3.1 *AquaCrop*: concepts, rationale and operation

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EVOLVING CONCEPTS IN YIELD RESPONSE TO WATER

Intercepted solar radiation is the driving force for both crop transpiration and photosynthesis. A direct relation exists therefore between biomass production and water consumed through transpiration. Water stress and reduced transpiration result in a reduced biomass production that normally also reduces yields. The yield response to water approach adopted in the FAO *Irrigation and Drainage Paper* No. 33 (Doorenbos and Kassam, 1979) linked a reduction in evapotranspiration to a proportional reduction in yield. As discussed in Chapter 2, the approach suffers drawbacks as a result of the aggregation of variables, i.e. final yield rather than its components and evapotranspiration rather than transpiration only. As a result, the yield response factor has proved, in several cases, to be significantly variable.

Maintaining the original concept of a direct link between crop water use and crop yield, the *AquaCrop* model evolved from the FAO *I&D Paper* No. 33 approach (Equation 1, Chapter 2) by separating non-productive soil evaporation (E) from productive crop transpiration (Tr) and estimating biomass production directly from actual crop transpiration through a water productivity parameter. The changes lead to the following equation, which is at the core of the *AquaCrop* growth engine:

$$B = WP \cdot \Sigma Tr \tag{1}$$

Where, B is the biomass produced cumulatively (kg per m^2), Tr is the crop transpiration (either mm or m^3 per unit surface), with the summation over the time period in which the biomass is produced, and WP is the water productivity parameter (either kg of biomass per m^2 and per mm, or kg of biomass per m^3 of water transpired).

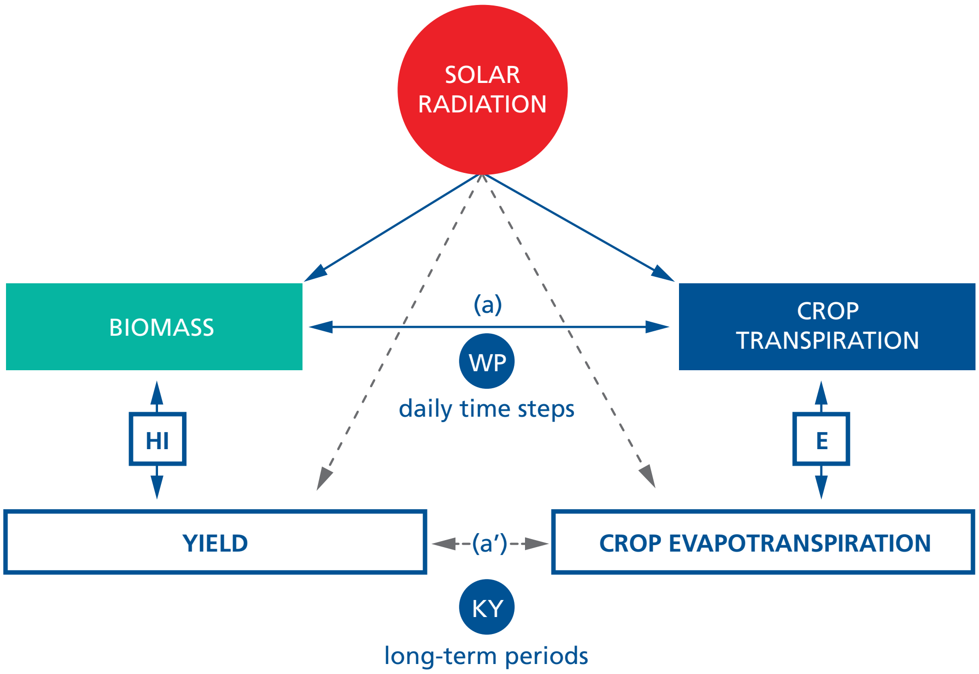
For most crops, only part of the biomass produced is partitioned to the harvested organs to give yield (Y), and the ratio of yield to biomass is known as harvest index (HI), hence:

$$Y = HI \cdot B \tag{2}$$

The underlying processes culminating in B and in HI are largely distinct from each other. Therefore, separation of Y into B and HI makes it possible to consider effects of environmental conditions and stresses on B and HI separately.

Understanding of crop-water-yield relationships has improved markedly since 1979 and made the step-up from Equation (1) of Chapter 2 to Equation (1) and (2) of this Chapter possible. WP, when normalized for evaporative demand, behaves conservatively (Steduto *et al*, 2007). That is, normalized WP (designated as WP*) remains virtually constant over a range of environments. This has fundamental implications for the robustness of the model, which is further enhanced by quantification of the harvest index day-by-day over the yield formation period. Improved knowledge of plant responses to water stress on short time scales (from second to hours), enhanced computation capacity, and more accurate procedures to determine daily soil water status made it possible to simulate in daily time steps. This allowed the important change from a static approach to a dynamic growth model. A schematic representation of the evolution of *AquaCrop* from Equation (1) of Chapter 2 to Equation (1) and (2) of this Chapter is shown in Figure 1.

FIGURE 1 Evolution of *AquaCrop* from Equation (1) of Chapter 2, based on the introduction of two intermediary steps: the separation of soil evaporation (E) from crop transpiration (Tr) and the attainment of yield (Y) from Biomass (B) and harvest index (HI). The relationship **(a')**, linking yield to crop evapotranspiration, is expressed through Equation (1) of Chapter 2 via the K_y parameter and normally applies to long-term periods. The relationship **(a)**, linking biomass to crop transpiration, is expressed through Equation (1) of this Chapter via the WP parameter and has a daily time step.



STRUCTURE AND COMPONENTS OF *AQUACROP*

AquaCrop is a dynamic model that simulates the attainable yield of herbaceous crops as a function of water consumption. In addition to its core functions, represented by equations (1) and (2), an extensive set of additional model components have been incorporated that includes:

- the **climate**, with its thermal regime, rainfall, evaporative demand and carbon dioxide concentration;
- the **crop**, with its development, growth and yield processes;

- the **soil**, with its water (and salt) balance;
- the **management,** with practices including irrigation, fertilization and mulching.

AquaCrop allows simulations of yield response to water under various management and environmental conditions, including climate change scenarios but, like most crop models, it does not account for the effects of pests and diseases.

These fundamental model components of *AquaCrop*, and their functions, are briefly described in this Section. For more detailed information, the user is referred to the *AquaCrop Reference Manual* (Raes *et al.*, 2011), which is regularly updated as the model develops.

The climate

The atmospheric environment is identified by four daily weather variables: maximum and minimum air temperatures (T_x and T_n, respectively), rainfall and the evaporative demand of the atmosphere expressed as reference evapotranspiration (ET_o) to be calculated according to the FAO Penman-Monteith equation (Allen *et al.*, 1998). In addition, the annual mean carbon dioxide concentration (CO_2) of the atmosphere is required. Temperature influences crop development (phenology). Additional effects of more extreme temperatures are reduction of WP (hence biomass accumulation) when it is too cold, and reduction in pollination (hence HI) when it is either too cold or too hot. Rainfall, irrigation and ET_o are determinants of water balance of the soil root zone and water stress. Atmospheric CO_2 concentration affects WP, canopy expansion and stomatal conductance. T_x, T_n, ET_o and rainfall are derived from typical records of agrometeorological stations. Aside from its continuous rise over years, atmospheric CO_2 varies with an annual cycle and also with location. These variation are small and of minimal significance in terms of impact on crops. For simplicity, *AquaCrop* provides as default values the annual mean atmospheric CO_2 concentration from 1902 to the last year measured at Mauna Loa Observatory in Hawaii. Users may enter their own data set or the forecasted CO_2 following pre-determined climate change scenarios.

The crop

The crop component of the model includes the following subcomponents: phenology, canopy cover, rooting depth, crop transpiration, soil evaporation, biomass production, and harvestable yield.

After emergence, the crop grows and develops over its growth cycle by expanding its canopy and deepening its root system, transpiring water and cumulating biomass, while progressing through its phenological stages. The harvest index (HI) alters the portion of biomass that will be harvestable. It is important to note that in *AquaCrop*, beyond the partitioning of biomass into yield, there is no other partitioning among the various plant organs. This choice avoids dealing with the complexity and uncertainties associated with the partitioning processes, which remain among the most difficult to model. The relationships between root and shoot (biomass) or canopy in *AquaCrop* are not direct. Instead, root deepening rate is slowed by an empirical function once the stress becomes severe enough to initiate partial stomatal closure.

Phenology

The stages of crop development and their duration are characteristics frequently differentiating cultivars of the same crop from each other, and needs to be specified by the user for the cultivar in question. *AquaCrop* uses the *growing degree days* (GDD) as the internal default clock to account for effects of temperature regimes on phenology. The simulation runs and displays, however, in daily (calendar) time step. GDD is calculated following procedures described by McMaster and Wilhelm (1997), but with the exception that the minimum temperature (T_n) is not changed to be equal to the base temperature when it drops below the base temperature in the calculation. This is believed to represent better the damaging or inhibitory effects of cold on plant processes.

AquaCrop is applicable to all major herbaceous crop types: fruit or grain crops; root and tuber or storage-stem crops; leafy or floral vegetable crops, and forage crops typically subjected to several cuttings per season. For all but forage crops, the key developmental stages are: emergence, start of flowering (anthesis) or root/tuber/storage-stem initiation, time when maximum rooting depth is reached, start of canopy senescence, and physiological maturity. For forage cops, the list may be shortened to only emergence or start of regrowth in spring, time of cuttings, and start of senescence.

Genetic differences among species require calibration of the model for each species. Although some crop cultivars may require some adjustment of parameters in the calibrated model, in addition to phenology, calibration and validation using data from different studies in different parts of the world have given confidence that most of the fundamental parameters considered to be conservative (virtually constant) will be applicable even to different cultivars. The calibrated parameters available should at least serve as solid starting values, and can be adjusted if good data sets, used to test the values, indicate clearly a need. In this regard, it must be pointed out that calibrations should be done with data obtained from crops grown without any mineral nutrient limitation, as deficiencies of major nutrients (N, P, and K) do alter, to some extent, a number of the conservative parameters in *AquaCrop*.

Canopy development

Canopy cover (CC), more precisely green canopy cover, is a crucial feature of *AquaCrop*. Its expansion, ageing, and senescence, along with its conductance as controlled by stomata, determine the amount of water transpired, which in turn determines the amount of biomass produced. Expressing amount of foliage in terms of canopy cover (in fraction or percentage) and not as leaf area index (LAI) is one of the distinctive features of *AquaCrop*. This results in a significant simplification of the simulation, allowing the user to enter actual values of CC, even if only estimated visually. Moreover, CC is easily obtained from remote-sensing sources, either to check the simulated CC or as input for *AquaCrop*.

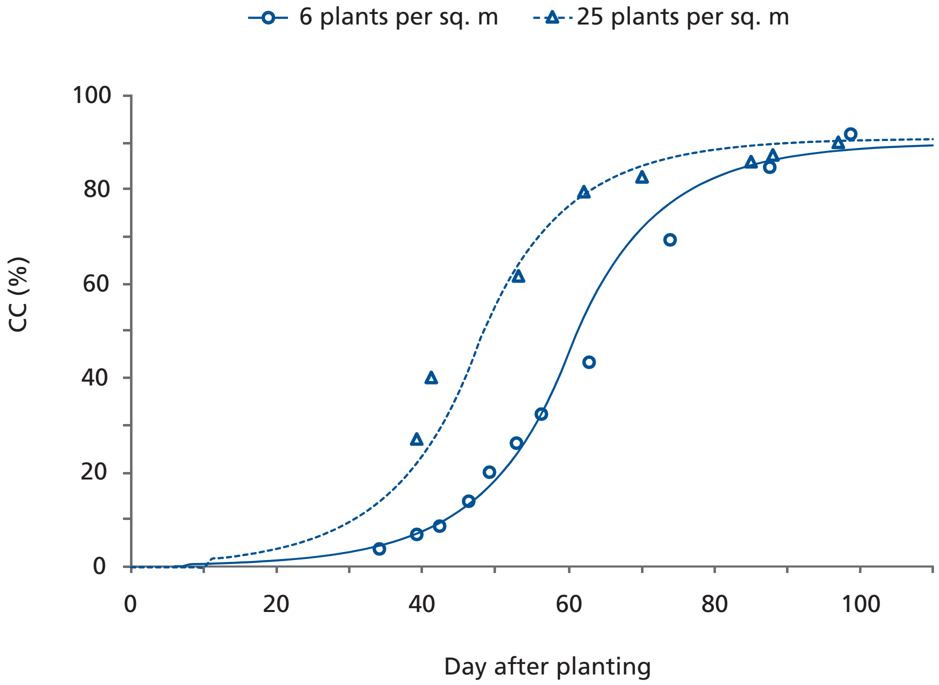
For the first half of the CC increase or development curve, an exponential equation, analogous to the equation for relative growth rate, is used for the simulation. Specifically,

$$CC = CC_O \cdot e^{CGC \cdot t} \tag{3}$$

where CC is the fractional coverage of the soil by the canopy at time t, CC_o is initial CC (at t = 0) also in fraction, and CGC is canopy growth coefficient in fraction or percentage of existing CC at time t. CC_o is a composite of canopies of individual plants and is calculated by multiplying plant density by the mean canopy size per plant (cc_o). This feature is used by the model to account for effects of plant density on canopy size. For simulations starting at emergence, cc_o is defined as the canopy size for the average seedling at the time of 90 percent emergence. For a number of crop species the value of cc_o has been assessed and found to be conservative; only small adjustments may be required for specific cultivars. CGC is also conservative, as long as time is expressed as GDD. This was demonstrated for a number of crop species when the same CGC gave good prediction of canopy development over time for a number of cultivars at different locations around the world (e.g. Hsiao *et al.*, 2009; Heng *et al.*, 2009, for maize).

CC calculated with Equation (3) over the canopy development period is compared with measured values in Figure 2. Also shown is the difference in canopy development due to plant density. As noted earlier, the fact that CC_o is the product of cc_o and plant density provides a simply but fundamentally based procedure to account for variations in density.

FIGURE 2 An example of canopy development simulated with Equation 3 and 4 (lines) as compared with measured canopy data (symbols), for two different cotton plant densities. Dashed and solid lines represent 25 and 6 plants/m^2, respectively. Simulations were run with the same CGC and cc_o. The measured data were obtained from two different cultivars, one at low density and the other at high density, grown in different years at two different locations in California. Source: T.C. Hsiao and R. Radulovich, unpublished data.



The concept underlying Equation (3) (Bradford and Hsiao, 1982) is based on the reasoning that when green canopy cover is sparse, the growth of canopy, being dependent on the existing canopy size to capture radiation and carry out photosynthesis, should be proportional to the canopy size existing on that day. This led to the use of an exponential growth equation with a constant coefficient to simulate canopy development up to half of the maximum CC. When canopy grows further and covers more than half of the soil, radiation capture and photosynthesis begin to increase less than in proportion to the increase in CC because of mutual shading among the plants.

Therefore, Equation (3) no longer applies and for the second half of canopy development, CC follows an exponential decay equation,

$$CC = CC_x - (CC_x - CC_0) \cdot e^{-CGC \cdot t} \tag{4}$$

where CC_x is the maximum canopy cover for optimal conditions. *AquaCrop* simulates with Equation (3) up to the point when CC = 0.5 CC_x, then switches to simulate with Equation (4) until CC_x is reached. Default values for CC_x are provided for the calibrated crops, based on various studies. Since CC_x is determined also by plant density, a farm management option, the user should adjust the default CC_x to the actual field situation.

As the crop approaches maturity, CC enters a declining phase resulting from leaf senescence. The decline of green canopy cover in *AquaCrop* is characterized by an empirical canopy decline coefficient (CDC), with units of fractional reduction in CC per unit of time, and can be adjusted to either lengthen or shorten the time span required to go from the start of senescence to the time when no green canopy remains (CC = 0).

The starting time for canopy senescence is critical because it determines the duration of the canopy when it is most effective in photosynthesis. As senescence starts both transpiration and photosynthesis decline, and biomass accumulations slow. Canopy senescence should be considered to start at the time when leaf senescence (indicated by yellowing) becomes significant, but only when canopy cover of the soil is incomplete and LAI is no more than 3 to 4.

Calibration of senescence requires accurate field observation or measurement of LAI during the late phase near maturity, as there is no effective way to assess green canopy cover during this phase because of the interference by the yellow or dead leaves. LAI can be converted to CC using equations in the literature arrived at by regressing CC against LAI (see Section 3.3). The progression of CC over a full crop cycle under non-stress conditions, as simulated with Equation (3) and (4) and CDC, and as measured on a crop, is depicted in Figure 3.

Root deepening

Root water uptake in *AquaCrop* is simulated by defining effective rooting depth (Z_e) and the water extraction pattern. Z_e at planting to near emergence is the soil depth from which the germinating seed or the young seedling can extract water. For water balance calculation by *AquaCrop*, a minimum effective rooting depth of 0.2 to 0.3 m (Z_n) at the beginning is generally considered appropriate. Studies show that under favourable conditions, roots deepen at a relatively constant rate up to the time when fruit/grain begin to accumulate the major portion of photosynthetic assimilates. At this time root deepening is likely to slow. *AquaCrop* simulates this with an exponential function that makes the deepening of the root zone faster after planting in an early stage than later in the life-cycle of the crop (Figure 4).

Under optimal conditions, with no soil restrictions, the maximum effective rooting depth (Z_x) is expected to be reached near the end of the crop's life cycle, around the beginning of canopy senescence. If, at a certain depth, a soil layer is restricting root growth, roots will deepen at the normal rate until the restrictive layer is reached and then stops completely (Figure 4). Also a shallow groundwater table will limit rooting to the depth of the water table.

FIGURE 3 An example of the progress of green canopy cover through a crop life-cycle under non-stress conditions, for maize.

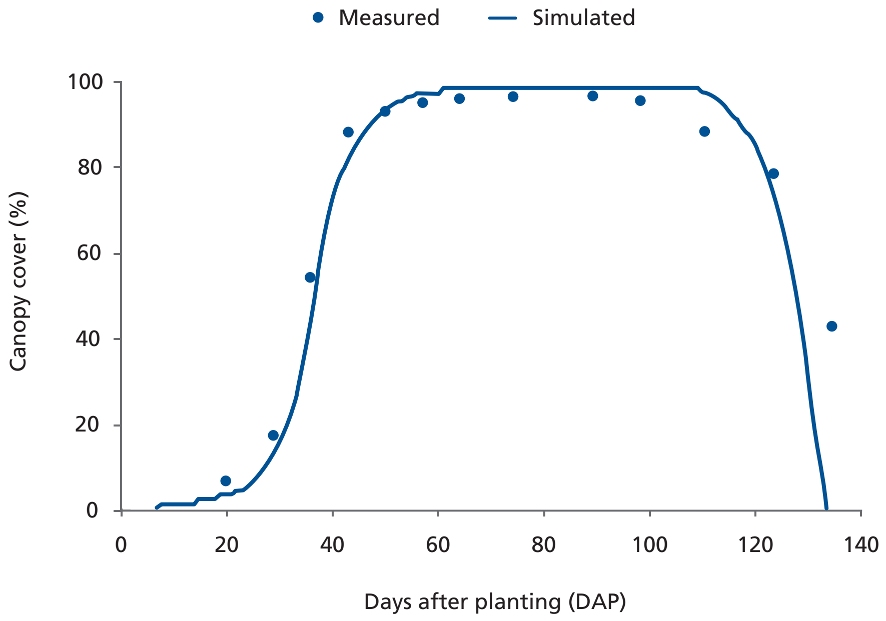
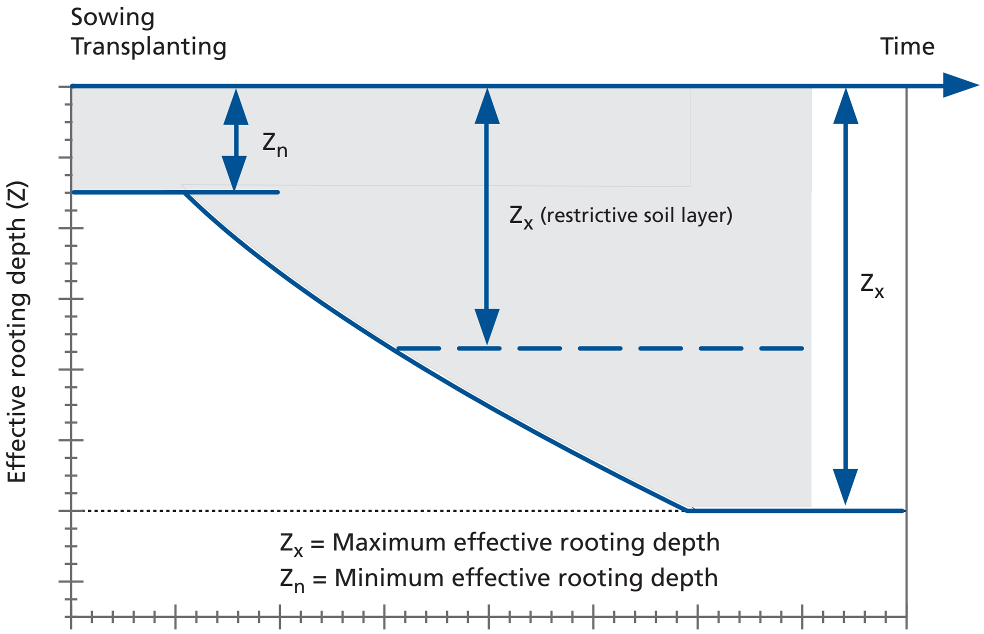


FIGURE 4 Schematic representation of a generalized rooting depth with time, in the presence (dashed line) and absence (full line) of a restrictive soil layer limiting root development.



Water extraction by roots follows the common pattern used in simulations. Namely, 40 percent, 30 percent, 20 percent, and 10 percent of the required water is taken from the upper to the lower quarter of Z_e, when water content is adequate. The pattern can be changed by the user, in cases warranted by specific physical or chemical characteristics of the soil.

Crop transpiration

Transpiration per unit land area is dependent on the fraction of land area covered by the canopy (CC) when there is insufficient stress to limit stomatal opening. The dependence is not strictly linear, because inter-row micro-advection supplies energy to the canopy in addition to that supplied by radiation, causing Tr to be somewhat more than being proportional to CC when CC is substantially incomplete. *AquaCrop* adjusts for this by assuming a slightly larger effective canopy cover with an empirical equation, developed from literature data. Tr is calculated from ET_o with crop transpiration coefficient, denoted by $K_{c,Trx}$, defined as the crop coefficient (K_c) for transpiration when the canopy fully covers the ground (CC is close to and approaching 1.0) and stresses are absent. The effective CC is then multiplied by $K_{c,Trx}$ and ET_o to arrive at Tr. Restriction of Tr by water stress is elaborated on later in this section.

After maximum canopy cover (CC_x) is reached and before the onset of senescence, the canopy ages slowly and undergoes a progressive though small reduction in transpiration and photosynthetic capacity. This is simulated by applying an ageing coefficient (f_{age}) that decreases $K_{c,Trx}$ by a constant and slight fraction (e.g. 0.3 percent) per day. After senescence is triggered, transpiration and photosynthetic capacity of the canopy drop more markedly with time.

Soil evaporation

Evaporation is mostly from the wetted soil surface unshaded by the canopy. *AquaCrop* calculates soil evaporation (E) separately from Tr, and for simplicity assumes that E takes place only from unshaded soil and is slightly less than being proportional to (1-CC) as the results of the adjustment for inter-row advection. The other key factor determining E is the wetness of the soil surface layer. When the soil surface is fully wet, E proceeds at the potential rate determined by the energy supply, and is about 10 percent more than the rate of ET_o. This phase is known as Stage I evaporation and lasts from less than to a little more than 1 day, and can be adjusted in the model. As the soil surface begins to dry and water vapour pressure at the surface drops, E declines exponentially with the decline of the soil water in the top soil (a very thin surface layer). This phase is known as Stage II evaporation. *AquaCrop* simulate this by multiplying the potential E rate with an exponentially declining coefficient.

As the canopy senesces, it still shades the soil, but not as effectively, because canopy structure begins to disintegrate and dead leaves may be lost. The model continues to base soil E on CC_x, but applies a simple factor to reduce the sheltering effect of the dying canopy.

Biomass production

The biomass water productivity (WP) is central to the operation of *AquaCrop* (Equation 1) and has shown a remarkable conservative behaviour (remaining nearly constant) when normalized for different evaporative demands. This has been demonstrated already in early studies of, among others, de Wit (1958) and was further advanced in studies by Tanner and Sinclair (1983), Hsiao and Bradford (1983) and Steduto *et al.* (2007).

The WP parameter introduced in *AquaCrop* is normalized for atmospheric evaporative demand, defined by ET_o, and for the CO_2 concentration of the atmosphere. The normalized biomass water productivity (WP*) proved to be nearly constant for a given crop when mineral nutrients are not limiting, regardless of water stress except for extremely severe cases. Calibration of WP and normalization for evaporative demands has been based on the equation:

$$WP^* = \left[\frac{B}{\sum\left(\frac{Tr}{ET_O}\right)} \right]_{[CO_2]} \tag{5}$$

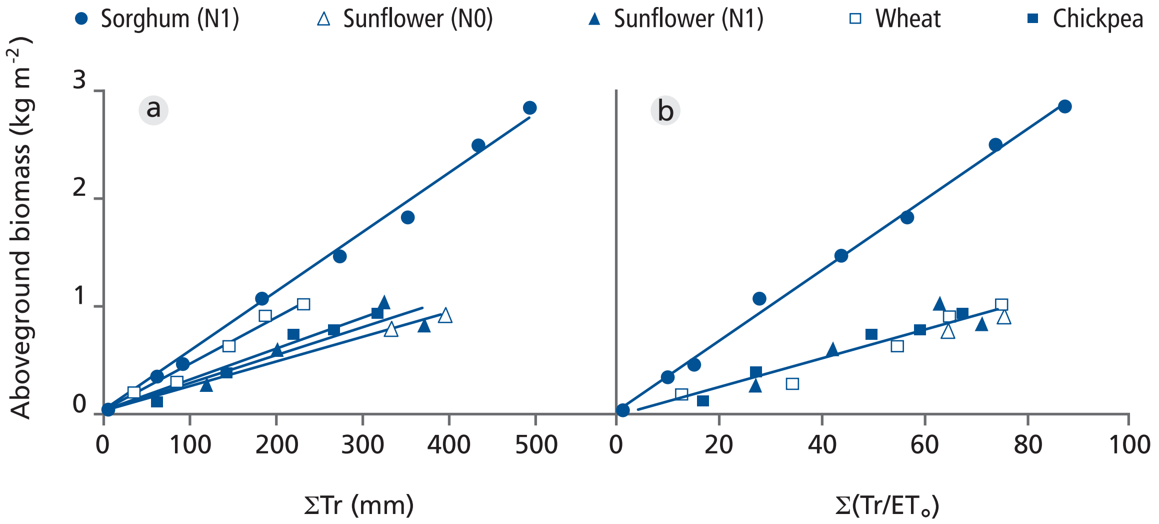
The summation is taken over the time intervals spanning the period when B is produced. $[CO_2]$ outside the bracket indicates that the normalized value is for a particular air CO_2 concentration. For most crop species, WP* increases as air CO_2 concentration increases, allowing the simulation of impact on yield under various CO_2 and climate change scenarios. The equation is directly applicable when Tr and ET_o data are for daily time intervals. When Tr and ET_o are available for time interval larger than daily, the normalization requires caution. Background information and more details on normalization, including that for CO_2 concentration, are given in Steduto *et al.* (2007).

In the literature WP is commonly normalized for evaporative demand using air vapour pressure deficit (VPD) instead of ET_o. The choice of using ET_o was made because it has been demonstrated to be superior and accounts for advective energy transfer, which is ignored using VPD (Steduto *et al.*, 2007). WP* is conservative for a given level of mineral nutrition, but may be reduced by nutrient deficiencies, particularly nitrogen. The calibrated WP* in the model for various crops are for situations where nutrients are ample. For nutrient limited situations, the model provides categories of soil fertility stress ranging from mild to severe nutrient deficiencies, with corresponding lower default WP* values.

The conservative nature of WP* is demonstrated in Figure 5, where cumulative B vs. cumulative Tr are plotted in (a), and cumulative B vs. cumulative normalized Tr (Tr/ET_o) in (b), over the season for sweet sorghum (a C_4 crop), sunflower, wheat and chickpea (all three are C_3). It is seen in Figure 5a that the regression lines for different crops are linear but with different slopes. This means WP is constant for each crop but differs among the crops. In Figure 5b it is seen that normalization by ET_o has coalesced the lines for the three C_3 crops into one, meaning their WP* are very similar. In this study sunflower was grown in May-August, wheat in February-May, and chickpea in April-June. So growth of these crops occurred in periods differing in atmospheric evaporative demand. Normalizing by ET_o accounted for the difference in evaporative demand and showed that the three crops have very similar intrinsic water productivity (very similar WP*).

The single value of WP*, as show in Figure 5b, is used for the entire crop cycle for most of the crops. However, for crops with yields high in fat and protein content, more photosynthetic assimilates or energy is required per unit of dry matter produced after flowering and during the grain/fruit filling stage. For such crops, *AquaCrop* uses a single value for the WP* up to flowering, then declining gradually towards a lower WP* value to account for yield composition.

FIGURE 5 Relationship (a) between aboveground biomass and cumulative transpiration (ΣTr) and (b) between aboveground biomass and cumulative normalized transpiration [$\Sigma(Tr/ET_o)$], during the cropcycle of sunflower (under two N levels and up to anthesis), sorghum, wheat, and chickpea (redrawn from Steduto and Albrizio, 2005).



Harvestable yield

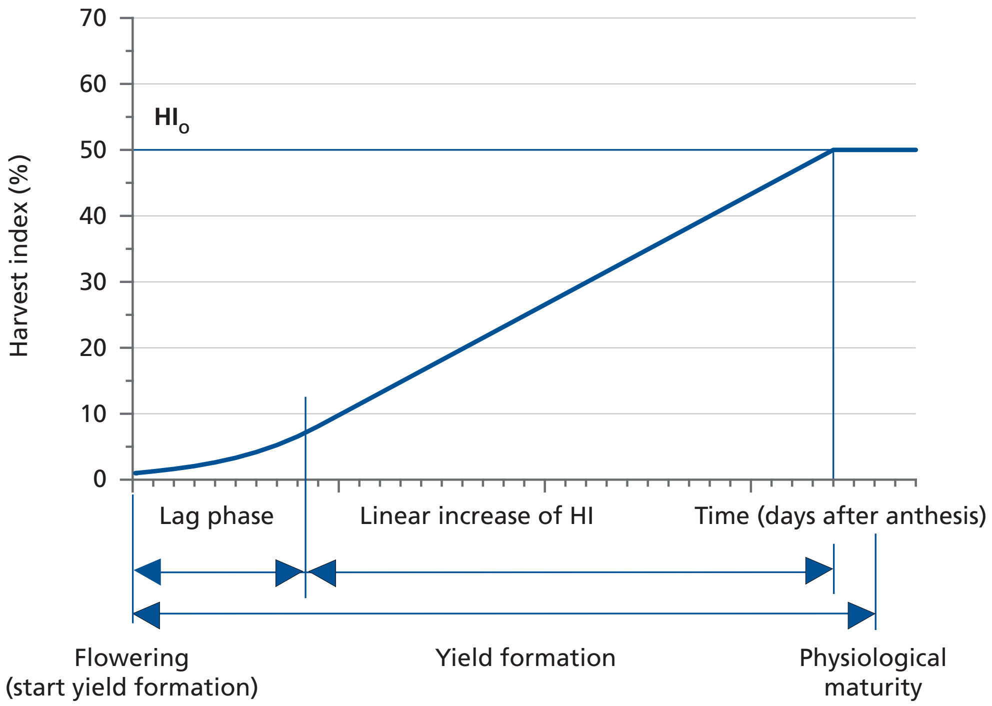
The partition of biomass into yield part (Y) is simulated by means of a harvest index (HI). For fruit or grain crops, published data on different species indicate there is a linear increase with time in the ratio of fruit or grain biomass to total above-ground biomass, from the time not too long after pollination and fruit set until maturity or near maturity. In common usage, HI is this ratio at maturity or harvest time. In *AquaCrop*, this ratio at earlier stages is also referred to as HI, for simplicity. For fruit/grain crops, HI is set to increase from zero at flowering, first over a short lag phase, when the increase starts slowly but accelerates with time, followed by a steady phase with the highest, but at constant rate of, increase (Figure 6). For root/tuber crops, HI is the ratio of the storage organ biomass to the total biomass (root plus shoot). The limited published data on root/tuber crops indicate that instead of increasing linearly after a lag phase, HI increases quickly shortly after storage organ initiation, then gradually slows until maturity. So HI is described by a logistic curve for these crops.

A reference point is needed for the upper range of HI. This point, termed reference HI (HI_o), is the HI representative of well-developed cultivars adapted to their environments and grown under optimal conditions without limiting inputs. Calibrated HI_o can be changed based on good data for a particular cultivar. The progression of HI for fruit/grain crops is exemplified in Figure 6.

The soil

In *AquaCrop* the soil is described by a soil profile and the characteristics of the groundwater table (if any). In *AquaCrop* the soil can be subdivided vertically up to five layers of variable depth, each layer (or horizon) accommodating different soil physical characteristics: the soil-water content at saturation; the upper limit of water content under gravity (commonly referred as field capacity (FC) for easy of reference); the lower limit of water content where a crop can reach the permanent wilting point (PWP); and the hydraulic conductivity at saturation (K_{sat}). From these characteristics *AquaCrop* derives other parameters governing soil evaporation,

FIGURE 6 Building up of harvest index from flowering until physiological maturity for fruit and grain producing crops with indication of the reference harvest index (HI_o).



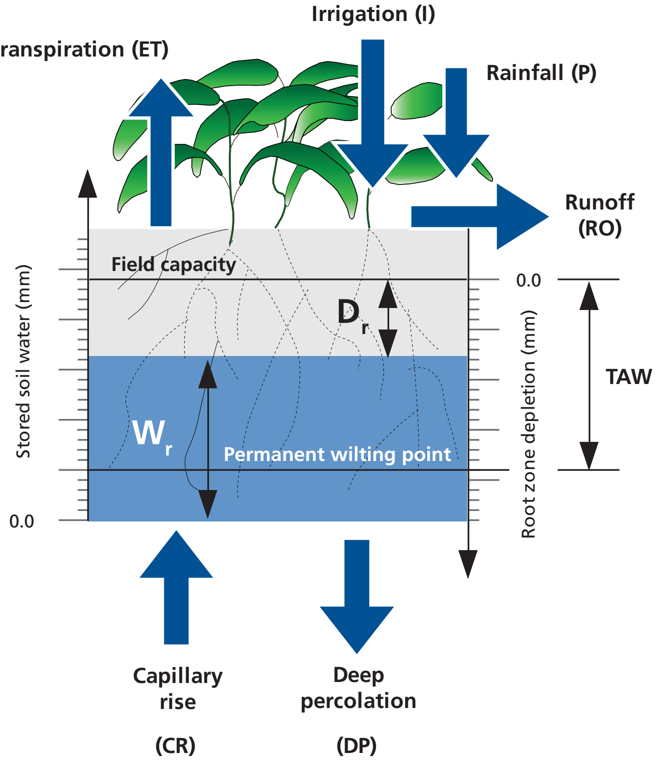
internal drainage and deep percolation, surface runoff, and capillary rise. The considered characteristics of the groundwater table are its depth below the soil surface and its salinity. The characteristics can remain constant during the season or vary throughout the simulation period.

By keeping track of the incoming (rainfall, irrigation and capillary rise) and outgoing (runoff, evapotranspiration and deep percolation) water and salt fluxes at the boundaries of the root zone, the amount of water and salt retained in the root zone can be calculated at any moment of the season (Figure 7).

When calculating the soil-water balance, the amount of water stored in the root zone can be expressed as an equivalent water depth (Wr) or as root zone depletion (D_r). The total available soil water (TAW) is the amount of water held in the root zone between field capacity and permanent wilting point. At field capacity root zone depletion (D_r) is zero, and at permanent wilting point Dr is equal to TAW.

To accurately describe surface runoff, the retention and movement of water and salt in the soil profile, soil evaporation and crop transpiration throughout the simulation period, *AquaCrop* divides both the soil profile and time into small fractions. *AquaCrop* divides the soil profile into 12 soil compartments with thickness Δz and runs with a time step Δt of 1 day. As such the one-dimensional vertical water and salt flow and root water uptake can be solved by means of a finite difference technique. Each of the 12 soil compartment has the hydraulic characteristics of the soil layer to which it belongs (Figure 8). The default size of the compartments (0.10 m) is automatically adjusted to cover the entire root zone. For deep root zones, ΔZ is not constant

FIGURE 7 The root zone depicted as a reservoir with indication of the equivalent water depth (Wr) and root zone depletion (D_r).

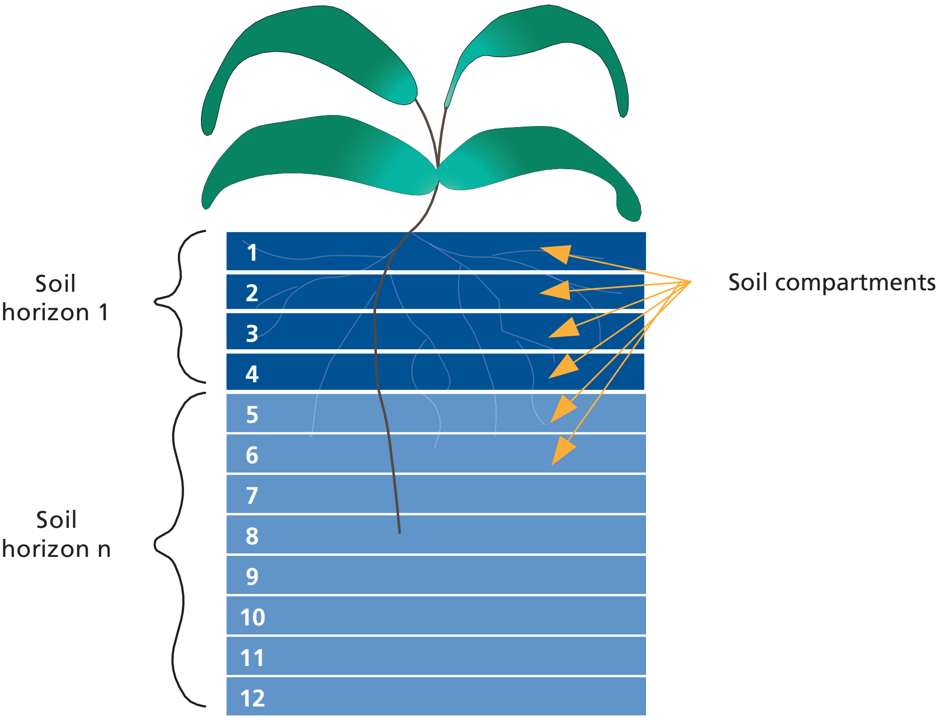


but increases exponentially with depth, so that infiltration, evaporation and transpiration from the top soil layers can be described with sufficient detail.

To simulate water movement in and out of the soil profile, *AquaCrop* considers surface runoff, infiltration, capillary rise, soil evaporation and crop transpiration. 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 an exponential drainage function that describes the declining water movement between saturation and field capacity. Upward water movement from a groundwater table to the soil profile is described by an exponential relationship between the capacity for capillary rise and the height above the groundwater table. The amount of water that moves upward depends not only on the depth of the groundwater table but also on the wetness of the top soil and the hydraulic characteristics of the soil layers. By considering the water fluxes in response to the processes listed above, the soil-water content is updated at the end of the daily time step in each of the 12 compartments (for full details see Raes *et al.*, 2011).

While performing the water balance, *AquaCrop* also deploys the salt balance. Salts enter the soil profile by capillary rise from a saline groundwater table or together with the irrigation water. Salts are leached out of the soil profile by excessive rainfall or irrigation. Vertical salt movement in a soil profile is described by assuming that salts are transferred downwards by soil-water flow in macro pores as simulated by the drainage function. Since the solute transport in the macro pores bypass the soil water in the matrix, a diffusion process is considered to describe the transfer of solutes from macro pores to the soil matrix. Therefore the soil

FIGURE 8 A soil profile with more than one soil horizon and 12 soil compartments. The total number of compartments remains always 12, regardless of the number of horizon (varying from 1 to 5).



compartments are divided into a number of cells where salts can be figuratively stored. A cell is a representation of a bundle of pores with a specific diameter. The driving force for the horizontal diffusion is the salt concentration gradient that exists between the water solution in the cells at a particular soil depth. To avoid the building up of high salt concentrations at a particular depth, vertical salt diffusion is also taken into account. The driving force for this vertical redistribution process is the salt concentration gradient that builds up at various soil depths in the soil matrix.

The management

AquaCrop encompasses two categories of **management** practices: the **irrigation management**, which is quite complete in its various features, and the **field management**, which is limited to selected aspects and is relatively simple in approaches.

Irrigation management

Here options are provided to assess and analyse crop production and water management and use, under either rainfed or irrigated conditions. Management options include the selection of water application methods (sprinkler, surface, or drip either surface or underground), defining the schedule by specifying the time, depth and quality of the irrigation water of each application, or let the model automatically generate the schedule based on fixed time interval, fixed depth per application, or fixed percentage of allowable water depletion. An additional feature is the estimation of full water requirement of a crop in a given climate.

Field management

Three aspects are considered here: (i) fertility of the soil for growing the crop, whether native or by fertilization; (ii) mulching of the soil to reduce soil evaporation; and (iii) use of soil bunds (small dykes) to pond water or control surface runoff and enhance infiltration.

Effects of fertility on crop growth and productivity are not directly simulated. Instead, *AquaCrop* provides default adjustments of the pivotal crop parameters for several limiting fertility categories, ranging from near optimal to poor. The adjustments are multipliers, used to reduce: (1) CGC; (2) CC_x; (3) CC, from the time when CC_x is reached to maturity, but only gradually; and (4) WP*. These adjustments are based on the pattern of canopy evolution, photosynthesis, and WP at different fertility levels reported in several studies (e.g. Wolfe *et al.*, 1988). To make the adjustments more reliable, biomass production data and observed canopy development, obtained at different fertility levels, should be used to do a local calibration, as provided for in *AquaCrop*.

Mulching is considered only for its effect on reducing soil E, and is to be specified by the user in terms of the percentage of soil surface covered and effectiveness of the mulching material.

The last management aspect concerns soil bunds and runoff. A bund and its height can be specified to prevent runoff and force all water from rain or irrigation to infiltrate the soil. Equally important, bunds allow the simulation of crops under ponding water such as paddy rice. For soils that are especially permeable, it is also possible to choose 'no runoff' without building bunds.

THE DYNAMICS OF CROP RESPONSES TO STRESSES IN *AquaCrop*

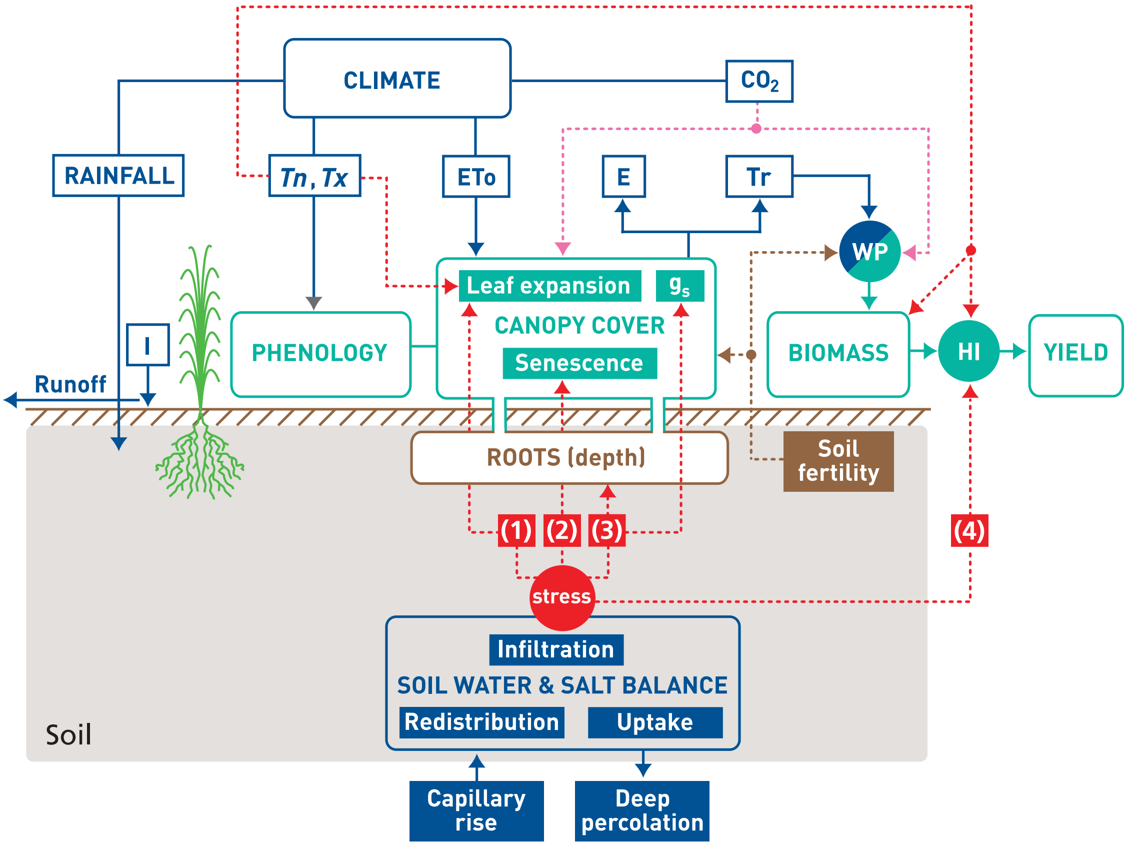
Environmental abiotic stresses such as water and temperature can have major negative impacts on canopy development, biomass production and yield, depending on timing of occurrence, severity and duration. In addition, stress from soil salinity or low soil fertility may have similar negative impacts, but be less dynamic in terms of speed of response and recovery. *AquaCrop* is designed to simulate crop responses first to water, but with sufficient attention also to temperature. *AquaCrop* takes an indirect approach to the deficiencies of mineral nutrients or the presence of salts in the root zone, avoiding attempts to simulate nutrient balances and their complex cycles that would make the model too complex. This indirect approach is outlined in the *Fertility and Salinity stress* section below.

The structural components of *AquaCrop*, including stress responses, and the functional linkages among them, are shown schematically in the diagram of Figure 9, to serve as a framework for the following discussion.

Stress response functions

Any type of stress is described in *AquaCrop* by means of a stress coefficient (Ks) which is an indicator of the relative intensity of the effect on a specific growth process and growth stage. In essence, Ks is a modifier of its target model parameter, and varies in value from one (no stress) to zero (full stress).

FIGURE 9 Chart of *AquaCrop* showing the main components of the soil–plant–atmosphere continuum and the parameters driving phenology, canopy cover, transpiration, biomass production and final yield. Continuous lines indicate direct links between variables and processes. Dotted lines indicate feedbacks. Symbols are: I, irrigation; T_n, minimum air temperature; T_x, maximum air temperature; ET_o, reference evapotranspiration; E, soil evaporation; Tr, canopy transpiration; g_s, stomatal conductance; WP, water productivity; HI, harvest index; CO_2, atmospheric carbon dioxide concentration; (1), (2), (3), (4), water stress response functions for leaf expansion, senescence, stomatal conductance and harvest index, respectively. Modified from Steduto *et al.* (2009).



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 (Figure 10). For water stresses, the thresholds are soil water depletions (D_r) from the root zone. The upper threshold refers to the soil water that can be depleted before the stress starts to affect the process, while the lower threshold is the root zone depletion at which the stress inhibits the process completely. Indicators for air temperature stress are growing degrees, minimum air temperatures (cold stress) or maximum air temperatures (heat stress), while the electrical conductivity of the soil water in the root zone (ECe) determines salinity stress. When running a simulation, the degree of soil fertility selected as the Field management practice is the indicator for soil fertility stress. It varies from 0 percent, when soil fertility is non-limiting (Ks = 1), to a theoretical 100 percent when soil fertility stress is so severe that crop production is no longer possible (Ks = 0).

The relative stress level and the shape of the Ks curve determines the magnitude of the effect of the stress on the process between the thresholds. The relative stress is 0.0 at the upper threshold and 1.0 at the lower threshold (Figure 10). The shape of most of the Ks curves are typically convex, and the degree of curvature is set during model calibration.

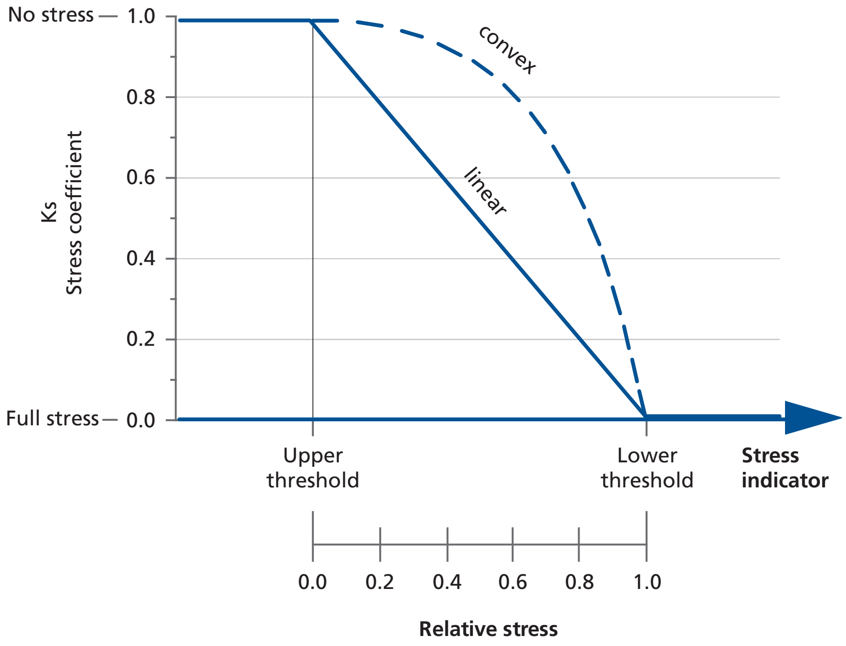
Water stress

AquaCrop distinguishes stresses related to *deficit* and to *excess* water. In this publication, water stress routinely refers to the stress caused by a lack of water, and stress caused by excessive water is referred to as aeration stress. Water stress effects on productivity and water use processes are simulated by impacting: (1) canopy growth; (2) stomata conductance; (3) canopy senescence; (4) root deepening, and (5) harvest index. The normalized water productivity is assumed to be not impacted, based on extensive evaluation of the literature. The discourse that follows discusses the first three impacted processes together, and includes root depending at the end. Harvest index, a complex subject, is covered on its own in the last section on water stress.

Water stress response functions

For water stresses, the stress indicator is the root zone depletion (D_r), and the thresholds are soil water depletions from the root zone expressed as fractions (p) of the total available soil water (TAW). At the point when there is no depletion Ks = 1.0. As depletion progresses Ks does not drop below 1.0 until the upper threshold for stress effect is reached. This threshold is referred to as p_{upper}. Further increase in root zone depletion, brings about lower values of Ks, until the lower threshold (designated as p_{lower}) is reached, where Ks becomes zero and the stress effect is maximum (Figure 11). Further depletion below p_{lower} has no additional effect and Ks remains zero. For water stresses the shape of the curve can vary between very convex to mildly convex to linear. Conceptually, the more convex the curve, the higher is the crop's capacity to adjust and acclimate to the stress. A linear relationship indicates minimal or no

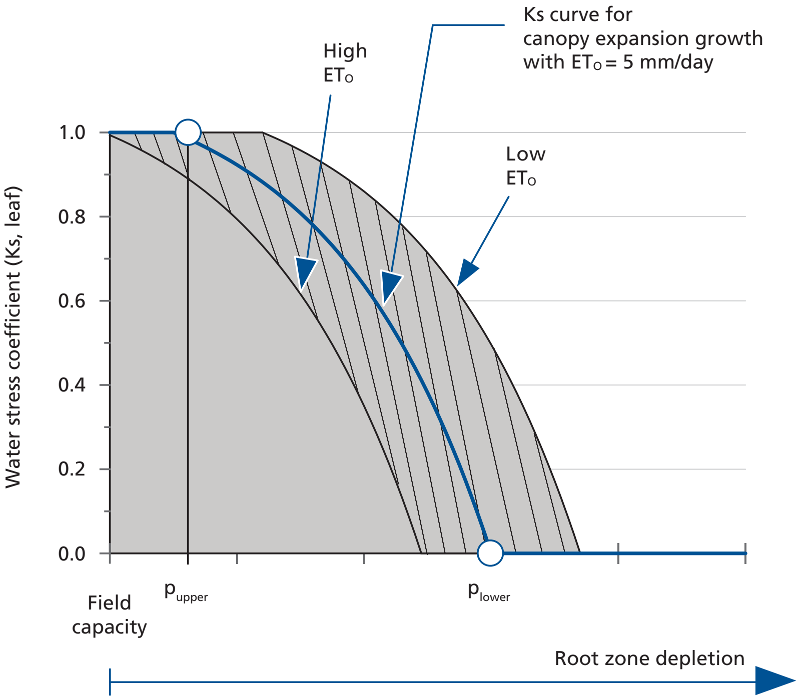
FIGURE 10 The stress coefficient (Ks) for various degrees of stress and for 2 sample shapes of the Ks curve.



acclimation. The stress thresholds, as well as the curve shape, are set by calibration and should be based on knowledge of the crop's drought resistance or tolerance.

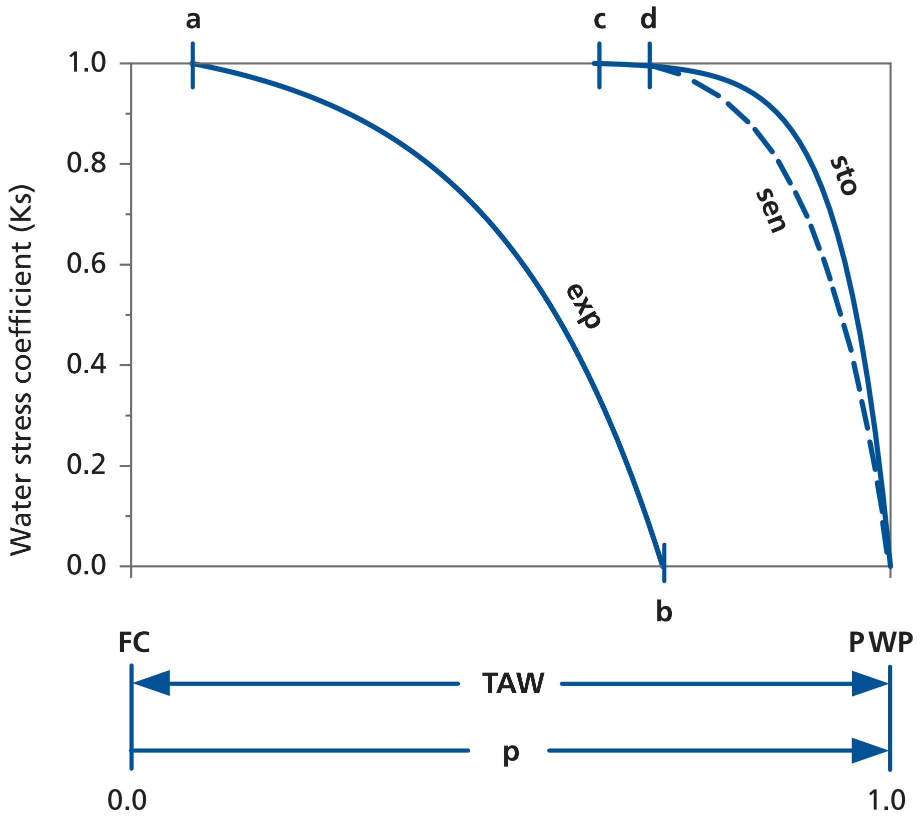
Being the middle link in the soil-plant-atmosphere continuum, the plant water status depends not only on soil-water status, but also on the rate of transpiration determined by atmospheric evaporative demand. The crop is more sensitive to soil-water depletion on days of high ET_o, and less on days of low ET_o. For simplicity, instead of modelling the soil-plant-atmosphere continuum, *AquaCrop* adjusts the thresholds of the Ks curve according to ET_o, a measure of evaporative demand. As the threshold is set for environments with ET_o = 5 mm/day, the model automatically adjusts the thresholds each day according to daily ET_o when running a simulation. The extent of the adjustment is depicted in Figure 11.

FIGURE 11 Sample Ks curve for canopy expansion. The thick blue line represents Ks for days when ET_o = 5 mm/day. The line on the left indicates that the value of Ks decreases (stronger stress effect) when ET_o increases, and the line on the right that Ks increases when ET_o decreases. The hatched area spans the range of adjustment as dictated by ET_o.



Of the first three processes affected by water stress, extensive studies have shown that expansion of the leaf (hence the canopy) is the most sensitive, and stomatal conductance is substantially less sensitive. Depending on the species, leaf (hence canopy) senescence may be equally or slightly less sensitive than stomatal conductance (Bradford and Hsiao, 1982). Setting of the three upper thresholds for water stress for a crop should be consistent with these observations. Differences in the Ks curves for the three processes can be seen in the example for maize in Figure 12.

FIGURE 12 The stress coefficient (Ks) curve for canopy expansion (exp,), stomatal conductance (sto), and canopy senescence (sen) of maize as function of root zone water depletion (p). The upper threshold for expansion is indicated by **a**, and the lower threshold is indicated by **b**. The upper threshold for stomatal closure and canopy senescence are indicated by **c** and **d**, respectively. The lower threshold for both stomata and senescence are fixed at PWP in *AquaCrop* (reproduced from Steduto *et al.*, 2009).



Quantifying stress dynamics with Ks

Generally, Ks is used as a multiplier to modulate the processes in question. For canopy expansion, its CGC (Equation 3 and 4) is actually multiplied by its specific Ks. This has no effect on the value of CGC as long as **p** is small (little depletion) and Ks remains 1.0. As soil water depletion pass the upper threshold (point **a** in Figure 12), Ks drops to less than 1.0, causing a reduction in the calculated effective CGC, and the canopy development slows as a result. As water depletes further, canopy grows even slower because of further decreases in Ks, and stops completely when the depletion reaches the lower threshold (point **b** in Figure 12) where Ks = 0.

If there is no replenishment of water in the root zone, the final size of CC would be less than the specified CC_x. If the crop is indeterminant with the potential of growing leaves over much of its life-cycle, late replenishment of water would raise Ks above the lower threshold and restart canopy expansion. If the crop is determinant, however, late replenishment of water would not renew canopy expansion because the crop has no potential for leaf growth past the peak of the flowering period, and the model is programmed to end CC expansion.

As mentioned, stomata are considerably less sensitive to soil-water depletion than canopy growth, so its Ks is set not to decrease until the soil water is substantially more depleted. Tr is also calculated by multiplying with its Ks, and is not affected by water stress as long as root zone depletion is less than the upper threshold for its Ks. As more water depletes and the upper threshold (point **c** in Figure 12) is passed, Ks drops below 1.0 and calculated Tr becomes less than potential. Further depletion causes more reduction in Tr, and if it passes the upper threshold for senescence (point **d** in Figure 12), canopy starts to senesce and CC, made up of green foliage, decreases. If root zone water is replenished to above the upper thresholds at this point, stomata would open fully and Tr will increase, and canopy senescence will cease. Tr, however, will be lower than if there had not been water stress, because CC is now smaller. CC would increase gradually if the crop is at a stage when the potential for leaf growth is still there; otherwise CC would remain smaller, but would endure to the normal time of maturation if there is no additional depletion passing the upper threshold for senescence.

Senescence of the canopy can be triggered and accelerated by water stress any time during the crop life-cycle, provided the stress is severe enough. This is simulated by adjusting CDC, in units of fractional reduction of CC per unit of time, with an empirical equation based on Ks for senescence arranged in such a way that the value of CDC is zero when Ks is 1.0, but rises exponentially above zero when Ks falls below 1.0.

Root deepening is another process affected by water stress. It is well established that root growth is substantially less sensitive to water stress than leaves, and that the ratio of root to shoot is enhanced by mild to moderate water stress (Hsiao and Xu, 2000). In *AquaCrop* there is no link between roots and shoot (canopy and biomass) except indirectly via the effect of root zone water depletion on components of the production process. Specifically, deepening enlarges the root zone and reduces Dr (fractional water depletion) if the deeper soil layers are high in water content. This raises the value of particular Ks, leading to favourable changes in shoot processes. On the other hand, deepening into quite dry soil layers may actually increase Dr, because volume of the root zone becomes larger but there is little increase in its water the volume. Fractional depletion could then become larger with lower Ks and negative consequences on shoot processes.

Because root growth is less sensitive to water stress than leaves, root deepening is simulated in *AquaCrop* to proceed normally as root zone water depletes until p_{upper} for stomatal closure is reached. At this point, a reduction as a function of Tr (hence Ks for stomata) is applied to the deepening rate. In this simple way, the model mimics the increase in root-shoot ratio under mild to moderate water stress, because canopy expansion starts to be inhibited at a much higher fractional water content of the root zone than Tr. So roots grow better than the canopy, down at least to the upper threshold for stomata.

Water stress effects on harvest index

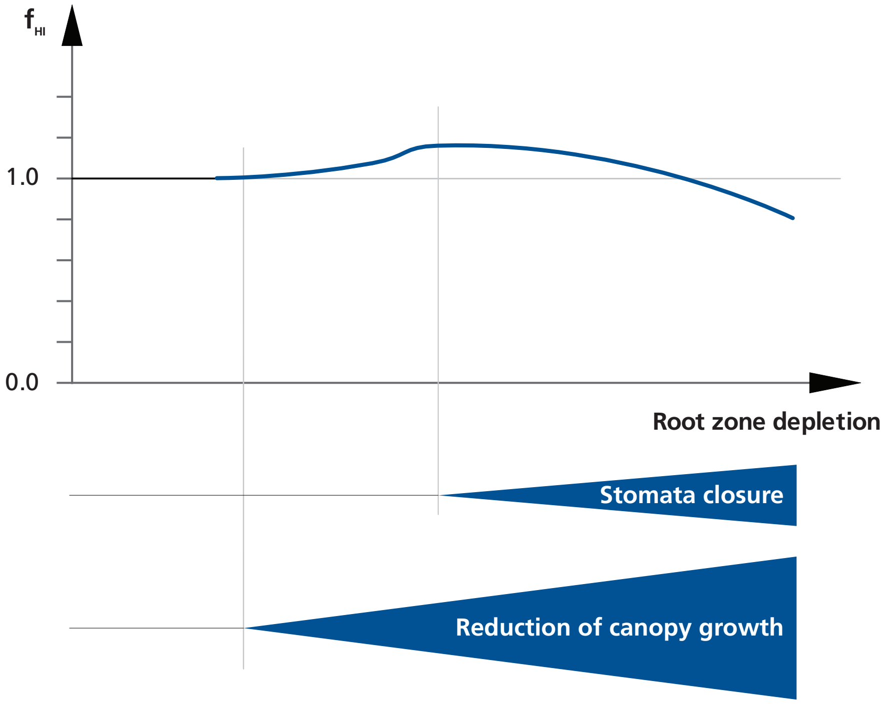
So far attention has been on processes leading to biomass production, on which yield depends (Equation 2). Yield also depends on HI, and the impact of water stresses on HI can be pronounced, depending on the timing and extent of stress during the crop cycle. Effects of water stress on HI can be negative or positive.

Two of the negative effects are more straightforward. One is the inhibition of water stress on pollination and fruit set (successful formation of the embryo). If the stress is severe and long enough, the number of set fruit (or grain) would be reduced sufficiently to reduce HI and limit yield, in some cases drastically. Under good conditions most, if not all crop species, have been selected with a tendency to set more fruit than can be filled with the available photosynthetic assimilates, leading to the abortion of a portion of the set fruit early in their development. So reduction of fruit set by water stress may or may not reduce HI, depending on the extent of the reduction and the extent of the excessive fruit setting. *AquaCrop* simulates this also with the Ks approach, to reduce pollination (hence fruit set) each day according to the extent of water depletion. The effect on HI is adjusted for tendency to set excess fruit by providing categories differing in excessiveness.

Another negative impact on HI is the underfilling and abortion of younger fruits resulting from a lack of photosynthetic assimilates. Photosynthesis is tightly correlated with stomatal conductance. Water stress, by reducing stomatal opening, diminishes the amount of assimilates available to fill all developing fruit. The youngest fruit are then the most likely to be aborted and only the older fruit mature, but likely underfilled. This occurs during the grain filling and maturing period, when most of the vegetative growth has already taken place and most of the assimilates go to the grain. *AquaCrop* simulates this in two ways, one is simply by reducing HI with a coefficient that is a function of Ks for stomata. Stomatal closure may often be only the minor cause, however, because water stress at this growth stage commonly accelerates canopy senescence, resulting in an early decline in photosynthetic surface area and shortens the duration of the canopy. As programmed in *AquaCrop*, HI increases continuously up to the time of normal maturity (Figure 6), but only if a portion of the green canopy remains. As CC declines to some low limit value, HI is considered to have reached its final value. With CC reaching this low limit earlier because of stress induced early senescence, HI is automatically reduced. This effect can be dramatic if canopy duration is shortened substantially.

The last of the negative impacts on HI has to do with not having sufficient water stress. This centres on the competition between vegetative and reproductive growth, which also accounts for the positive impact of water stress on HI. As demonstrated for cotton and some other crops, HI can be reduced by overly luxurious vegetative (leaf) growth during the reproductive phase when water is fully available, while restricting vegetative growth by mild water (and nitrogen) stress is known to enhance HI. The cause is apparently the competition for assimilates. Negative effect on HI comes about when high water availability stimulates fast leaf growth, with too many assimilates diverted to the vegetative organs, depriving the younger potential flowers or nascent fruits so they drop off the crop. The end result is that too few fruits mature, reducing HI. On the other hand, mild water stress would reduce leaf growth substantially because it is most sensitive to water stress, while stomata, being substantially less sensitive, would remain open to maintain photosynthesis. Consequently, without the excessive diversion to vegetative organs, an ample amount of assimilates are available to enhance fruit retention and growth, leading to higher HI. *AquaCrop* simulates this behaviour relying on the Ks functions for leaf growth ($Ks_{exp,w}$) and for stomata closure (Ks_{sto}), with HI being enhanced as $Ks_{exp,w}$ declines, and being reduced as Ks_{sto} declines. In the adjustment, HI is first enhanced as stress develops and vegetative growth is inhibited, then is more enhanced as stress intensifies, until stomata begin to close restricting photosynthesis, at which point the HI does not change. At some level of stress severity HI is reduced to the normal value because the positive effect of leaf growth inhibition is counterbalanced by the negative effect of stomata closure. As stress intensifies beyond this level, the overall effects would switch to negative with proper programme setting parameters (Figure 13).

FIGURE 13 Multiplier (f_{HI}) adjusting the reference harvest index (HI_o) for various root zone depletions with indication of the degree (blue shaded area) of the reduction in canopy growth and the closure of stomata when root zone depletion (D_r) increases.



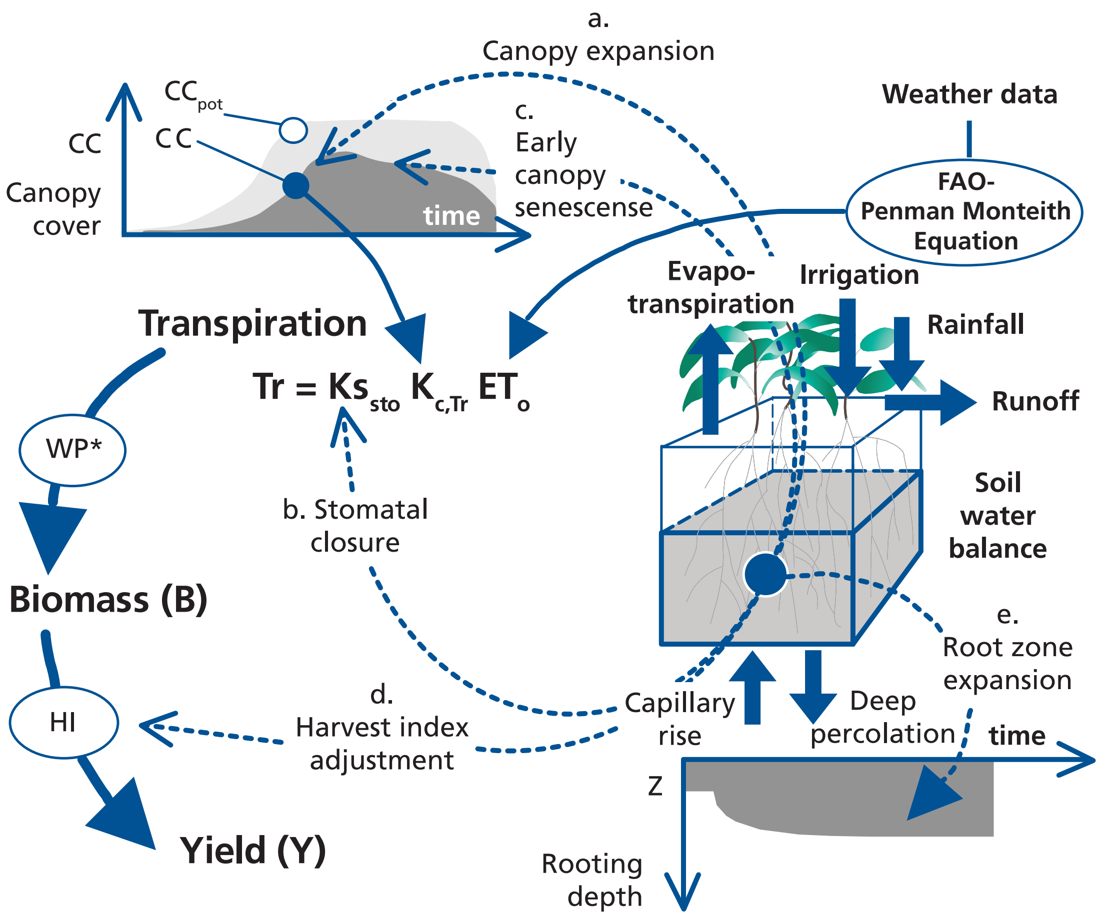
In addition to water stress effects on competition for assimilates during fruit set and grain filling, studies have shown that mild to moderate water stress just before the reproductive phase (pre-anthesis) can enhance HI in some cases. The increase is correlated to the reduction in the accumulation biomass. *AquaCrop* includes an algorithm that operates in some crops to enhance HI based on the stress effect on reduction (relative to the potential) in biomass accumulated up to the start of flowering. The effect is dependent on the extent of reduction and limited to a range with optimal effect before the midpoint of the range.

Overall, in *AquaCrop* the reference HI is adjusted daily for water stress effects based on the inhibition of leaf growth, closure of stomata, reduction in biomass at pre-anthesis, reduction of green canopy duration resulting from accelerated senescence and failure of pollination.

Schematic representation

A schematic representation of the dynamics of the crop response to water stress, as simulated by *AquaCrop*, is given in Figure 14.

FIGURE 14 Schematic representation of the crop response to water stress, as simulated by *AquaCrop*, with indication (dotted arrows) of the processes (a to e) affected by water stress. CC is the simulated canopy cover, CC_{pot} the potential canopy cover, Ks_{sto} the water stress for stomatal closure, $K_{c,Tr}$ the crop transpiration coefficient (determined by CC and $K_{c,Trx}$), ET_o the reference evapotranspiration, WP* the normalized water productivity and HI the harvest index (adjusted from Raes *et al.*, 2009).

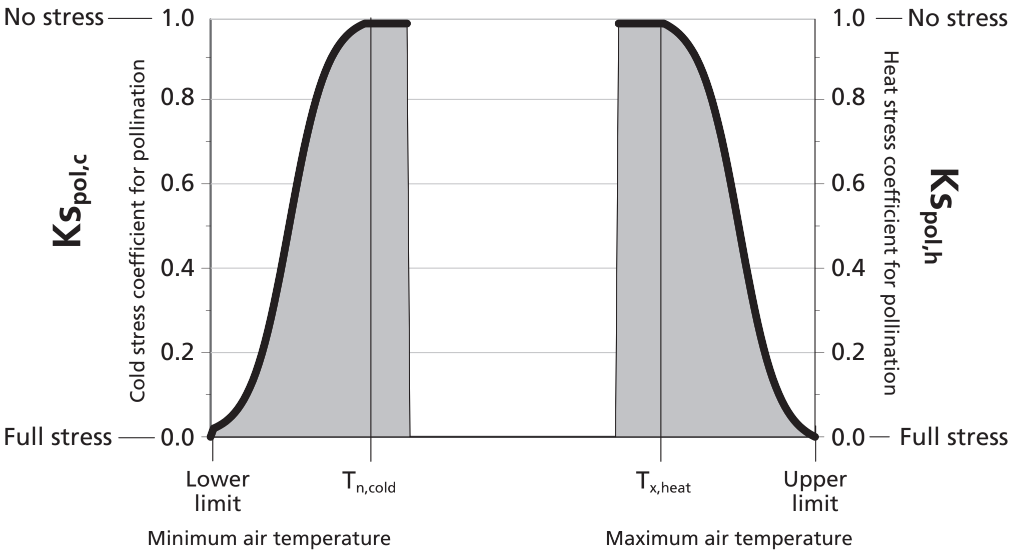


Temperature stress

By using GDD as the thermal clock, much of the temperature effects on crops, such as on phenology and canopy expansion rate, are presumably accounted for. The effect of temperature on transpiration is accounted for separately by ET_o. Damaging effects of extreme or close to extreme temperatures, however, fall into the stress category and require different considerations.

In general *AquaCrop* simulates temperature stress effects with temperature stress coefficients, which vary from zero to 1.0 and are functions of air temperature or GDD. Value of GDD for a given day may be considered as an integrated measure of the daily temperature. Lower and upper thresholds delineate the temperature window wherein the process is affected. Lacking more definitive data currently, the shape of the Ks vs. temperature curve (Figure 15) is taken to be logistic, and may be changed in the future when better data become available.

FIGURE 15 Variation of the temperature stress coefficient (Ks) for cold (left) and heat stresses (right) on pollination.



One important temperature stress effect is on pollination, which is inhibited by temperatures either too high or too low. The left graph in Figure 15 illustrates the $Ks_{pol,c}$ curve for cold stress on pollination, with daily minimum temperature (T_n) as the independent variable and the upper threshold set at a specified threshold temperature ($T_{n,cold}$) and lower threshold at 5 °C below $T_{n,cold}$. The curve for heat stress on pollination is the mirror image of the cold stress (right graph in Figure 15), except the independent variable is maximum temperature (T_x) and the range would be higher and the thresholds also higher. Analogous to the case of water stress, for cold stress pollination begins to be inhibited once the T_n drops below the upper threshold and $Ks_{pol,c}$ drops below 1.0. Pollination decreases further as T_n and $Ks_{pol,c}$ drop further, and is halted ($Ks_{pol,c} = 0$) at the lower T_n threshold or below. For heat stress it is the other way round: below the lower threshold $Ks_{pol,h}$ is 1.0 and pollination is unaffected, and above the upper threshold Ks is zero and pollination is halted (Figure 15). The ultimate effect of temperature stresses on pollination is on HI, in exactly the same way as the effect of water stress.

In addition to effects on pollination, cold temperature may hamper biomass production beyond the restriction accounted for by GDD and irrespective of Tr and ET_o. *AquaCrop* adjusts for this with again the stress coefficient approach. The biomass produced each day is multiplied by the Ks for cold stress ($Ks_{b,c}$) to account for the restriction on production. Since biomass is derived from Tr using WP*, a constant, adjusting biomass this way, in essence, is an adjustment of WP*.

Aeration stress

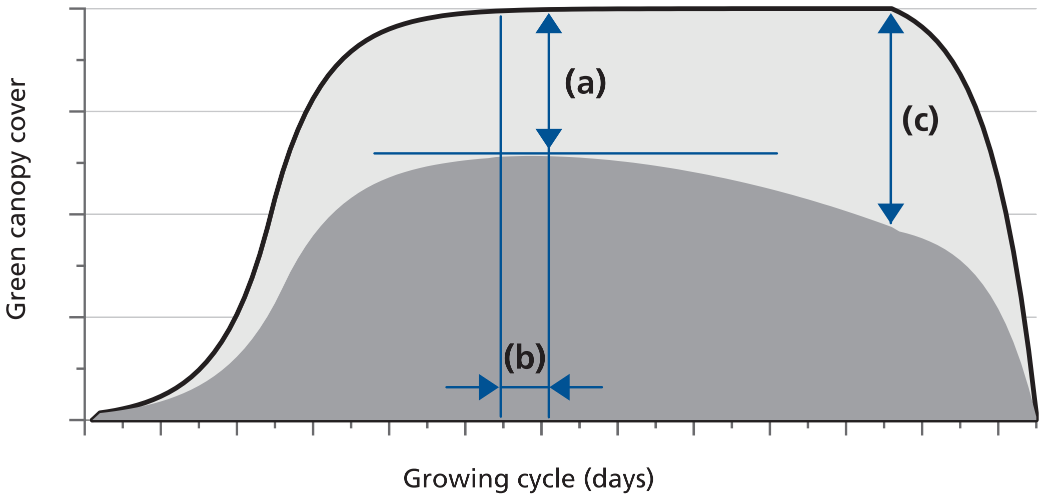
The lack of soil aeration is another abiotic stress considered by *AquaCrop*. The treatment is simple, using the stress coefficient approach to modulate Tr, hence biomass production and ET. The independent variable for the Ks function (Ks_{aer}) is the percentage of soil pore volume occupied by air in the root zone. The function is assumed to be linear with a settable upper threshold and the lower threshold fixed at zero (fully saturated soil). When the percentage air volume drops below the upper threshold, Ks_{aer} starts to decrease below 1.0, causing proportional reduction in Tr.

The sensitivity of the crop to waterlogging is specified by setting the upper threshold, and by indicating the number of days waterlogging must remain before the stress becomes fully effective and Tr is affected. It should be pointed out that so far aeration stress parameters given for the crops already calibrated are all default values, because definitive data for crop under aeration stress are rare.

Low soil fertility (or mineral nutrient stress)

As already mentioned under *Field management*, *AquaCrop* does not simulate nutrient cycles and balances, but provides the means to adjust for fertility effects with a set of soil fertility stress coefficients, to simulate the impact on the growing capacity of the crop in terms of four pivotal components of productivity: canopy growth coefficient (CGC), maximum canopy cover (CC_x), canopy decline, which includes a slow but substantial decline upon reaching CC_x in addition to the senescence near maturity, and WP*. Accounting for the first three of these components, as affected by fertility, results in simulated pattern of CC vs. time very similar to plots based on measured data (Figure 16). The last component, WP*, is also adjusted downward for low fertility. The basis for making these adjustments are the following observations, well established in the literature: plants grown on soil deficient in nutrients (N, P, and/or K) produce leaves more slowly, with lower leaves senescing quite or very early but the upper and youngest leaves remain green until maturity or very near maturity. Photosynthetic capacity of

FIGURE 16 Green canopy cover (CC) for unlimited (light shaded area) and limited (dark shaded area) soil fertility with indication of the processes resulting in (a) a reduced maximum canopy cover, (b) a slower canopy development, as indicated by the reduced slope of CC vs. time in early season, and (c) a continuous and slow decline of CC once the maximum canopy cover is reached.



the deficient leaves is less and their ratio of photosynthesis to transpiration is lower, consistent with the observed changes in WP in field studies.

AquaCrop provides default adjustments of the pivotal components for several categories differing in fertility limitation, ranging from near optimal to poor. To make the adjustments more reliable, biomass production data obtained at different fertility levels at the same location and time should be used to make a local calibration, as provided for in *AquaCrop*.

Soil salinity stress

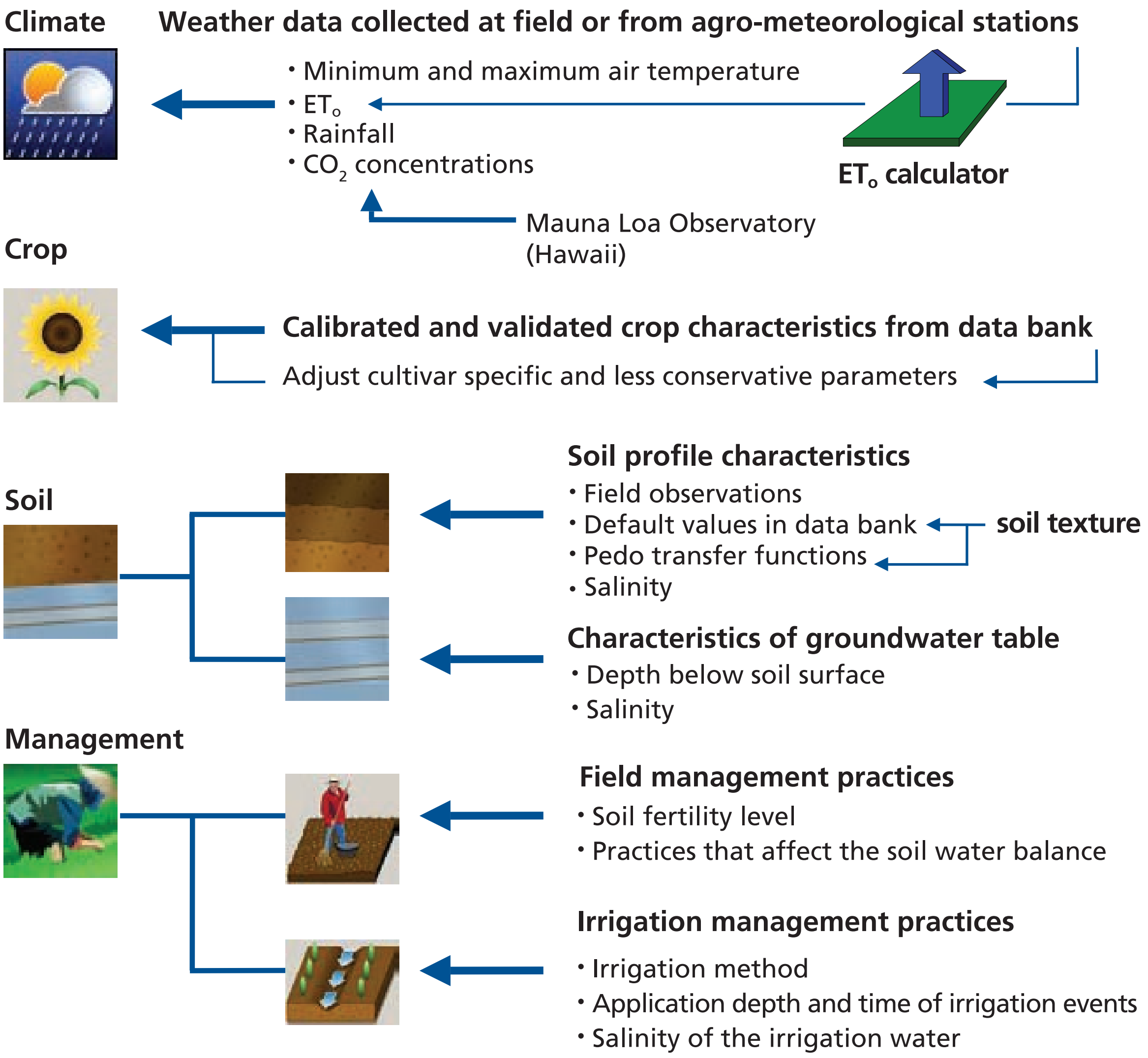
The average electrical conductivity of saturation soil paste extract (ECe) from the root zone is the indicator of soil salinity stress. At the lower threshold of soil salinity (ECe_n), Ks becomes smaller than 1 and the stress starts to affect biomass production. Ks becomes zero at the upper threshold for soil salinity (ECe_x) and the stress becomes so severe that biomass production ceases. Values for ECe_n and ECe_x for many agriculture crops are given by Ayers and Westcot (1985) in the FAO *Irrigation & Drainage Paper No. 29*.

The soil water in the root zone becomes less available for root extraction when salts build up in the soil profile. This affects crop development, crop transpiration and hence biomass production and harvestable yield. *AquaCrop* does not simulate each of these crop responses but simulates only its global effect on biomass production. Given a user calibrated relationship between soil salinity stress and relative biomass production, *AquaCrop* translates the expected reduction in production into a stress resulting in stomata closure (Ks_{sto}) and affecting the canopy development (CGC, CC_x and canopy decline upon reaching CC_x). The simulation is similar as the approach used to simulate the crop response to low soil fertility.

INPUTS

AquaCrop uses a relative small number of parameters and fairly intuitive input variables, either widely used or largely requiring simple methods for their determination. Input consist of weather data, crop and soil characteristics, and management practices that define the environment in which the crop will develop, and are summarized schematically in Figure 17. The inputs are stored in climate, crop, soil and management files and can be easily retrieved from *AquaCrop*'s database and adjusted with the user interface.

FIGURE 17 Input data defining the environment in which the crop develops.



Climate data

For each day of the simulation period, *AquaCrop* requires minimum (T_n) and maximum (T_x) air temperature, rainfall, and reference evapotranspiration (ET_o) as a measure of the evaporative demand of the atmosphere. Further, the yearly mean atmospheric CO_2 concentration has to be known.

For consistency and as the standard, ET_o is to be calculated using the Penman-Monteith equation (Allen *et al.*, 1998), from full daily weather data sets. The full data set consists of radiation, T_x and T_n, wind run or speed, and humidity, all daily. An ET_o calculator, a free public domain software, is available from the FAO website for the calculation (FAO, 2009). The calculator accepts weather data given in a wide variety of units. In the absence of full daily data set, the calculator can also estimate ET_o from 10-day or monthly mean data, and make approximations when one or several kinds of the required weather data are missing. This makes it possible for a user to run rough simulations even when the weather data are minimal.

Care must be taken, however, to avoid misuse of the calculator's versatility. For validation and parameterization of the model for a particular crop, such approximation should not be relied on. The more the weather elements are missing the rougher the approximation of ET_o, the less reliable would be the simulated results and derived *AquaCrop* parameters.

The daily, 10-day or monthly air temperature, ET_o and rainfall data for each specific environment are stored in their own climate folder in the *AquaCrop* database from where the programme retrieves data at run time. In the absence of daily weather data, because the programme runs in daily steps, it invokes built-in procedures to approximate the required daily data from the 10-day or monthly means. Again, the more approximate, the less reliable is the outcome. This is particularly an acute problem for rainfall data. With its extremely heterogeneous distribution over time, the use of 10-day or monthly rainfall data completely grosses over the dynamic nature of crop response to water stress.

Additionally, *AquaCrop* provides the mean yearly CO_2 concentration required for the simulation, applicable for most locations. These yearly values are measured at the Mauna Loa Observatory in Hawaii and encompass the period from 1902 to the most recent available data. Several projected values can be retrieved from the *AquaCrop* database or entered by the user, following the climate change scenario to be investigated.

Crop parameters

Although grounded on basic and complex biophysical processes, *AquaCrop* uses a relative small number of crop parameters to characterize the crop. FAO has calibrated crop parameters for several crops (Section 3.4), and provides them as default values in the crop files stored in *AquaCrop* database. The parameters fall into two categories, distinguished as *conservative* or *cultivar* and *conditions dependent* (see also Section 3.3).

- The *conservative* crop parameters do not change with time, management practices, climate, or geographical location. Regarding cultivar differences, so far tests show the same value of a conservative parameter is applicable to many cultivars, although some deviation may be expected for cultivars of extreme characteristics. The decision to assign a particular parameter to the conservative category is based on conceptual and theoretical analysis, and on extensive empirical data demonstrating near constancy. Depending on extensiveness of the data sets used for the calibration, the calibrated value for a conservative parameter may require some small adjustment. This should be done, however, only if the adjustment is based on high quality experimental data. Generally and in principle, the conservative parameters require no adjustment to the local conditions or for the common cultivars, and can be used as such in simulations. The conservative crop parameters are listed in Table 1.

- The *cultivar* and *condition dependent* crop parameters are generally known to vary with cultivars and situations. Outstanding examples are life-cycle length and phenology of cultivars. In Table 2, an overview is given of crop parameters that are likely to require an adjustment to account for the local cultivar and or local environmental and management conditions. Reference HI (HI_o) is usually conservative for well developed high yielding cultivars, and therefore is not included in Table 2 as a cultivar specific parameter. It is known, however, that some special cultivar may have HI consistently either slightly higher or lower than the common cultivars. Adjustment in HI_o would be justified in such cases.

TABLE 1 Conservative crop parameters.

Crop growth and development
• Base temperature and upper temperature for growing degree days • Canopy size of the average seedling at 90 percent emergence (cc_o) • Canopy growth coefficient (CGC); Canopy decline coefficient (CDC) • Crop determinacy linked/unlinked with flowering; Excess of potential fruit (%)
Crop transpiration
• Decline of crop coefficient as a result of ageing
Biomass production and yield formation
• Water productivity normalized for ET_o and CO_2 (WP*) • Reduction coefficient describing the effect of the products synthesized during yield formation on the normalized water productivity • Reference harvest index (HI_o)
Stresses
Water stresses • Upper and lower thresholds of soil-water depletion for canopy expansion and shape of the stress curve • Upper threshold of soil-water depletion for stomatal closure and shape of the stress curve • Upper threshold of soil-water depletion for early senescence and shape of the stress curve • Upper threshold of soil-water depletion for failure of pollination and shape of the stress curve • Possible increase of HI resulting from water stress before flowering • Coefficient describing positive impact of restricted vegetative growth during yield formation on HI • Coefficient describing negative impact of stomatal closure during yield formation on HI • Allowable maximum increase of specified HI • Anaerobiotic point (for effect of waterlogging on Tr)
Temperature stress • Minimum and maximum air temperature below which pollination starts to fail • Minimum growing degrees required for full biomass production

TABLE 2 List of crop parameters likely to require adjustments to account for the characteristics of the cultivar and local environment and management.

Phenology (cultivar specific)
• Time to flowering or the start of yield formation • Length of the flowering stage • Time to start of canopy senescence • Time to maturity (i.e. the length of crop cycle)
Management dependent
• Plant density • Time to 90 percent emergence • Maximum canopy cover (depends on plant density and cultivar, see Section 3.3)
Soil dependent
• Maximum rooting depth • Time to reach maximum rooting depth
Soil and management dependent
• Response to soil fertility • Soil salinity stress

It should be emphasized that for temperature dependent processes, such as canopy expansion with its conservative parameter CGC, the constancy of their parameters is entirely based on operating the model in the GDD mode. It is obvious, that for simulation of production and water use under different yearly climate or different times of the season, *AquaCrop* must be run in the GDD mode, otherwise temperature effects on key crop processes would be completely ignored by the model.

Another important consideration is the thoroughness of the calibration and the extensiveness of the data set on which the calibration is based. Diverse data sets are necessary to cover a wide-range of climate and soil conditions, and more cultivars. Particularly crucial are data sets for water-deficient conditions, on which the calibration of the water-stress parameters depend, and are often not readily available.

Of the number of crops calibrated by FAO, the thoroughness ranges from very good to fair and limited. Users need to consult the rating, available on the *AquaCrop* website, to determine the firmness of the conservative parameters. With time, calibration of the various crops will be improved based on additional data sets, and more crop species will be calibrated.

The reader is referred to Section 3.3 of this Chapter and the *AquaCrop Reference Manual* (Raes *et al.*, 2011) for procedures on how to calibrate a crop for local conditions and how to modify the crop parameters in the data files.

Soil data

Needed parameters are: volumetric water content at field capacity (FC), permanent wilting point (PWP), and saturation, and the saturated hydraulic conductivity (K_{sat}), for each differentiated soil layers encompassing the root zone. From these characteristics *AquaCrop* derives other parameters governing soil evaporation, internal drainage and deep percolation, surface runoff and capillary rise (Raes *et al.*, 2011). The default values for these parameters can be adjusted if the user has access to more precise information. In case some of the first four parameters values are missing, the user can make use of the indicative values provided by *AquaCrop* for various soil texture classes, or import locally-determined or derived data from soil texture with the help of pedo-transfer functions (see for example The Hydraulic Properties Calculator on the web: http://hydrolab.arsusda.gov/soilwater/Index.htm). These functions are based on primary particle size distribution of the different soil textures. Since these functions depend on texture class only, they do not account for differences in soil aggregation and should be taken as rough approximations. Users should adjust their estimates based on their own data and experience.

If a layer exists in the soil to stop root deepening, its depth has to be specified as well. In addition, the water content of the soil profile layers at the start of the simulation period need to be specified if it is not at field capacity.

Management data

Management practices are divided into irrigation management and field management. Under field management practices are choices of soil fertility levels, level of weed infestation, and practices that affect the soil-water balance such as mulching to reduce soil evaporation, soil bunds to store water on the field, and the elimination of runoff by conservation practices.

The fertility levels range from non-limiting to poor, with effects on WP, on the rate of canopy growth, on the maximum canopy cover and on senescence.

Under irrigation management the user chooses whether the crop is rainfed or irrigated. If irrigated, the user specifies the application method (sprinkler, drip or surface), the fraction of surface wetted, and for each irrigation event, the irrigation water quality, the timing and the applied irrigation amount.

There are also options to asses the net irrigation requirement and to generate irrigation schedules based on specified time and depth criteria. Since the criteria can be changed during the season, the programme provides the means to test deficit irrigation strategies by applying chosen amounts of water at various stages of crop development.

THE USER INTERFACE AND OUTPUT

AquaCrop has a menu-driven software programme with a well-developed user interface. Multiple graphs and schematic displays in the menus help the user to discern the consequences of input changes and to analyse the simulation results.

The main menu

The *Main Menu* of *AquaCrop* provides three panels (Figure 18): *Environment and Crop*, *Simulation* and *Project*.

On the *Environment* and *Crop* panel of the *Main menu*, users have access to a whole set of menus of the four structural components of *AquaCrop* (climate, crop, management, soil), where files are selected, input data are displayed or updated and the planting date is specified. Data can be retrieved from input files stored in the database. In the absence of input files, default settings are provided.

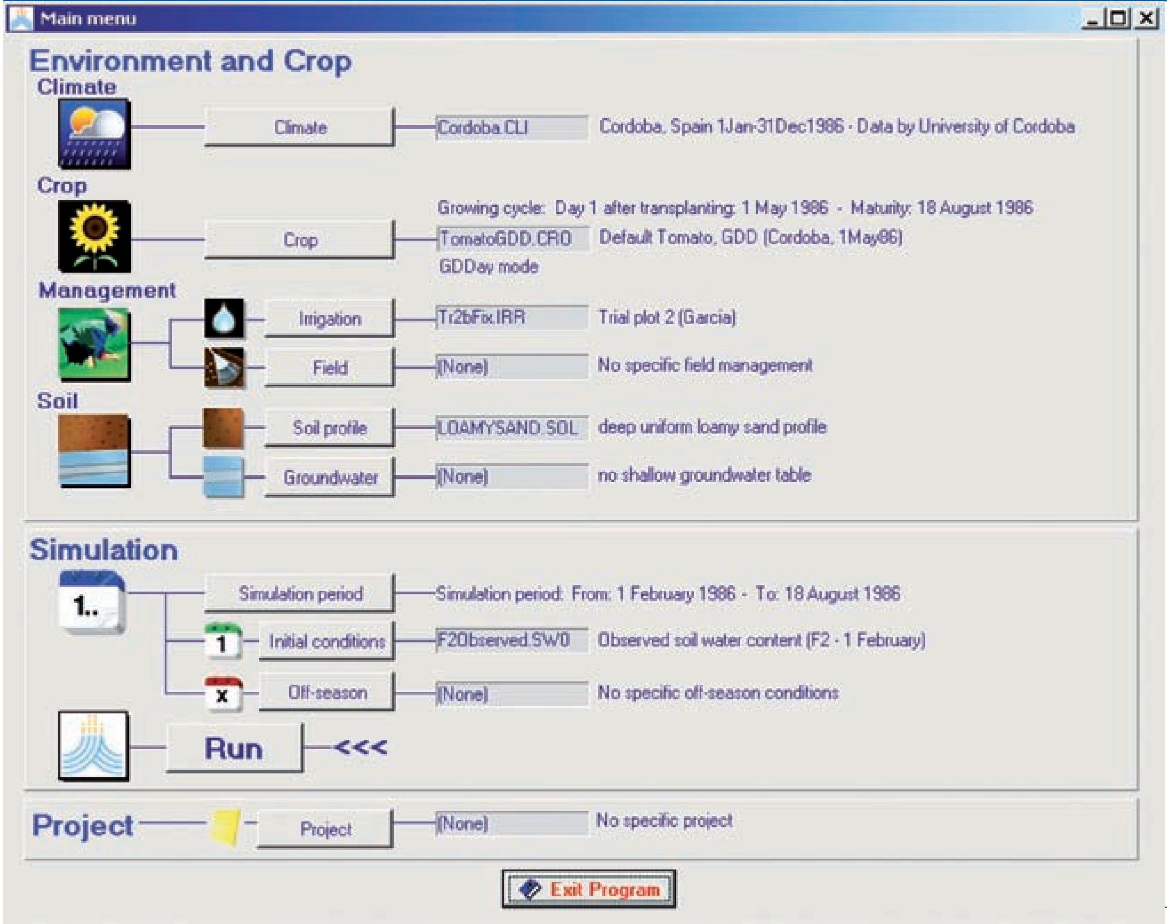
On the *Simulation* panel, a simulation period different from life-cycle of the crop, and conditions of the soil water and salt content in the soil profile at the start of the simulation can be specified. Also, off-season (outside the growing period) practices (mulching or irrigation) can be specified. These features make it possible to simulate effects of fallow and pre-season irrigation.

On the *Project* panel, users can define projects to simulate multi-year cropping, either of the same crop or crop rotations. Note that the climate file needs to span the total simulation years. Under *Project*, users can also specify all the input files for any simulation trial for a single year or season, to avoid having to choose again each file individually when resuming the trial after exiting *AquaCrop*.

Display of simulation results

When running a *Simulation*, the user can track changes in soil-water and salt content, components of soil water balance, canopy development, transpiration, biomass accumulation, and yield and water productivity. The key simulation results are displayed in a number of graphs, updated at the end of each daily time step. From these graphs and associated displays the user can follow the dynamic effects of water, temperature, fertility and salinity stress on crop development and production and water use. By switching among different output

FIGURE 18 The Main *AquaCrop* menu.



Cordoba.CLI Cordoba, Spain 1Jan-31Dec1986 - Data by University of Cordoba

Growing cycle: Day 1 after transplanting: 1 May 1986 - Maturity: 18 August 1986

TomatoGDD.CRO Default Tomato, GDD (Cordoba, 1May86)

GDDay mode

Tr2bFix.IRR Trial plot 2 (Garcia)

(None) No specific field management

LOAMYSAND.SOL deep uniform loamy sand profile

(None) no shallow groundwater table

Simulation period: From: 1 February 1986 - To: 18 August 1986

F2Observed.SW0 Observed soil water content (F2 - 1 February)

(None) No specific off-season conditions

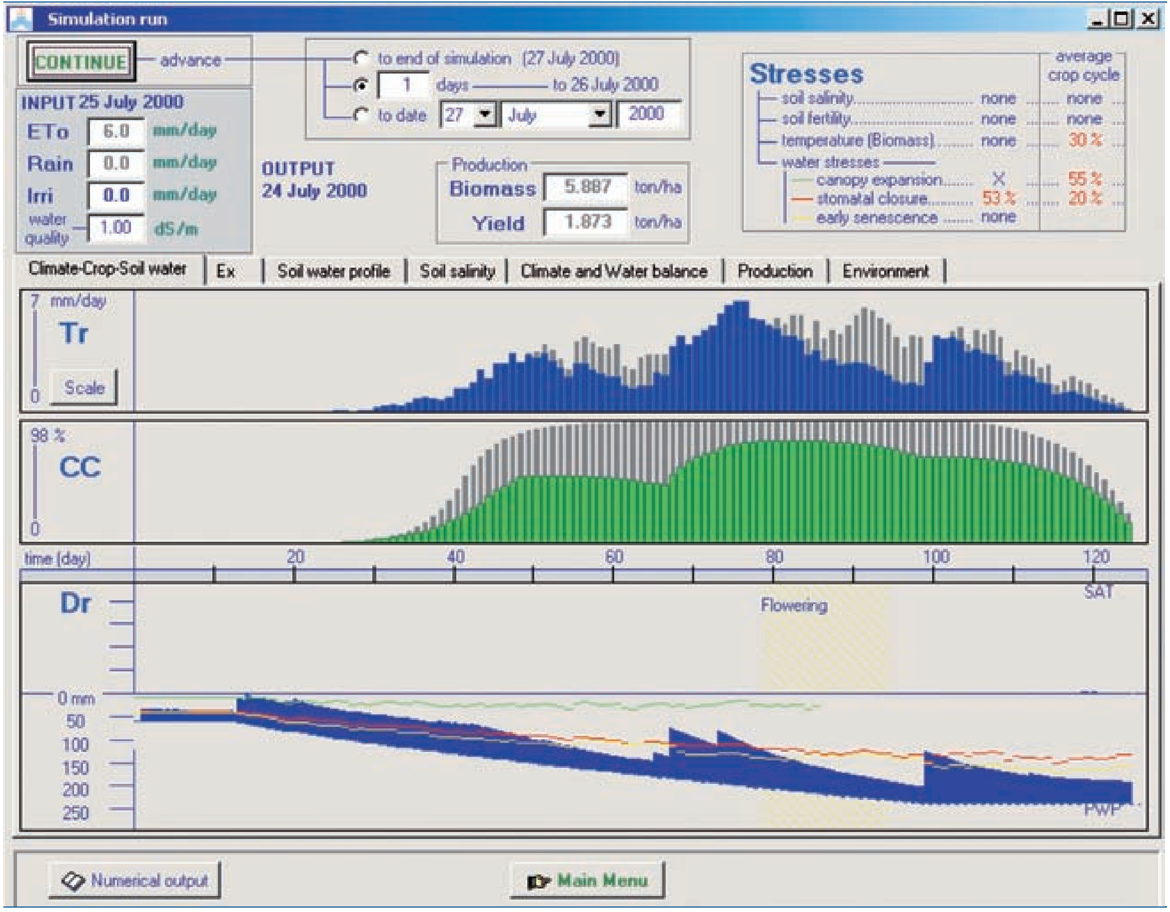
(None) No specific project

displays on *tab* sheets for different aspect of crop, soil water and salt balance, the user can observe and analyse a particular event on a specific parameter.

Climate-Crop-Soil water is the most useful of the *tab* sheets (Figure 19). It displays three graphs plotted as a function of time: (i) depletion of root zone soil water (D_r), with the three water stress thresholds represents by lines of different colours; (ii) the corresponding progression of green canopy cover (CC), with the potential CC (no stresses) shaded gray; and (iii) the transpiration (Tr) of the canopy (for the simulated CC size), with potential Tr shaded gray. On top of the menu the biomass and yield are displayed along with the status of the water, temperature, soil fertility and salinity stresses. The graphs vividly show how canopy expansion and transpiration are affected when the absence of rain and irrigation led to drops in root zone water content below the threshold (green line, bottom graph) affecting canopy expansion, below the threshold for stomata (red line) affecting Tr, and below the threshold (yellow line) triggering canopy senescence. The reversal effects of water supply or irrigation are also obvious in the graphs.

One feature of the *Simulation run* menu is particularly helpful to users seeking to develop a regulated deficit irrigation schedule to optimize water use. By selecting short simulation time steps (1 to 3 days), a chosen amount of irrigation can be specified on the upper left panel at any time step (and date) during a simulation run, allowing quick and close scrutiny of the resultant benefits in the context of irrigation time, frequency, and amount. For more details, see Section 3.3 and the *AquaCrop Reference Manual* (Raes *et al.*, 2011).

FIGURE 19 Graphical displays of Climate-Crop-Soil water output in the *Simulation run* menu.



○ to end of simulation (27 July 2000)
● 1 days — to 26 July 2000
○ to date 27 July 2000

INPUT 25 July 2000
ETo 6.0 mm/day
Rain 0.0 mm/day
Irri 0.0 mm/day
water quality 1.00 dS/m

OUTPUT 24 July 2000
Production
Biomass 5.887 ton/ha
Yield 1.873 ton/ha

Stresses		average crop cycle
soil salinity	none	none
soil fertility	none	none
temperature (Biomass)	none	30 %
water stresses		
canopy expansion	X	55 %
stomatal closure	53 %	20 %
early senescence	none	

Output

On exiting the *Simulation run* menu, the user is asked whether to save the output, and can choose one or more of the categories of output: daily (Table 3) and/or seasonal. The files are automatically assigned the file extension OUT, with the name of the category of file contents forming the last part of the default file name as shown in Table 3.

TABLE 3 Default file name and content of the seven output files with daily simulation results.

Default file name	Nature and number (in parenthesis) of output variables in the file
ProjectCrop.OUT	crop processes, production, & related data (18)
ProjectWabal.OUT	soil water balance and related data (16)
ProjectProf.OUT	water content of root zone profile (10)
ProjectSalt.OUT	soil salinity of root zone profile (8)
ProjectCompWC.OUT	soil water content of model compartments (12)
ProjectCompEC.OUT	soil salinity of model compartments (12)
ProjectInet.OUT	net irrigation requirement (if simulated) (5)

Users should change the first part (Project) of file name to identify the particular simulation, otherwise the next simulation would be automatically assigned the same default file name and overwrite the files resulting from the preceding simulation. Daily simulation results are also summarized as seasonal totals. The files are stored by default in the OUTP directory of *AquaCrop*. The data in the files can be retrieved in spreadsheet programmes for further processing and analysis.

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