**Food and Agriculture Organization
of the United Nations**

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

AquaCrop
Version 7.0

Reference manual

August 2022

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

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

A set of training videos are available on YouTube (see link in AquaCrop website of FAO: http://www.fao.org/nr/water/aquacrop.html

1.1 From the Ky approach to the AquaCrop model

Yield response to water describes the relationship between crop yield and water stress as a result from insufficient supply of water by rainfall or irrigation during the growing period. In the FAO Irrigation & Drainage Paper n. 33 (Doorenbos and Kassam, 1979) an empirical production function is used to asses the yield response to water:

$$\left(1 - \frac{Y}{Y_x}\right) = K_y \left(1 - \frac{ET}{ET_x}\right) \tag{Eq.1.1a}$$

where Y_x and Y are the maximum and actual yield, $(1-Y/Y_x)$ the relative yield decline, ET_x and ET the maximum and actual evapotranspiration, $(1- ET/ET_x)$ the relative water stress, and K_y the proportionality factor between relative yield decline and relative reduction in evapotranspiration (Fig. 1.1a).
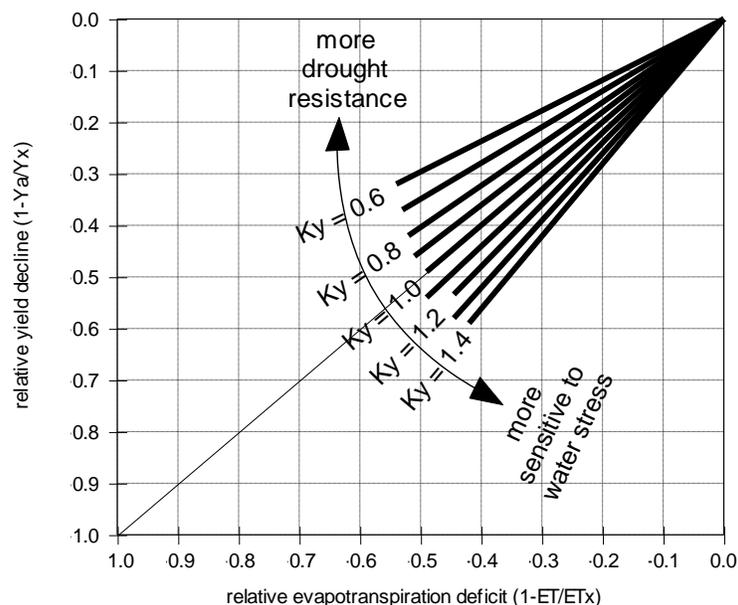
Figure 1.1a – Relationship between relative yield decline (1-Ya/Ym) and relative evapotranspiration deficit (1-ET/ETc) for the total growing period for various values of the seasonal yield response factor (Ky)

AquaCrop (Steduto et al., 2007; Raes et al., 2007; Hsiao et al., 2007) evolves from the Ky approach by separating (i) the actual evapotranspiration (ET) into soil evaporation (E) and crop transpiration (Tr) and (ii) the final yield (Y) into biomass (B) and harvest index (HI):

$$ET = E + Tr$$
$$Y = HI \ B$$

(Eq. 1.1b)

The separation of ET into soil evaporation and crop transpiration avoids the confounding effect of the non-productive consumptive use of water (soil evaporation). This is important especially when ground cover is incomplete early in the season or as the result of sparse planting. The separation of yield into biomass and harvest index allows the partitioning of the corresponding functional relations as response to environmental conditions. These responses are in fact fundamentally different and their separation avoids the confounding effects of water stress on B and on HI. The changes described leads to the following equation at the core of the *AquaCrop* growth engine:

$$B = WP \cdot \Sigma Tr$$

(Eq. 1.1c)

where Tr is the crop transpiration (in mm) and WP is the water productivity parameter (kg of biomass per m^2 and per mm of cumulated water transpired over the time period in which the biomass is produced). This step-up from Eq. (1.1a) to Eq. (1.1c) has a fundamental implication for the robustness of the model due to the conservative behavior of WP (Steduto et al., 2007). It is worth noticing, though, that both equations have water as driving force for growth.

To be functional, Eq. 1.1c was inserted in a complete set of additional model components, including: *the soil*, with its water balance; *the crop*, with its development, growth and yield processes; and *the atmosphere*, with its thermal regime, rainfall, evaporative demand and carbon dioxide concentration. Additionally, some *management* aspects are explicitly considered (e.g., irrigation, fertilization, mulches, weeds, etc.), as they will affect the soil water balance, crop development and therefore final yield. AquaCrop can also simulate crop growth under climate change scenarios (global warming and elevated carbon dioxide concentration) while pests and diseases are not considered. The functional relationships between the different model components are depicted in Fig. 1.1b and described in section 1.2.

Particular features that distinguishes AquaCrop from other crop models are:
- its focus on water;
- the use of canopy cover instead of leaf area index;
- the use of water productivity (WP) values normalized for atmospheric evaporative demand and CO_2 concentration that confer the model an extended extrapolation capacity to diverse locations, seasons, and climate, including future climate scenarios;
- the relatively low number of parameters;
- input data which requires only explicit and mostly intuitive parameters and variables;
- a well developed user interface;
- its considerable balance between accuracy, simplicity, and robustness;
- its applicability to be used in diverse agricultural systems that exists world wide.

Although the model is relatively simple, it emphasizes the fundamental processes involved in crop productivity and in the responses to water deficits, both from a physiological and an agronomic perspective.

Figure 1.1b – Chart of *AquaCrop* indicating the main components of the soil–plant–atmosphere continuum and the parameters driving phenology, canopy cover, transpiration, biomass production, and final yield. [I, irrigation; T_n, minimum airtemperature; T_x, maximum air temperature; ET_o, reference evapotranspiration; E, soil evaporation; Tr, canopy transpiration; gs, 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]. Continuous lines indicate direct links between variables and processes. Dashed lines indicate feedbacks. See section 1.2 for a more extensive description.

It is important to realize that several crop models are already available in literature to simulate yield response to water. They are used mostly by scientists, graduate students, and advanced users in highly commercial farming. However, it is also important to recognize that these models present substantial complexity and are rarely used by the majority of FAO target users, such as extension personnel, water user associations, consulting engineers, irrigation and farm managers, planners and economists. Furthermore, these models require an extended number of variables and input parameters

not easily available for the diverse range of crops and sites around the world. Some of these variables are much more familiar to scientists than to end users (e.g., leaf area index –LAI– or leaf water potential –ψ_l–). Lastly, the insufficient transparency and simplicity of model structure for the end user were considered strong constraints for their adoption.

1.2 AquaCrop operation

1.2.1 Calculation scheme

A general calculation scheme of AquaCrop is depicted in Figure 1.2a.
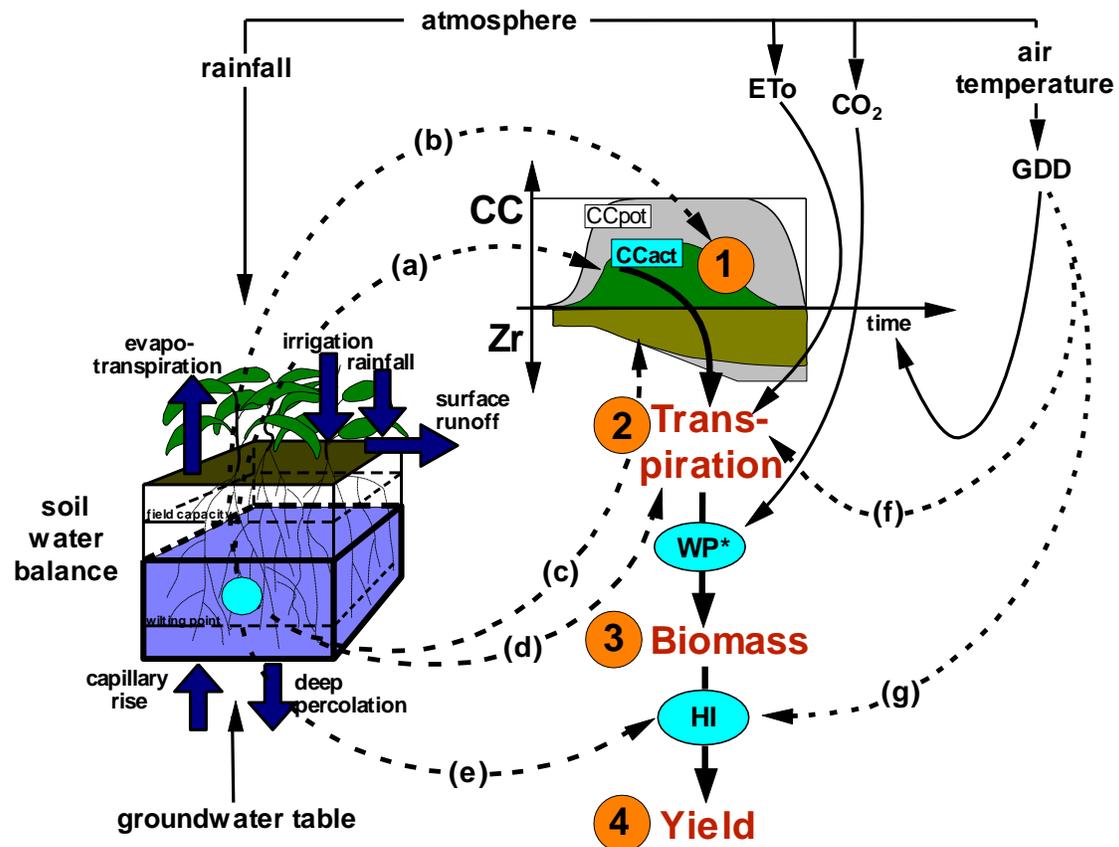
Figure 1.2a – Calculation scheme of AquaCrop with indication (dotted arrows) of the processes affected by water stress (a to e) and temperature stress (f to g). CC is the simulated canopy cover, CC$_{pot}$ the potential canopy cover, Zr the rooting depth, ETo the reference evapotranspiration, GDD the growing degree days, WP* the normalized crop water productivity, and HI the Harvest Index.

The amount of water stored in the root zone is simulated by accounting for the incoming and outgoing water fluxes at its boundaries. The root zone depletion determines the magnitude of water stresses affecting: (a) green canopy (CC) expansion, (b) canopy senescence and decline, (c) the root system deepening rate, (d) stomatal conductance and hence transpiration, and (e) the harvest index (Fig. 1.2a). Cold temperature stress (f) reduces crop transpiration. Hot and cold temperature stresses (g) inhibit pollination and reduce HI.

With a daily time step the model simulates successively the following processes of crop development and production:

1. Crop development. In the simulation of crop development, the canopy expansion is separated from the expansion of the root zone. The interdependence between shoot and root is indirect via water stress. AquaCrop uses green canopy cover (CC) to describe crop development. The canopy is a crucial feature of AquaCrop. Through its expansion, ageing, conductance and senescence, it determines the amount of water transpired (Tr), which in turns determines the amount of biomass produced (B) and the final yield (Y). If water stress occurs, the simulated CC will be less than the potential canopy cover (CC_{pot}) for no stress conditions and the maximum rooting depth might not be reached (dark shaded areas in Fig. 1.2a);

2. Crop transpiration (Tr). Crop transpiration is obtained by multiplying the evaporating power of the atmosphere (ET_o) with a crop coefficient. The crop coefficient (Kc_{Tr}) is proportional to CC and hence continuously adjusted. The evaporating power is expressed by the reference grass evapotranspiration (ET_o) as determined by the FAO Penman-Monteith equation. Water stress does not only affect canopy development but might induces stomatal closure as well and hence affect, also directly, crop transpiration. Green canopy cover and duration represent the source for transpiration, stomatal conductance represents transpiration intensity;

3. Above ground biomass (B) production. The cumulative amount of water transpired (Tr) translates into a proportional amount of biomass produced through the biomass water productivity (Eq. 1.1c). In AquaCrop the water productivity normalized for atmospheric demand and air CO_2 concentrations (WP*) is used. It expresses the strong relationship between photosynthetic CO_2 assimilation or biomass production and transpiration independently of the climatic conditions. Beyond the partitioning of biomass into yield (Step 4), there is no partitioning of above-ground biomass among various organs. This choice avoids dealing with the complexity and uncertainties associated with the partitioning processes, which remain among the least understood and most difficult to model;

4. Yield (Y) formation. Given the simulated above ground biomass (B), crop yield is obtained with the help of the Harvest Index (HI). In response to water and/or temperature stresses, HI is continuously adjusted during yield formation.

Temperature and water stresses directly affect one or more of the above processes (Fig. 1.2a). AquaCrop considers also the effect of soil fertility and soil salinity stress on canopy development, crop transpiration and biomass production.

1.2.2 Simulation of the soil water balance

In a schematic way, the root zone can be considered as a reservoir (Fig. 1.2b). By keeping track of the incoming (rainfall, irrigation and capillary rise) and outgoing (runoff, evapotranspiration and deep percolation) 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.

To accurately describe surface run-off, water infiltration and retention, water and salt movement, and to separate soil evaporation from crop transpiration, AquaCrop divides both the soil profile and time axis into small fractions. The simulations run with a daily time step (Δt) and the soil profile is divided into 12 compartments (Δz), which size is adjusted to cover the entire root zone.

The effect of water stress is described by stress coefficients (Ks). Above an upper threshold of root zone depletion, water stress is non-existent (Ks is 1) and the process is not affected. Soil water stress starts to affect a particular process when the stored soil water in the root zone drops below an upper threshold level (Fig. 1.2c). Below the lower threshold, the effect is maximum (Ks is 0) and the process is completely halted. Between the thresholds the shape of the Ks curve determines the magnitude of the effect of soil water stress on the process. Since the effect of water stress might differ along the processes, each process has its own Ks coefficient and threshold values.
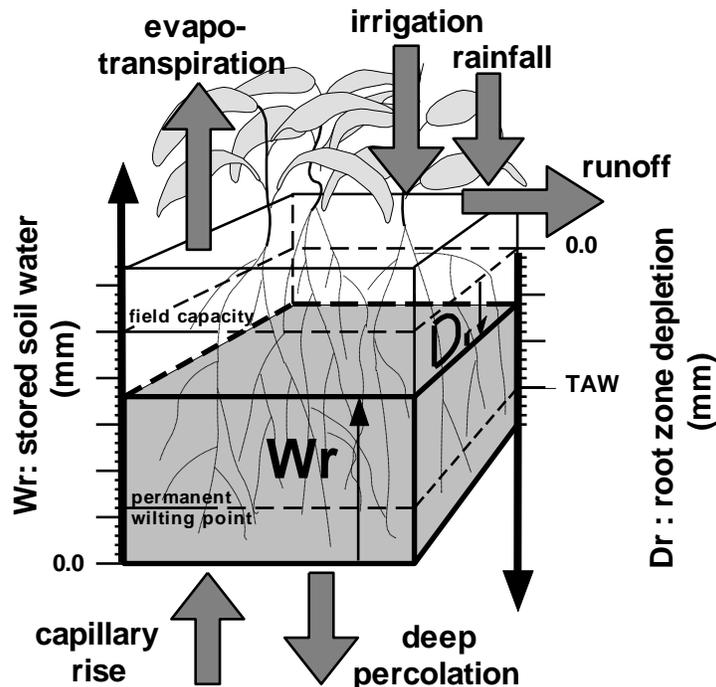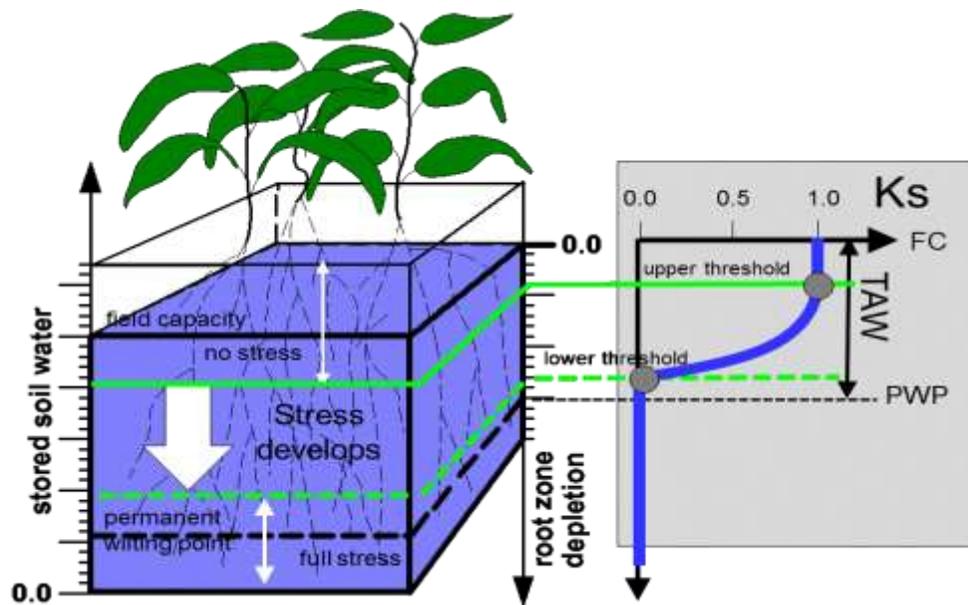

Figure 1.2b – The root zone as a reservoir with indication of the fluxes at its boundaries affecting the water stored in the root zone (Wr) and the root zone depletion (Dr)

Figure 1.2c – The water stress coefficient (Ks) for various degrees of root zone depletion (Dr). TAW is the Total Available soil Water in the root zone which is the difference between the water content at Field Capacity and Permanent Wilting Point

1.2.3 Step 1 – simulation of green canopy development (CC)

In stead of leaf area index (LAI) AquaCrop uses green canopy cover (CC) to express foliage development. CC is the fraction of the soil surface covered by green canopy cover. Canopy development under optimal conditions is described by only a few crop parameters which are retrieved from the crop file at the start of the simulation:

- initial canopy cover at 90 % emergence (CC_o);
- maximum canopy cover when the canopy is fully developed (CC_x);
- canopy growth coefficient (CGC), used to describe the canopy expansion between cop emergence and full development;
- canopy decline coefficient (CDC), used to describe the declining phase due to leaf senescence as the crop approaches maturity.

In figure 1.2d, the variation of green canopy cover throughout a crop cycle under non-stress conditions is represented.

The effect of water stress on canopy expansion is simulated by multiplying the Canopy Growth Coefficient (CGC) with the water stress coefficient for canopy expansion ($Ks_{exp,w}$). As root zone depletion increases and drops below the upper threshold, the stress coefficient becomes smaller than 1 and the canopy expansion starts to be reduced (Fig. 1.2c). When the lower threshold of root zone depletion is reached, $Ks_{exp,w}$ is zero, and the process is completely halted. As a result, CC_x might not be reached or much later in the season than described in Fig. 1.2d for non-stressed conditions.
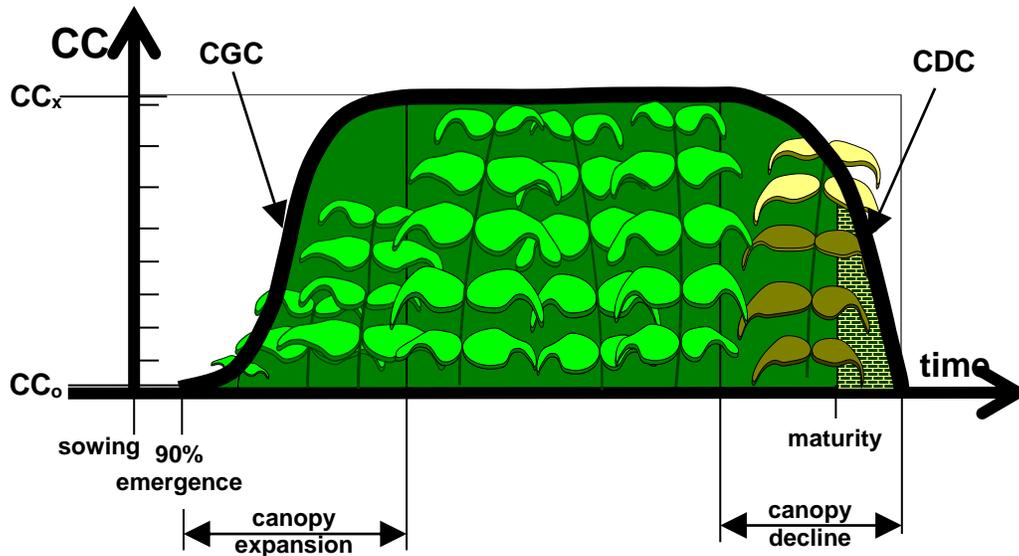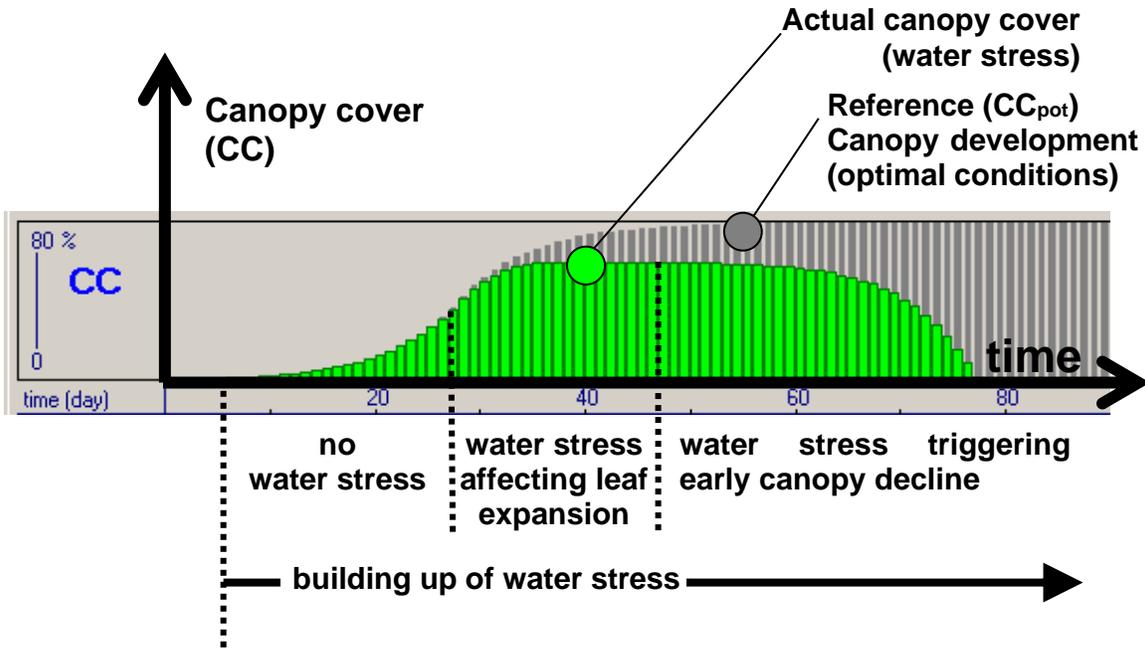
Figure 1.2d – Variation of the green canopy cover (CC) throughout the crop cycle under non-stress conditions. CC₀ and CCₓ are the initial and maximum green canopy cover, respectively; CGC is the green canopy growth coefficient; CDC is the green canopy decline coefficient

Early canopy senescence is triggered when water stress becomes severe. As a consequence the upper threshold of root zone depletion for senescence is much lower in Fig. 1.2c and close to permanent wilting point. The degree of senescence is described by the value of the water stress coefficient for early canopy senescence (Ks_{sen}) which modifies the canopy decline coefficient (CDC). Due to the induced early canopy senescence, the crop life might become much shorter than for non-stressed conditions. The simulation of the green canopy cover (CC) during the building up of water stress during the crop cycle is presented in Figure 1.2e.

Other stresses considered by Aquacrop affecting CC are:
- air temperature stress. The effect of air temperature on canopy development is simulated by running AquaCrop in growing degree days (GDD). For the purpose of GDD calculations, a base temperature (below which crop development does not progress) and an upper temperature (above which the crop development no longer increases) are required;
- Mineral nutrient stress. AquaCrop does not simulate nutrient cycles and balance but provides a set of soil fertility stress coefficients (Ks), to simulate the effect of soil fertility on the growing capacity of the crop and the maximum canopy cover (CC_x) that can be reached at mid season. A distinction is made between a soil fertility coefficient for leaf expansion ($Ks_{exp,f}$) which reduces CGC and a soil fertility coefficient for maximum canopy cover (Ks_{CCx}) which reduces CC_x. Next to the effect on leaf expansion and maximum canopy cover, AquaCrop simulates a steady decline of the canopy cover once CC_x is reached (Fig. 1.2f). The average daily decline is given by a decline factor ($f_{CDecline}$);
- soil salinity stress. Since soil salinity reduces the availability of the water in the root zone reservoir, the presence of dissolved salts increase the effect of soil water stress.

The effect of soil salinity stress on green canopy development is considered as similar to the effect of soil fertility stress in AquaCrop.

Figure 1.2e – Simulation of the green canopy cover (CC) when water stress builds during the crop cycle with reference to the canopy development for non stressed conditions (CCpot)
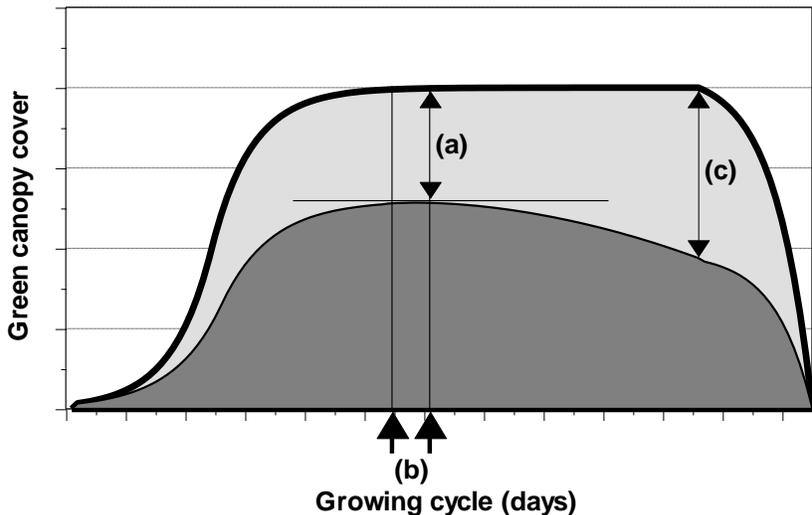
Figure 1.2f – Green canopy cover (CC) for unlimited (light shaded area) and limited (dark shaded area) soil fertility with indication of the processes resulting in (a) a less dense canopy cover, (b) a slower canopy development, and (c) a steady decline of CC once the maximum canopy cover is reached
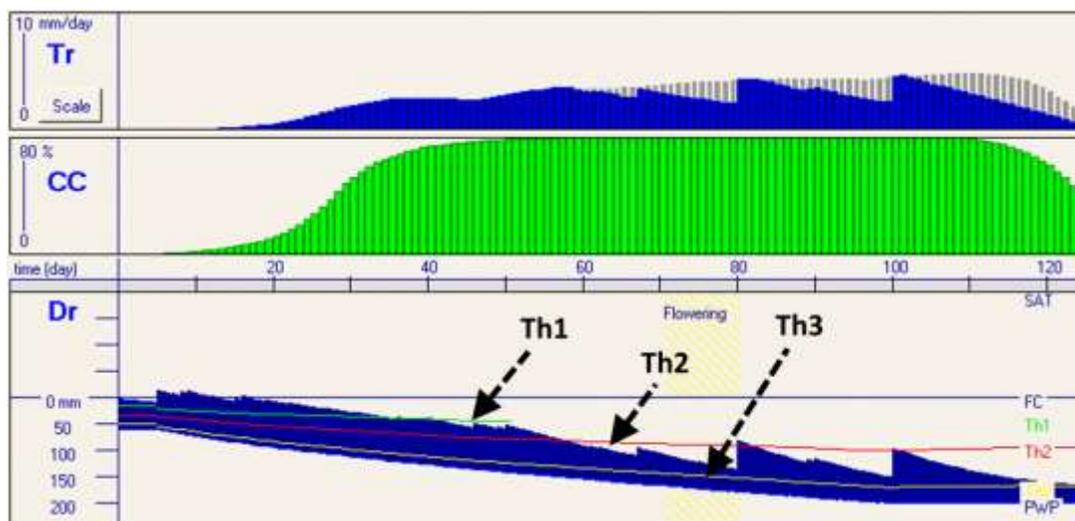
1.2.4 Step 2 – simulation of crop transpiration (Tr)

Crop transpiration (Tr) is calculated by multiplying the evaporating power of the atmosphere with the crop coefficient (Kc_{Tr}) and by considering water stresses (Ks) and temperature stress (Ks_{Tr}):

$$Tr = Ks \; Ks_{Tr} \left(Kc_{Tr,x} \; CC * \right) ETo \qquad \text{(Eq. 1.2a)}$$

where the evaporating power (ET_o) is expressed by the reference grass evapotranspiration as determined by the FAO Penman-Monteith equation.

The crop transpiration coefficient ($Kc_{Tr} = Kc_{Tr,x} \; CC^*$) is proportional to the fractional canopy cover (CC) and as such continuously adjusted to the simulated canopy development. The proportional factor ($Kc_{Tr,x}$) integrates all the effects of characteristics that distinguish the crop transpiration from the grass reference surface. As the crop develops, $Kc_{Tr,x}$ is adjusted for ageing and senescence effects. In Eq. 1.2a, CC is replaced by CC^* to account for interrow micro-advection which make extra energy available for crop transpiration. When canopy cover is not complete the contribution is substantial.

Either a shortage or an excess of water in the root zone might reduce crop transpiration. This is simulated by considering water stress coefficients (Ks). When water shortage in the root zone provokes stomatal closure a stress coefficient for stomatal closure (Ks_{sto}) is considered. When the excess of water results in anaerobic conditions, the effect of stress on transpiration is expressed by the coefficient for water logging (Ks_{aer}). According to the general rule in AquaCrop, the water stress coefficients range between 1, when water stress is non-existent and 0, when the stress is at its full strength and crop transpiration is completely halted. The simulation of crop transpiration affected by water stress during the crop cycle is presented in Figure 1.2g.


Figure 1.2g – Simulated root zone depletion (Dr), green canopy cover (CC) and crop transpiration (Tr) throughout the crop cycle with indication of the soil water thresholds affecting canopy development (Th1), inducing stomata closure (Th2), and triggering early canopy senescence (Th3)

The presence of dissolved salts increases the effect of water stress on stomatal closure. This is simulated in AquaCrop by further reducing Ks_{sto} with an additional stress coefficient ($Ks_{sto,salt}$).

The stomatal conductance is lowered at low temperature. This is simulated by considering the cold stress coefficient for crop transpiration (Ks_{Tr}). If the growing degrees generated in a day drops below an upper threshold, crop transpiration is reduced and Ks_{Tr} becomes smaller than 1 and might even reach zero when it becomes too cold to generate any growing degrees.

1.2.5 Step 3 – simulation of the above-ground biomass (B) production

The crop water productivity (WP) expresses the aboveground 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 for a given climatic condition (Eq. 1.1c).
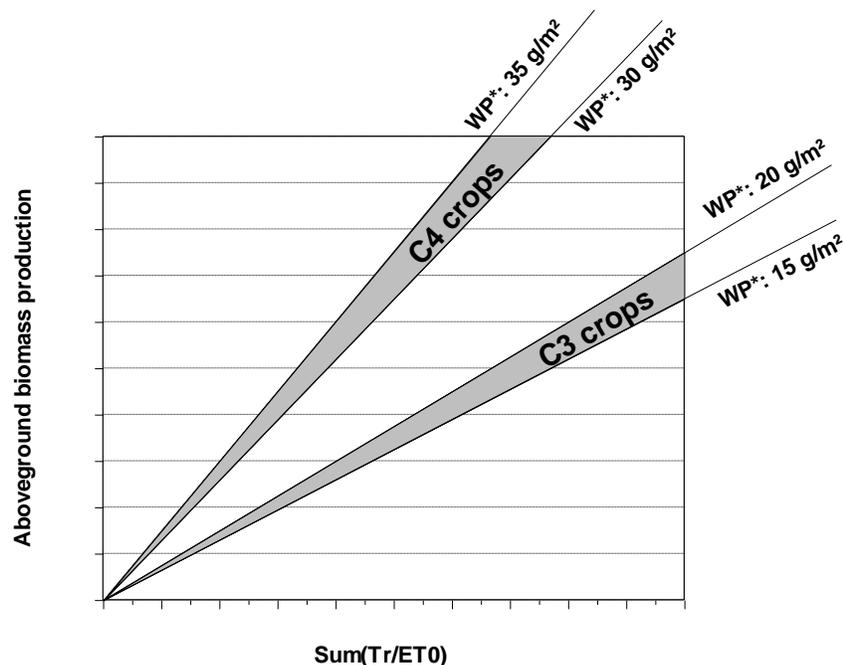
Figure 1.2h – The relationship between the aboveground biomass and total amount of water transpired for C3 and C4 crops after normalization for CO_2 and ET_0

To correct for the effect of the climatic conditions, AquaCrop uses the normalized water productivity (WP^*) for the simulation of aboveground biomass. The goal of the normalization is to make WP applicable to diverse location and seasons, including future climate scenarios. The normalization consists in a normalizing for:
-    the atmospheric CO_2 concentration. The normalization for CO_2 consists in considering the crop 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 evaporative demand of the atmosphere. The normalization for climate is obtained by dividing the daily amount of water transpired (Tr) with the reference evapotranspiration (ET_o) for that day:

After normalization, recent findings indicate that crops can be grouped in classes having a similar WP^*, which are depicted in Fig. 1.2h. Distinction can be made between C4 crops with a WP^* of about 30 to 35 g/m^2 (or 0.30 to 0.35 ton per ha) and C3 crops with a WP^* of about 15 to 20 g/m^2 (or 0.15 to 0.20 ton per ha).

The aboveground biomass production for every day of the crop cycle is obtained by multiplying the WP* with the ratio of crop transpiration to the reference evapotranspiration for that day (Tr/ET_o):

$$B = WP^* \sum_i \frac{Tr_i}{ETo_i} \qquad \text{(Eq. 1.2b)}$$

The simulated biomass production throughout the crop cycle for the canopy development and crop transpiration in Fig. 1.2g is presented in Figure 1.2i.
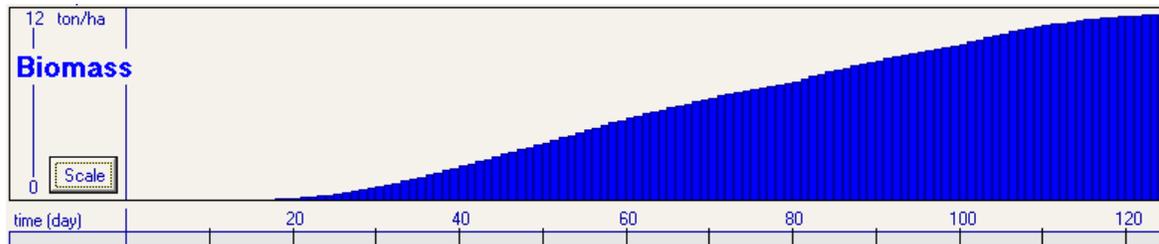
Figure 1.2i – Simulated biomass production throughout the crop cycle for the canopy development and crop transpiration presented in Fig. 1.2g

During the simulation, the normalized WP^* might be adjusted to consider:
- atmospheric CO_2 concentration different from its 369.41 ppm reference value (i.e. the concentration for the year 2000 at Mauna Loa Observatory in Hawaii). This is simulated by multiplying WP* with a correction factor. The correction factor is larger than 1 for CO_2 concentrations above 369.41 ppm, and smaller than 1 for CO_2 concentrations below the reference value;
- the type of products that are synthesized during yield formation. If they are rich in lipids or proteins, considerable more energy per unit dry weight is required then for the synthesis of carbohydrates. As a consequence, the water productivity during yield formation needs to be reduced. This is simulated by multiplying WP* with a reduction coefficient for the products synthesized;
- limited soil fertility. Since soil fertility stress might decrease the crop water productivity, the effect of stress is simulated with the help of the soil fertility stress coefficient for crop water productivity (Ks_{WP}) which varies between 1 and 0. As long as soil fertility does not affect the process, Ks_{WP} is 1 and WP* is not adjusted.

1.2.6 Step 4 – simulation of crop yield (Y)

Starting from flowering or tuber initiation the Harvest Index (HI) gradually increases to reach its reference value (HI_o) at physiological maturity (Fig. 1.2j). A too short grain/fruit filling stage or tuber formation stage as a result of early canopy senescence might result in inadequate photosynthesis and a reduction of the reference Harvest Index. For leafy vegetable crops HI builds up right after germination and reaches quickly HI_o.

Yield (Y) is obtained by multiplying the above ground biomass (B) with the adjusted reference Harvest Index:

$$Y = f_{HI}\ HI_o\ B \qquad\qquad (Eq.\ 1.2c)$$

where f_{HI} is a multiplier which considers the stresses that adjust the Harvest Index from its reference value. The adjustment of the Harvest Index to water deficits and air temperature depends on the timing and extent of stress during the crop cycle. The effect of stress on the Harvest Index can be positive ($f_{HI} > 1$) or negative ($f_{HI} < 1$). Distinction is made between stresses before the start of the yield formation, during flowering which might affect pollination, and during yield formation.
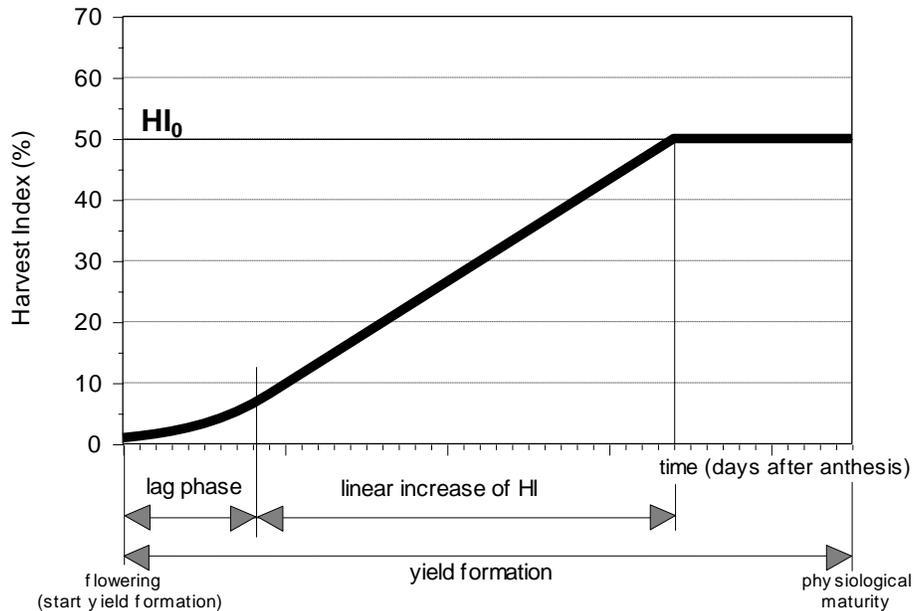
Figure 1.2j – Building up of Harvest Index from flowering till physiological maturity for fruit and grain producing crops

1.2.7 Water productivity

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

- The **biomass water productivity (WP)** refers to the amount of biomass that can be obtained with a certain quantity of water transpired (Fig. 1.2d). It is expressed as kg (biomass) per m^3 of water (transpired). This is the conceptual relation at the core of AquaCrop (B = WP x Σ(Tr)), and allows the model to estimate above ground biomass production (B) from the cumulative amount of water transpired (ΣTr);
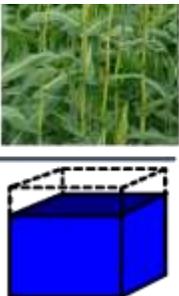
$$WP = \frac{biomass\ produced}{water\ transpired} \qquad \frac{kg\ (biomass)}{m^3\ (Tr)} \qquad \text{(Eq. 1.2d)}$$

Figure 1.2k – Biomass water productivity (WP)

- **ET water productivity (WP$_{ET}$)**, is the relationship between crop yield and evapotranspiration (Fig. 1.2m). It is expressed as kg (yield) per m^3 of water (evapotranspired). Yield is used in this equation since it is often the output in which one is most interested. ET (instead of crop transpiration) is used since soil evaporation needs to be considered as well, since water will evaporate from the crop and soil surface each time the soil is wetted by rainfall or irrigation. WP$_{ET}$ is typically used as an indicator to assess the performance of a system. AquaCrop uses WP$_{ET}$ to identify the environments in which (or management strategies by which) the yield per unit water (ET) can be maximized. This type of performance indicator is useful under conditions of scarcity of water resources. In literature WP$_{ET}$ is often referred to as water use efficiency (WUE).
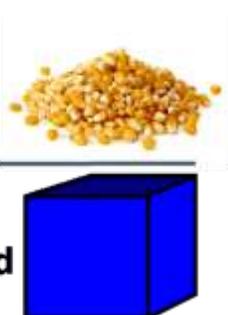
$$WUE = WP_{ET} = \frac{yield\ produced}{water\ evapotranspired} \qquad \frac{kg\ (yield)}{m^3\ (ET)} \qquad \text{(Eq. 1.2e)}$$

Figure 1.2m – ET water productivity (WP$_{ET}$)

1.3 Input requirement

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 consists of weather data, crop calendar, crop characteristics for the specific cultivar and tuned to the environment, soil characteristics, and management practices that define the environment in which the crop will develop. The input is summarized schematically in Figure 1.3. The inputs are stored in climate, calendar, crop, soil and management files and can be easily retrieved from *AquaCrop*'s data base and adjusted through the user interface.
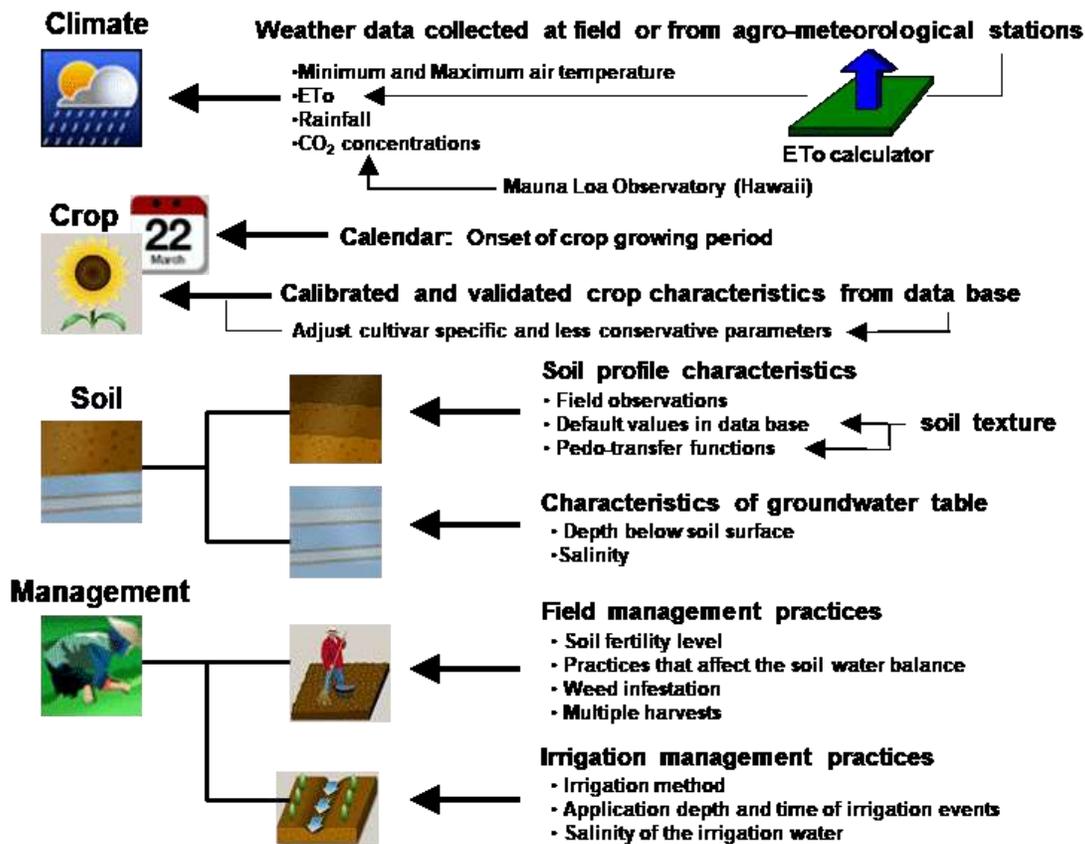

Figure 1.3 – Input data defining the environment in which the crop develops

1.3.1 Weather data

For each day of the simulation period, AquaCrop requires minimum (T_n) and maximum (T_x) air temperature, reference evapotranspiration (ET_o) as a measure of the evaporative demand of the atmosphere, and rainfall. Additional the mean annual CO_2 concentration has to be known. Temperature affects crop development (phenology), and when limiting, growth and biomass accumulation. Rainfall and ET_o are determinants for the water balance of the root zone and air CO_2 concentration affects biomass water productivity (WP*).

ET_o is derived from weather station data by means of the FAO Penman-Monteith equation (as defined in the Irrigation and Drainage Paper N° 56). An ETo calculator is integrated in AquaCrop for that purpose. The climatic data can be given in a wide variety of units, and procedures are available in the calculator to estimate missing climatic data.

The daily, 10-daily or monthly air temperature, ET_o and rainfall data for the specific environment are stored in climate files from where the program retrieves data at run time. In the absence of daily weather data, the program invokes built-in approximation procedures to derive daily temperature, ET_o and rainfall from the 10-daily or monthly means. For rainfall, with its extremely heterogeneous distribution over time, the use of 10-daily or monthly total rainfall data might strongly reduce the accuracy of the simulations. The use of daily rainfall data is strongly recommended.

Additionally, an historical time series of mean annual atmospheric CO_2 concentrations measured at Mauna Loa Observatory in Hawaii, as well as the expected concentrations for the near future are provided in AquaCrop. The data is used to adjust the WP* to the CO_2 concentration of the year for which the simulation is running. The user can load or enter other future year's CO_2 for prospective analysis of climate change.

1.3.2 Crop calendar

The likely time of planting/sowing can be specified in a crop calendar file. The crop calendar file contains either a pre-set fixed Onset Day or information to generate an Onset day by a rainfall or air temperature criterion.

1.3.3 Crop characteristics

Although grounded on basic and complex biophysical processes, AquaCrop uses a relative small number of crop parameters describing the crop characteristics. FAO has calibrated crop parameters for major agriculture crops, and provides them as default values in the model. When selecting a crop its crop parameters are downloaded from the Data base. Distinction is made between conservative, cultivar specific and less conservative parameters:
-   The conservative crop parameters do not change materially with time, management practices, or geographical location. They were calibrated with data of the crop grown under favourable and non-limiting conditions and remain applicable for stress conditions via their modulation by stress response functions. As such the conservative parameters require no adjustment to the local conditions and can be used as such in the simulations;
-   The cultivar specific and non-conservative crop parameters might require an adjustment when selecting a cultivar or environmental conditions different from the one considered for crop calibration. The non-conservative crop parameters are affected by planting, field management, conditions in the soil profile, or the weather (especially when simulating in calendar day mode). These parameters might require an adjustment after downloading to account for the local variety and or local environmental conditions.

When a crop is not available in the data bank, a crop file can be created by specifying only the type of crop (fruit or grain producing crops; root and tuber crops; leafy vegetables, or perennial herbaceous forage crops) and the length of its growth cycle. On

the basis of this information AquaCrop provides defaults or sample values for all required parameters. In the absence of more specific information these values can be used. Through the user interface the defaults can be adjusted.

1.3.4 Soil characteristics

The soil profile can be composed of up to five different horizons of variable depth, each with their own physical characteristics. The characteristics are the water retention in the fine soil fraction at saturation (θ_{sat}), field capacity (θ_{FC}), and at permanent wilting point (θ_{PWP}), and the hydraulic conductivity of the soil at saturation (K_{sat}). 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. The presence of gravel (which reduces the plant available water), and the penetrability (which might limits root zone expansion) are other soil profile characteristics.

The soil description is completed by specifying the depth and salinity of the groundwater table and its variation in time.

1.3.5 Management practices

Management practices are divided into two categories: field management and irrigation management practices:
- Under field management practices are choices of soil fertility levels, weed management, and practices that affect the soil water balance such as mulching to reduce soil evaporation, soil bunds to store water on the field, and tillage practices such as soil ridging or contours reducing run-off of rainwater. If the crop (e.g., alfalfa) is harvested several times during the growing period, a criterion to generate harvest events or the time of each individual harvest event can be specified. 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 can select the application method (sprinkler, drip, or surface), the fraction of surface wetted, and specify for each irrigation event, the irrigation water quality, the timing and the applied irrigation amount. There are also options to assess the net irrigation requirement and to generate irrigation schedules based on specified time and depth criteria. Since the criteria might change during the season, the program provides the means to test deficit irrigation strategies by applying chosen amounts of water at various stages of crop development.

1.4 Applications

AquaCrop can be used as a planning tool or to assist in management decisions for both irrigated and rainfed agriculture (Fig. 1.4). The model is particular useful:
- to understand the crop response to environmental changes (educational tool);
- to compare attainable and actual yields in a field, farm, or a region (yield gap analysis);

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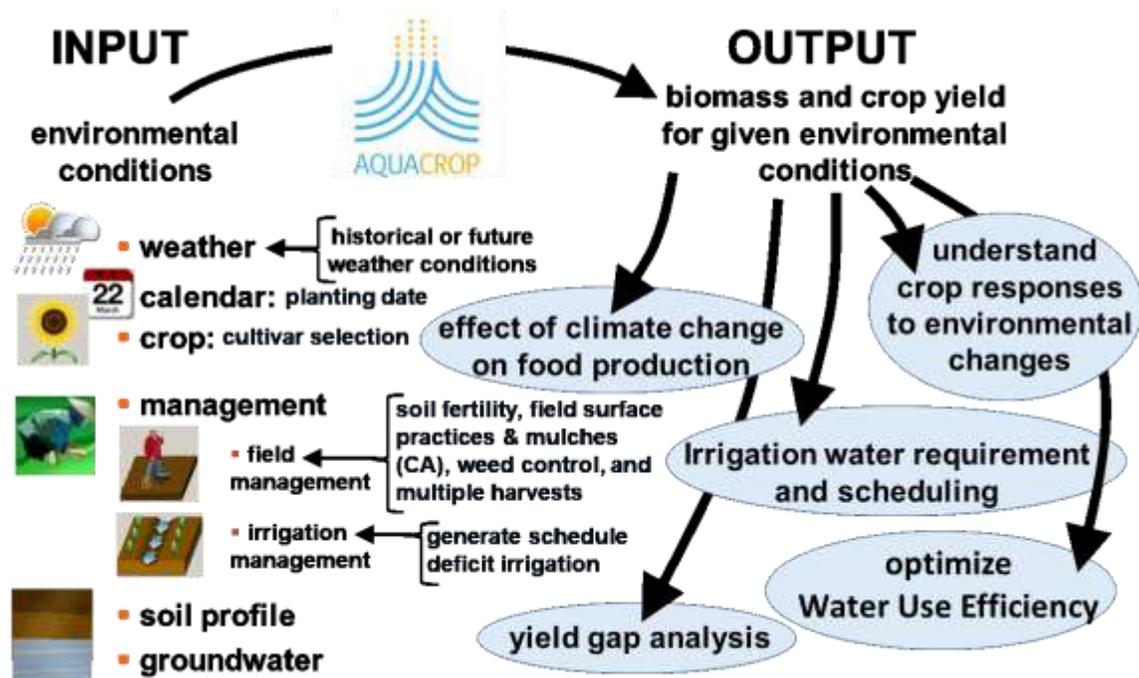

Figure 1.4 – Applications

1.5 Training videos introducing AquaCrop

A set of training modules (MP4 videos) are posted in an 'AquaCrop Training' channel of YouTube. The modules introducing the user to AquaCrop are listed in Table 1.1. For the playlist go to FAO AquaCrop website http://www.fao.org/nr/water/aquacrop.html

Table 1.1 Training videos introducing AquaCrop

Video	Learning objective	Length [min:sec]
01. Introduction to AquaCrop	Discover AquaCrop	-
– Part 1. Need for Models		05:16
– Part 2. Practical applications		04:00
– Part 3. Calculation scheme		22:58
– Part 4. Input requirements		05:24

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