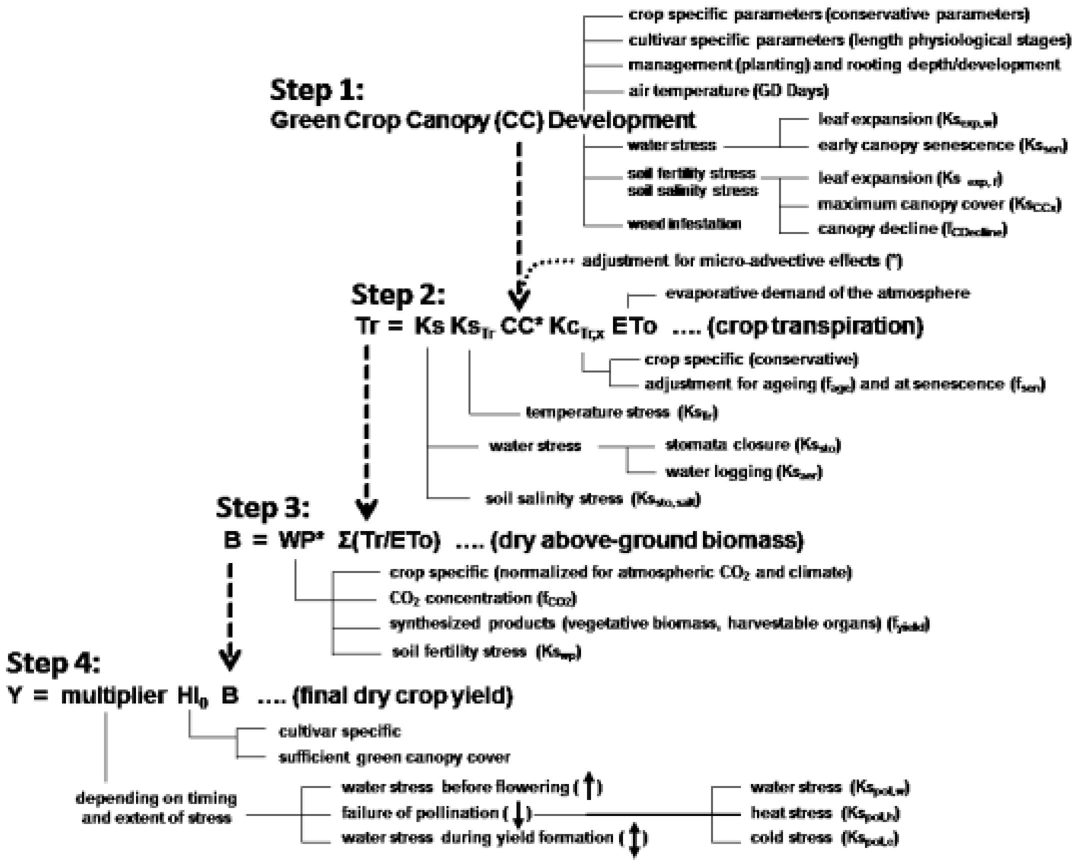


Figure 3.13 – Schematic outline of the model operation of AquaCrop

3.14 Simulation of the effect of soil fertility stress

3.14.1 Calibration of the crop response to soil fertility stress

To describe the effect of soil fertility stress on crop development and production, AquaCrop makes use of 4 stress coefficients (Table 3.14).

Table 3.14 - Soil fertility stress coefficients and their effect on crop growth

Soil fertility stress coefficient	Direct effect	Target model parameter
Ks_{CCx}: Stress coefficient for maximum Canopy Cover	Reduces canopy cover	CC_x
$Ks_{exp,f}$: Stress coefficient for canopy expansion	Reduces canopy expansion	CGC
$f_{CDecline}$: Decline coefficient of canopy cover	Decline of the canopy cover once the maximum canopy cover is reached	CC
Ks_{WP} : Stress coefficient for Biomass Water Productivity	Reduces biomass production	WP^*

The shape of each of the 4 soil fertility stress coefficients are fixed when calibrating the crop response to soil fertility stress (Fig. 3.14a). The calibration process is described in Chapter 2 (see 'Calibration for soil fertility stress') of the Reference Manual, by considering the effect of soil fertility stress in a stressed field. The calibration is done in the ***Crop characteristics*** menu.

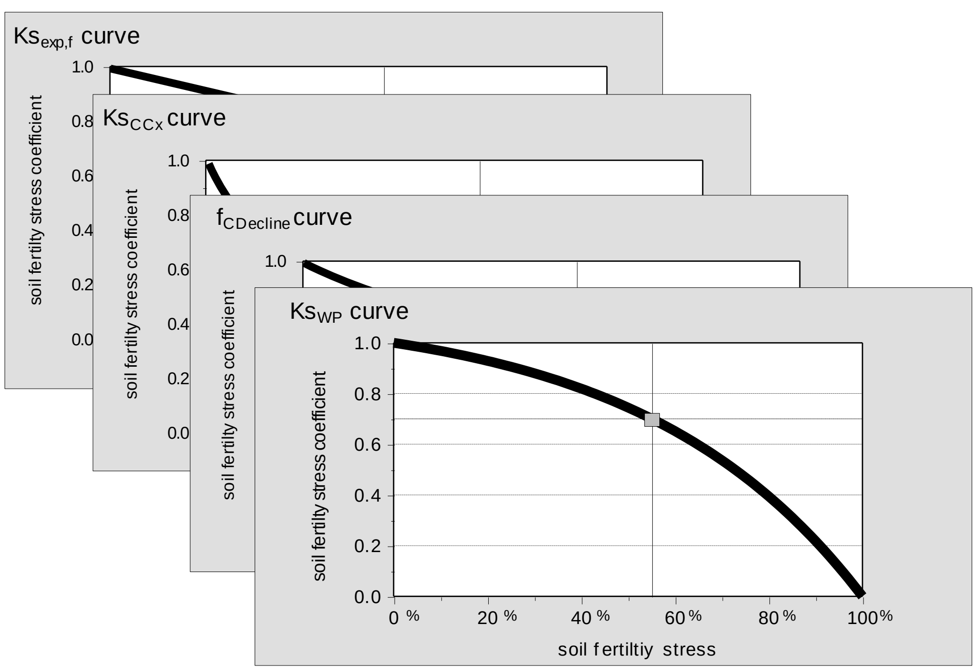


Figure 3.14a – The shape of the 4 Ks curves as determined by calibration

From the 4 calibrated Ks curves, the relation between Biomass and soil fertility stress (Fig. 3.14b) is obtained:

(i) by defining for various soil fertility stress levels the individual effect on (a) CGC, (b) CCx, (c) canopy decline, and on (d) WP* (as obtained from the 4 stress curves, Fig. 3.14a); and

(ii) by subsequently calculating for each of those soil fertility stress levels the corresponding biomass production (B) by considering the specific decrease of CGC, CCx, canopy decline and WP*.

Since the shapes of the 4 Ks curve are not necessary identical and the effect of stress on WP* increases when the canopy cover increases, the Biomass – soil fertility stress relationship is not linear (Fig. 3.14b).

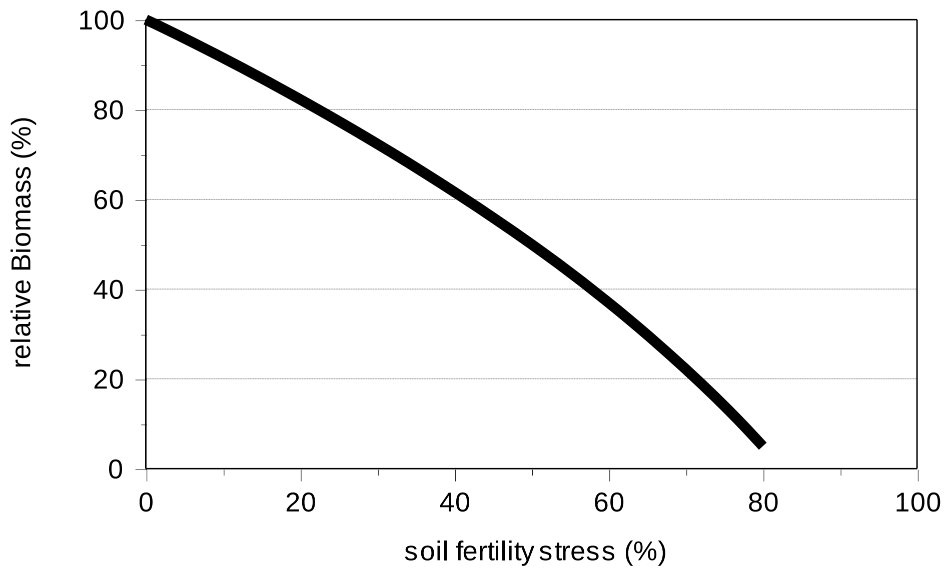


Figure 3.14b – Relationship between relative Biomass and soil fertility stress

3.14.2 Selection of a soil fertility level for simulation

In the ***Field management*** menu, the soil fertility level is specified indirectly when the user specifies the maximum *biomass* that can be expected in the field affected by soil fertility stress. The selected biomass is the biomass production that can be expected for the selected crop, for the given soil fertility level in the field, under the given climatic conditions, and in absence of any other stresses than soil fertility stress. It is the biomass that can be locally produced in a good rainy year or under irrigation when there is no water stress. This level of biomass might be available in statistical reports of local crop productions, or might be obtained from farmers. The selected biomass is expressed as a percentage of the biomass that can be obtained in the same field but for unlimited soil fertility.

From the relationship between relative Biomass and soil fertility stress (Fig. 3.14b), AquaCrop derives the ‘corresponding’ soil fertility stress in the field. This corresponding soil fertility stress level is required to know the corresponding values for each of the 4 stress coefficients. These values are derived from the shapes of the individual Ks curves (Fig. 3.14a).

3.14.3 Running a simulation

When running a simulation, AquaCrop considers the effect of soil fertility stress on canopy development and crop production with the help of the 4 stress coefficients and calculates at each time step the Biomass.

When due to soil water or soil salinity stress, the Biomass is less than what can be expected for the given soil fertility stress, AquaCrop decreases the soil fertility stress in its next time step(s). As such AquaCrop considers the rise in soil fertility because a water or salinity stressed crop is limited in its uptake of nutrients. The stronger the non-fertility stress, the more nutrients remain in the soil reservoir and the stronger the rise in soil fertility. If at a later stage the non-fertility stress is relieved by ample rainfall or irrigation, the soil fertility decreases since more nutrients are taken up by the crop and eventually returns to its original state if the Biomass production is in line with the one specified in the ***Field management*** menu. This dynamic adjustment of the soil fertility level makes that the effect of soil fertility stress is automatically adjusted to the effect of other stresses which affect the biomass production.

3.15 Simulation of the effect of soil salinity stress

The stress indicator for soil salinity in a well-watered soil is the average electrical conductivity of the soil-paste extract (ECe) in the root zone during the growing cycle. The electrical conductivity of the soil water (ECsw) will increase the effect of soil salinity, when the root zone depletion increases between wetting (rain and/or irrigation) events.

3.15.1 Soil salinity stress coefficient

The reduction of biomass production in a well-watered salt affected soil is described by a soil salinity stress coefficient (Table 3.15a).

Table 3.15a – Soil salinity stress coefficient and its effect on biomass production

Stress Coefficient	Direct effect	Target model parameter
Ks_{salt} : Soil salinity stress coefficient	Reduction of biomass production	Canopy cover (CGC, CCx and canopy decline) and Crop transpiration (stomatal closure)

The average electrical conductivity of the saturation soil-paste extract (ECe) from the root zone during the growing season is the indicator for soil salinity stress in a well-watered soil. At the lower threshold of soil salinity (ECe_n), Ks becomes smaller than 1 and the stress starts to affect biomass production. Ks becomes zero at the upper threshold for soil salinity (ECe_x) at which the soil salinity stress becomes so severe that biomass production ceases (Fig. 3.15a). The shape of the Ks curve is linear. Values for ECe_n and ECe_x for many agriculture crops are given by Ayers and Westcot (1985) in the Irrigation and Drainage Paper Nr. 29 and presented in Annex I.

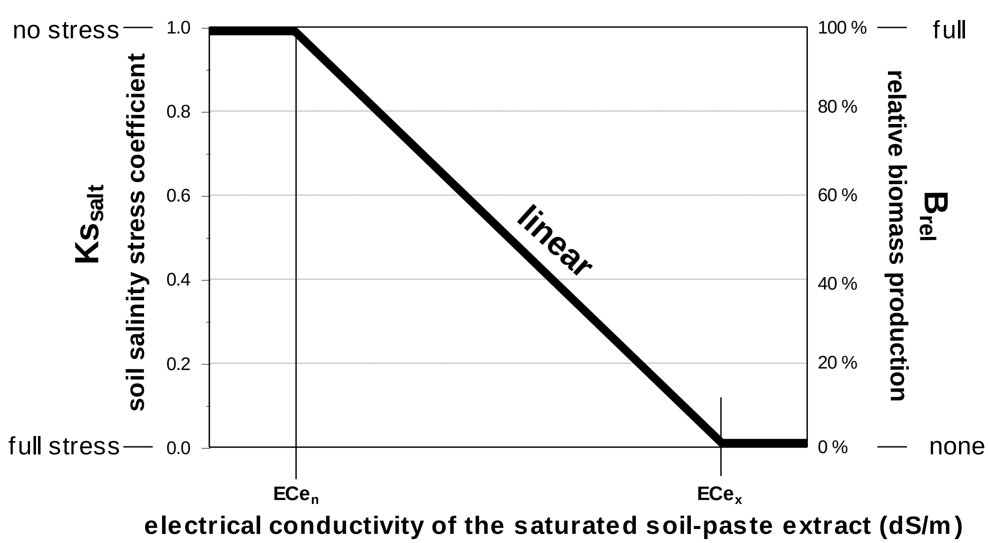


Figure 3.15a – The soil salinity stress (Ks_{salt}) and relative biomass production (Brel) for various electrical conductivity of the saturated soil-paste extract

3.15.2 Calibration of the crop response to soil salinity stress

The calibration process is described in Chapter 2 (see 'Calibration for soil salinity stress') of the Reference Manual, by considering the effect of soil salinity stress (i) in a well-watered soil, and (ii) when root zone depletion occurs. The calibration is done in the ***Crop characteristics*** menu.

- **Well-watered soil**

To describe the effect of soil salinity stress on crop development and production, AquaCrop makes use of 4 stress coefficients (Table 3.15b).

Table 3.15b - Soil salinity stress coefficients and their effect on crop growth

Soil salinity stress coefficient	Direct effect	Target model parameter
Ks_{CCx}: Stress coefficient for maximum Canopy Cover	Reduces canopy cover	CC_x
$Ks_{exp,f}$: Stress coefficient for canopy expansion	Reduces canopy expansion	CGC
$f_{CDecline}$: Decline coefficient of canopy cover	Decline of the canopy cover once the maximum canopy cover is reached	CC
$Ks_{sto,salt}$: Stress coefficient for stomatal closure	Reduces crop transpiration	Ks_{sto}

The shape of each of the 4 soil salinity stress coefficients are fixed when calibrating the crop response to soil salinity stress (expressed by ECe) in a well-watered soil (Fig. 3.15b).

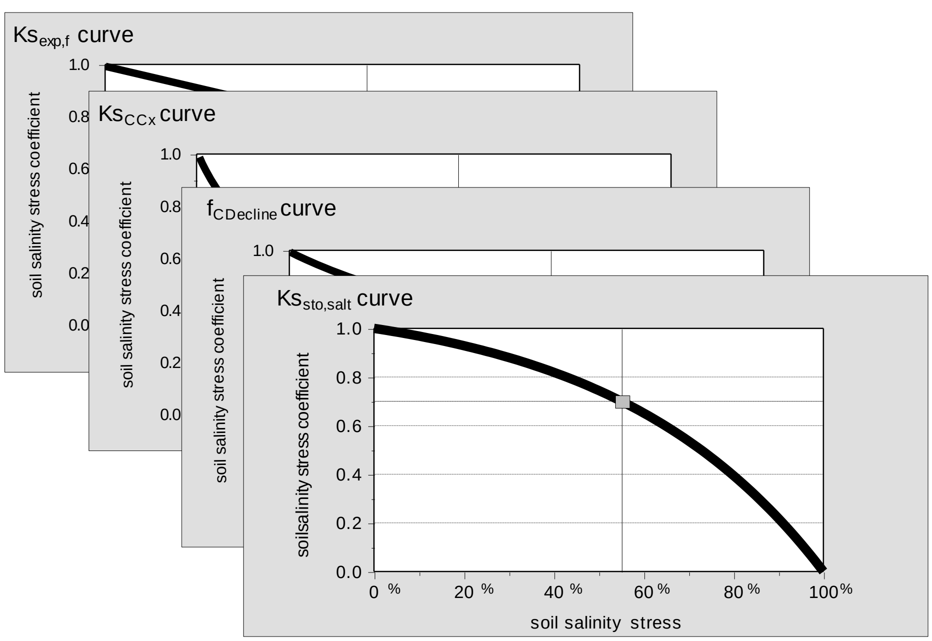


Figure 3.15b – The shape of the 4 Ks curves as determined by calibration in a well-watered soil

- **Root zone depletion**

When the soil is not well-watered, water depletion in the root zone results in an increase of the salt concentration in the remaining soil water. Although root zone depletion does not alter ECe (the indicator for soil salinity), it increases the electrical conductivity of the soil water (ECsw). The stronger the root zone depletion, the larger ECsw, and the more difficult it becomes for the crop to extract water from its root zone. This results in an stronger closure of the stomata when the soil dries out. The extra effect of ECsw on stomata closure is defined by calibration (Fig. 3.15c – effect 2).

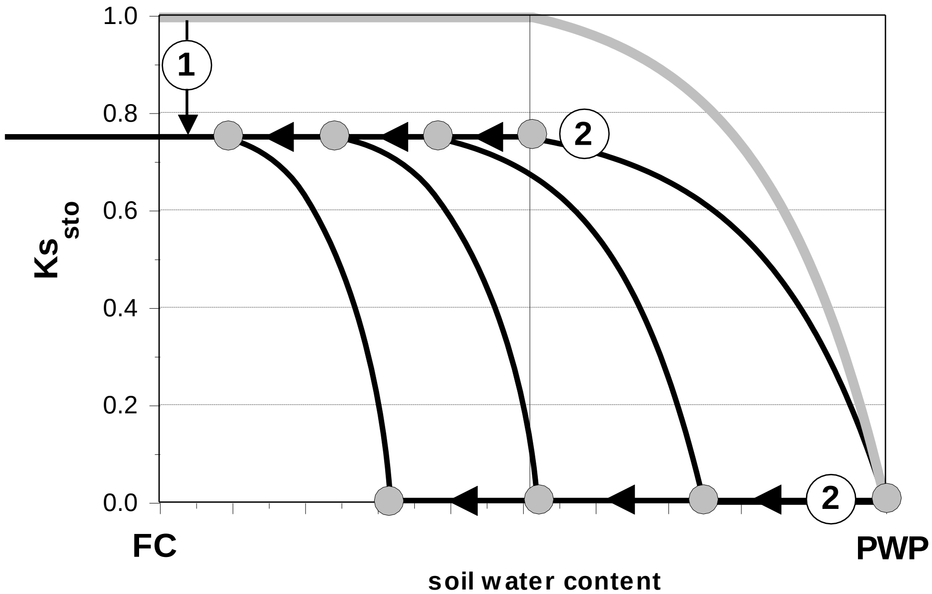


Fig. 3.15c – The soil water coefficient for stomatal closure (Ks_{sto}) without (gray line) and with (several alternative black lines) the effect of soil salinity stress. The decline of Ks_{sto} (effect 1) is linked with the effect of soil salinity stress in a well-watered soil (Fig. 3.15b), the shift of the upper and lower threshold (effect 2) is the effect of ECsw. The effect of ECsw on stomata closure (presented by the alternative black lines) is specified by calibration

3.15.3 Simulating the effect of soil salinity on biomass production

- **Well-watered soil:**

The average seasonal ECe (electrical conductivity of the soil-paste extract) in the root zone determines (Fig. 3.15a) the salinity stress (Ks_{salt}) and relative biomass production (B_{rel}):

$$B_{rel} = 100\ Ks_{salt} \qquad \text{(Eq. 3.15a)}$$

B_{rel} (percentage) expresses the expected biomass production under salt stress with reference to the maximal biomass that can be produced in the given environment in the absence of any other stress.

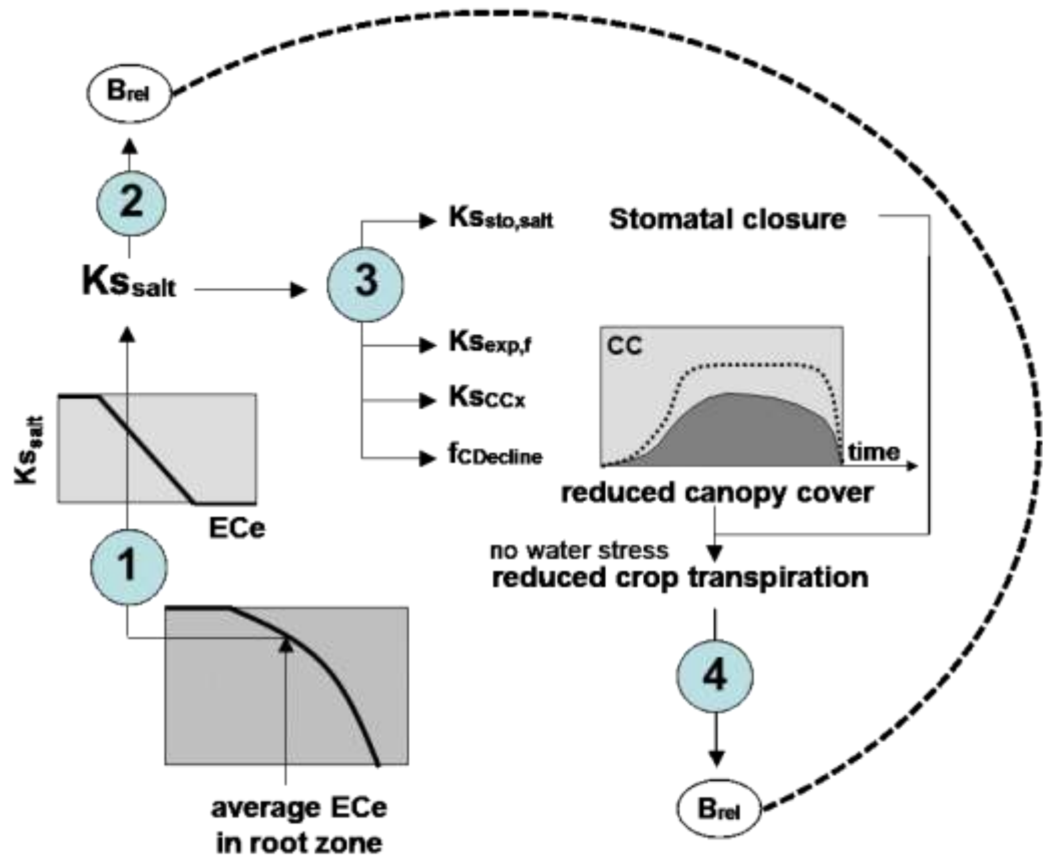


Figure 3.15d – The effect of soil salinity on biomass production in a well-watered soil with unlimited soil fertility

The relative biomass production is obtained by considering the calibrated effect on canopy development and of stomatal closure on crop transpiration in a well-watered soil. The calculation procedure is schematically depicted in Figure 3.15d and consists of the following 4 steps:

1. the average electrical conductivity of the saturation soil-paste extract (ECe) from the root zone determines the soil salinity stress (Ks_{salt}), as described in Fig. 3.15a;
2. the relative biomass (B_{rel}) that can be produced with the salinity stress (Ks_{salt}) is obtained by Eq. 3.15a;
3. the salinity stress (Ks_{salt}) determines (Fig. 3.15b) the value for (i) $Ks_{sto,salt}$ (resulting in stomatal closure and affecting crop transpiration, Tr), (ii) $Ks_{exp,f}$ (slowing down canopy development), (iii) Ks_{CCx} (reducing the maximum canopy cover) and (iv) $f_{CDecline}$ (triggering canopy decline) resulting in reduced canopy cover and reduced crop transpiration;
4. the reduced crop transpiration, results in a reduced biomass production. As a result of the calibration the resulting B_{rel} is identical to the expected B_{rel} (Eq. 3.15a) in the absence of soil water stress.

Changes in the average ECe in the root zone during the season require a continuous adjustment of Ks_{salt} (Fig. 3.15a) and the corresponding stress coefficients (Fig 3.15b): $Ks_{sto,salt}$, $Ks_{exp,f}$, Ks_{CCx}, and $f_{CDecline}$. However, since time is required to build up salts in the root zone (or to leach them out of the root zone) the adjustment of the stress coefficients remains modest throughout the simulation run.

The smaller canopy cover and stomatal closure as a result of salinity stress, results in a reduced crop transpiration which affects the soil water balance.

- **In presence of water-stress:**

Canopy development and crop transpiration might be further affected if next to soil salinity stress, also water stress develops during the growing season (Fig. 3.15e).

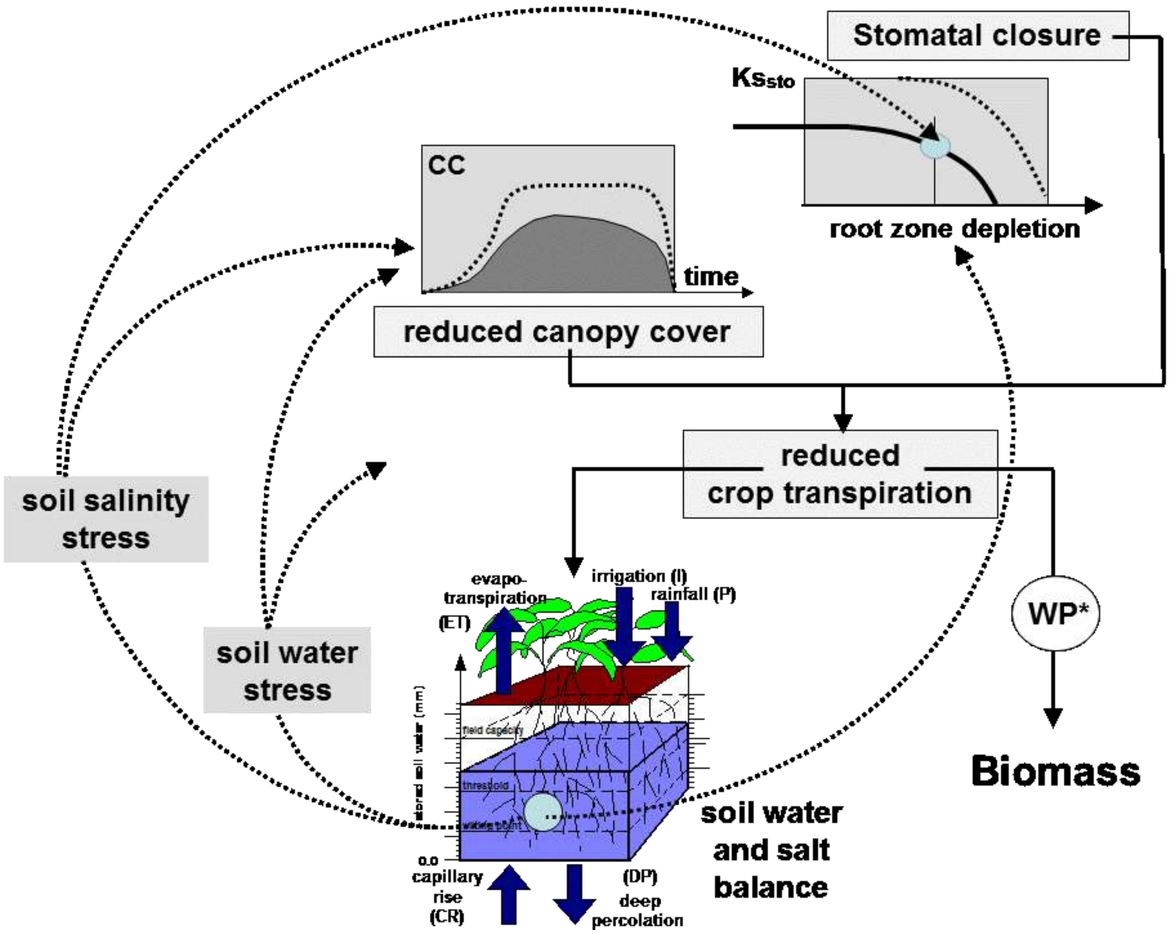


Figure 3.15e – The combined effect of soil salinity and soil water stress on canopy development, stomatal closure, crop transpiration and biomass production

3.16 Simulation of the combined effect of soil fertility and soil salinity stress

The effect of soil fertility and soil salinity stress on crop canopy (CC) development are not added up. If soil fertility and soil salinity stress affects CC, the resulting adjustment of canopy development at a time step, is determined by the strongest stress (corresponding with the lowest Ks value) at that moment (Fig.3.16).

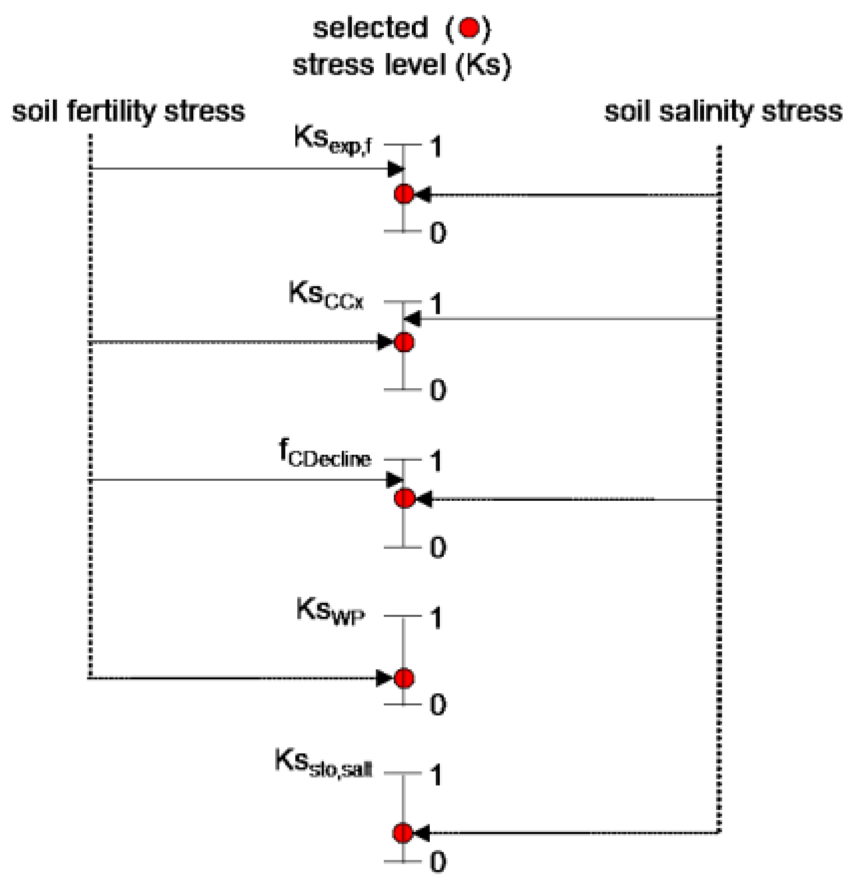


Figure 3.16 – Schematic outline of the combined effect of soil fertility and salinity stress on the values of the various stress coefficients: $Ks_{exp,f}$ (stress coefficient for canopy expansion); Ks_{CCx} (stress coefficient for maximum canopy cover); $f_{CDecline}$ (decline coefficient of canopy cover); Ks_{WP} (stress coefficient for biomass water productivity); $Ks_{sto,salt}$ (stress coefficient for stomatal closure);

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