Chapter 1

AquaCrop – The FAO crop model to simulate yield response to water

AquaCrop

Reference Manual
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Chapter 1.

AquaCrop – The FAO crop model to simulate yield response to water

1.1 Rationale

The complexity of crop responses to water deficits led to the use of empirical production functions as the most practical option to assess crop yield response to water. Among the empirical function approaches, FAO *Irrigation & Drainage Paper* n. 33 (Doorenbos and Kassam, 1979) represented an important source to determine the yield response to water of field, vegetable and tree crops, through the following equation

$$\left(\frac{Y_x - Y_a}{Y_x}\right) = k_y \left(\frac{ET_x - ET_a}{ET_x}\right) \qquad \text{(Eq.1.1)}$$

where Y_x and Y are the maximum and actual yield, ET_x and ET are the maximum and actual evapotranspiration, and k_y is the proportionality factor between relative yield loss and relative reduction in evapotranspiration.

Scientific and experimental progresses in crop-water relations from 1979 to date, along with the strong demand for improving water productivity as one of the major features to cope with water scarcity, induced FAO to revise its *Paper* n. 33. This was carried out through a consultative process with experts from major scientific and academic institutions, and governmental organizations worldwide.

The consultation led to a revision framework that treats separately field crops from tree crops. For the field crops, it was suggested to develop a model of proper structure and conceptualization that would evolve from Eq. 1.1 and be designed for planning, management and scenario simulations. The result is the AquaCrop model which differs from the main existing models for its balance between accuracy, simplicity and robustness.

The conceptual framework, underlying principles, and distinctive components and features of AquaCrop are described by Steduto et al. (2009), while the structural details and algorithms are reported by Raes et al. (2009). Calibration and performance evaluation for several crops are presented by Farahani et al. (2009); Garcia-Vila et al. (2009); Geerts et al. (2009); Heng et al. (2009), and Hsiao et al. (2009).

1.2 Model growth-engine and flowchart

AquaCrop evolves from the previous Doorenbos and Kassam (1979) approach (Eq. 1.1) by separating (i) the ET into soil evaporation (E) and crop transpiration (Tr) and (ii) the final yield (Y) into biomass (B) and harvest index (HI). The separation of ET into E and Tr avoids the confounding effect of the non-productive consumptive use of water (E). This is important especially during incomplete ground cover. The separation of Y into B and HI allows the distinction of the basic functional relations between environment and B from those between environment and HI. These relations are in fact fundamentally different and their use avoids the confounding effects of water stress on B and on HI. The changes described led to the following equation at the core of the AquaCrop growth engine:

$$B = WP \cdot \Sigma Tr \qquad \text{(Eq. 1.2)}$$

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 from Eq. 1.1 to Eq. 1.2 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 are different expressions of a *water-driven growth-engine* in terms of crop modeling design (Steduto, 2003). The other main change from Eq. 1.1 to AquaCrop is in the time scale used for each one. In the case of Eq. 1.1, the relationship is used seasonally or for long periods (of the order of months), while in the case of Eq. 1.2 the relationship is used for daily time steps, a period that is closer to the time scale of crop responses to water deficits. A schematic representation of the evolution of AquaCrop from Eq. 1.1 is shown in Figure 1.1.

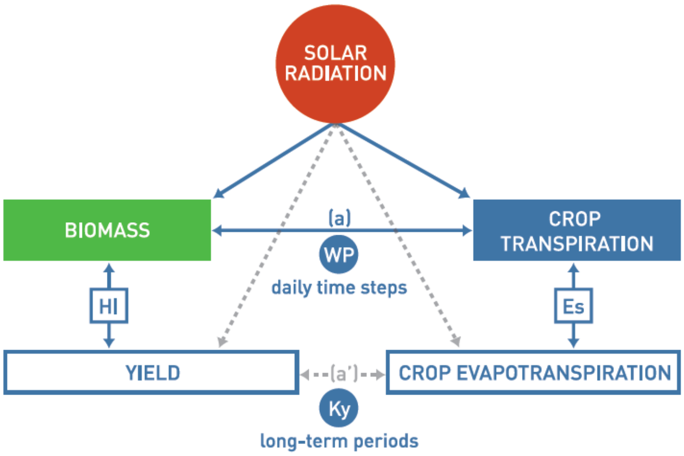

Figure 1.1
Evolution of AquaCrop from Eq. 1.1, based on the introduction of two intermediary steps: the separation of soil evaporation (E) from crop transpiration (Tr) and the attainment of yield (Y) from Biomass (B) and harvest index (HI)

To be functional, this growth engine (Eq. 1.2) needs to be inserted in a complete set of additional model components. In fact, similarly to many other models, AquaCrop has a structure that overarches the soil-plant-atmosphere continuum. It includes the soil, with its water balance; the plant, 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, etc.), as they will affect the soil water balance, crop development and therefore final yield. Pests, diseases, and weeds are not considered. The functional relationships between the different model components are depicted in the flow chart of Figure 1.2.

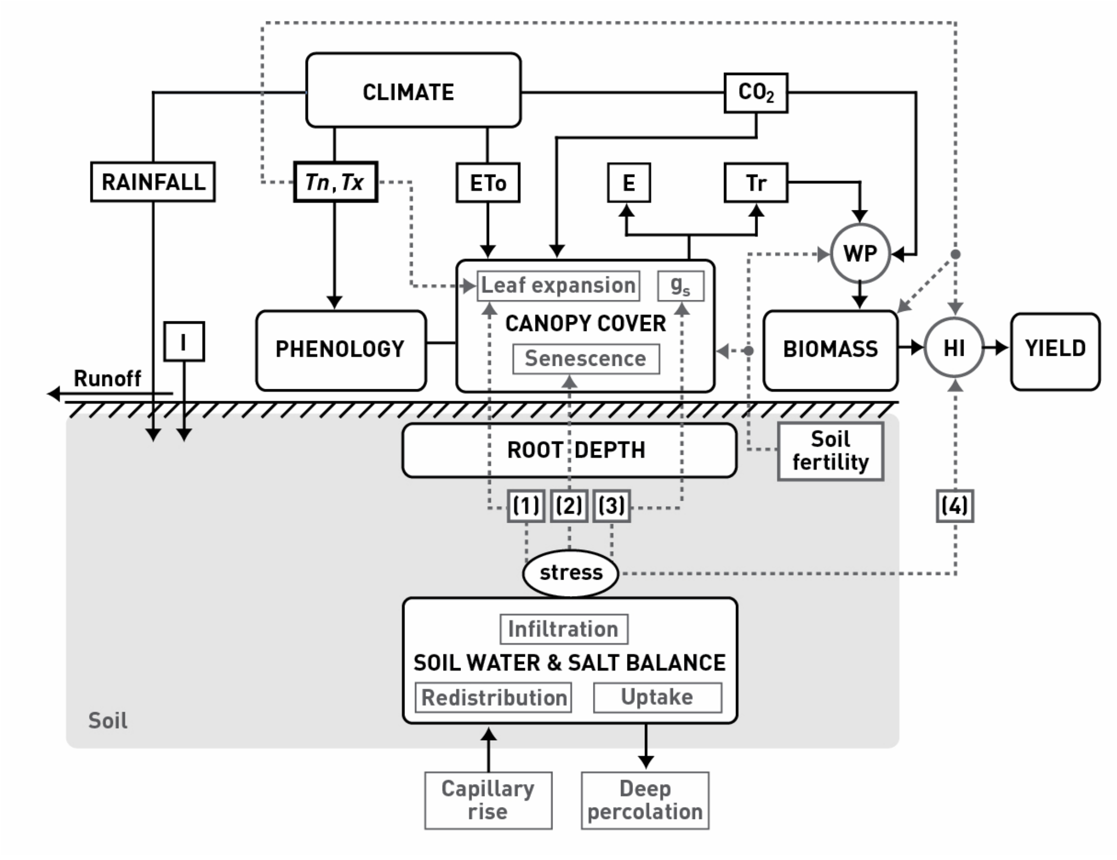

Figure 1.2
Flowchart of *AquaCrop*
indicating the main components of the soil-plant-atmosphere continuum

1.3 Soil-Plant-Atmosphere continuum

1.3.1 The atmosphere

The atmospheric environment of the crop is described in the *climate* component of AquaCrop and deals with key input meteorological variables (see Fig. 1.2). Five weather input variables are required to run AquaCrop: daily maximum and minimum air temperatures (T), daily rainfall, daily evaporative demand of the atmosphere expressed as reference evapotranspiration (ET_o), and the mean annual carbon dioxide concentration in the bulk atmosphere. While the first four are derived from typical agro-meteorological stations, the CO_2 concentration uses the Mauna Loa Observatory records in Hawaii.

ET_o is obtained following the procedures described in the FAO *Irrigation and Drainage Paper* 56 (Allen *et al.*, 1998). Where not all the required input variables for calculating ET_o are available, *Paper* 56 describes the methods to derive them. AquaCrop does not include the routines for calculating ET_o, but a separate software program (ETo calculator) based on the Paper 56 is provided to the user for such purpose.

Temperature (min and max), rainfall and ET_o may be provided at different time scales, specifically daily, 10-day, and monthly records. However, at run time AquaCrop processes the 10-day and monthly records into daily values. This flexibility for different time scales of weather input variables is required to use AquaCrop in areas of limited weather records.

As illustrated in Figure 1.2, the temperature (T) plays a role in influencing the crop development (phenology); the rainfall and ET_o are inputs for the water balance of the soil root zone; and the CO_2 concentration of the bulk atmosphere influences the crop growth rate and the WP.

1.3.2 The crop

In AquaCrop, the crop system has five major components and associated dynamic responses (see Fig. 1.2): phenology, aerial canopy, rooting depth, biomass production and harvestable yield. The crop grows and develops over its cycle by expanding its canopy and deepening its rooting system while at the same time the main developmental stages are established.

Crop responses to possible water stress, which can occur at any time during the crop cycle, occur through three major feedbacks (see Fig. 1.2): (1) reduction of the canopy expansion rate (typically during initial growth), (2) acceleration of senescence (typically during completed and late growth), and (3) closure of stomata (typically during completed growth). Water stress of particular relevance may also affect (4) the water productivity parameter (WP) and (5) the harvest index (HI).

The canopy, thus, represents the source for actual transpiration that gets translated in a proportional amount of biomass produced through the water productivity parameter, WP (Eq. 1.2). The harvestable portion of such biomass (yield) is then determined via the harvest index (HI), i.e.

$$Y = B \cdot HI \qquad \text{(Eq. 1.3)}$$

Even though AquaCrop uses a HI parameter, it does not calculate the partitioning of biomass into various organs (e.g., leaves, roots, etc.), i.e., biomass production is decoupled from canopy expansion and root deepening. 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. The relationship between shoot and root is maintained through a functional balance between canopy development and root deepening.

Depending on the data availability, preference of the user and/or simulation modes, crop growth and development can be described dynamically either in *calendar* or in *thermal* time. AquaCrop uses Growing Degree Days (GDD) to compute thermal time. Different crop developmental stages are completed once a given number of calendar days or GDD are reached.

AquaCrop distinguishes four major crop types on the basis of their harvestable yields: fruit or grain producing crops, root and tuber producing crops, leafy vegetable producing crops and forage crops. Each of this crop type has its own corresponding developmental stages. The genetic variation among species and cultivars may be implemented in the model through the variation in timing and duration of the various developmental stages, as well as through the rate of canopy expansion, rate of root deepening, the water productivity parameter and other response factors to environmental conditions.

The canopy is a crucial feature of AquaCrop through its expansion, ageing, conductance and senescence (Fig. 1.2), as it determines the amount of water transpired, which in turn determines the amount of biomass produced. The canopy expansion is expressed through the fraction of green canopy ground-cover (CC). For non stressed conditions, the expansion from emergence to full canopy development follows the exponential growth during the first half of the full development and follows an exponential decay during the second half. After the full development, the canopy can have a variable duration period before entering the senescence phase.

Being canopy development expressed through CC and not via leaf area index (LAI) is one of the distinctive features of AquaCrop. It introduces a significant simplification in the simulation, reducing the overall aboveground canopy expansion to a growth function and allowing the user to enter actual values of CC even estimated by eye. Moreover, CC may be easily obtained also from remote sensing. Beyond CC, where differences due to canopy architecture and height may influence other processes (e.g., aerodynamic conductance in determining evapotranspiration), corrections are introduced implicitly linked to the type of crop (e.g., maize will have a higher aerodynamic conductance than soybean due to expected difference in crop height).

The root system in AquaCrop is simulated through its *effective rooting depth* and its *water extraction pattern*. The *effective rooting depth* (Z) is defined as the soil depth where most of the root water uptake is taking place, even though some crops may have a few roots beyond that depth.

As previously indicated, the growth engine of AquaCrop is water driven through Eq. (1.2). The model does not simulate lower hierarchical processes expressing the intermediary steps involved in the accumulation of biomass. The underlying processes are "summarized" and synthetically incorporated into one single coefficient defined biomass water productivity (WP). The basis for using Eq. 1.2 as the core of the model growth engine lies on the conservative behaviour of WP (Steduto and Albrizio, 2005; Steduto *et al.*, 2007). The WP parameter of AquaCrop is normalized for ET_o and the carbon dioxide (CO_2) concentration of the bulk atmosphere, it may vary moderately in response to the fertility regime, and remains constant under water deficits except when severe water stress is reached. The normalization of WP for climate makes the model applicable to diverse location and seasons, including future climate scenarios.

Once the biomass (B) is obtained (Eq. 1.2), the crop yield is derived by multiplying B times the harvest index, HI (Eq. 1.3). Starting from flowering, HI is simulated after a lag phase, by a linear increase with time for a given period during yield formation that depends on the crop species and cultivar. HI can be adjusted for water deficits depending on the timing and extent of the water stress during the crop cycle.

1.3.3 The soil

The soil component of AquaCrop is configured as a dispersed system of a variable depth allowing up to 5 horizons of different texture composition along the profile. As default, the model includes all the classical textural classes present in the USDA triangle but the user can input its own specific value. For each texture class, the model associates a few hydraulic characteristics which can be estimated them from soil texture through pedotransfer functions. The hydraulic characteristics include the hydraulic conductivity at saturation, and the volumetric water content at saturation, field capacity, and wilting point.

For the soil profile explored by the root system, the model performs a water balance that includes the processes of runoff (through the curve number), infiltration, redistribution or internal drainage, deep percolation, capillary rise, uptake, evaporation, and transpiration. A daily step soil water balance keeps track of the incoming and outgoing water fluxes at the boundaries of the root zone and of the stored soil water retained in the root zone.

A distinctive feature of the water balance in AquaCrop is the separation of soil evaporation (E) from crop transpiration (Tr) based on a modification of the Ritchie's approach (Ritchie, 1972). In the simulation of E, AquaCrop includes the effects of mulches, withered canopy cover, partial wetting by localized irrigation, and the shading of the ground by the canopy.

1.3.4 The field management

The field management considers options related to the fertility level or regime to be adopted during the crop simulation, and to field-surface practices such as mulching to reduce soil evaporation, or the use of soil bunds to control surface run-off and infiltration. Four fertility levels are considered: non-limiting, near-optimal, medium, and poor fertility. These levels influence the water productivity parameter (WP), the canopy growth development and its maximum canopy cover and the rate of decline in green canopy during senescence. Thus, AquaCrop does not compute nutrient balances, but offers the user some options to incorporate the anticipated fertility regime into the overall yield response.

1.3.5 The irrigation management

The water management considers options related to (i) rainfed-agriculture (no irrigation), and (ii) irrigation where, after selecting the method (sprinkler, drip, or surface, either by furrow or flood irrigation), the user can define its own schedule on the basis of depth or timing criteria, or let the model to automatically generate the scheduling on the basis of fixed interval, fixed depth, or fixed percentage of soil water content criteria. The irrigation option is particularly suited for simulating the crop response under supplemental or deficit irrigation.

1.4 Conclusions

AquaCrop is a water-driven simulation model that requires a relatively low number of parameters and input data to simulate the yield response to water of most of the major field and vegetable crops cultivated worldwide. Its parameters are explicit and mostly intuitive and the model maintains sufficient balance between accuracy, simplicity and robustness.

The model is aimed at a broad range of users, from field engineers and extension specialists to water managers at the farm, district, and higher levels. It can be used as a planning tool or to assist in making management decisions, whether strategic, tactical or operational. The AquaCrop model represents an effort to incorporate current knowledge of crop physiological responses into a tool that can predict the attainable yield of a crop based on the water supply available. One important application of AquaCrop would be to compare the attainable against actual yields in a field, farm, or a region, to identify the constraints limiting crop production and water productivity (benchmarking tool). It can also be very useful for scenario simulations and for planning purposes for use by economists, water administrators and managers. It is suited for perspective studies such as those under future climate change scenarios. Overall, it is particularly suited to develop agricultural water management strategies for a variety of objectives and applications. Its performance has been tested for several crops with very satisfactory results.

The particular features that distinguishes AquaCrop from other crop models is its focus on water, the use of ground canopy cover instead of leaf area index, and the use of water productivity values normalized for atmospheric evaporative demand and of carbon dioxide concentration that confer the model an extended extrapolation capacity to diverse locations and seasons, including future climate scenarios. Moreover, although the model is simple, it gives particular attention to the fundamental processes involved in crop productivity and in the responses to water, from a physiological and agronomic background perspective.

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