



AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: I. Concepts and Underlying Principles

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ABSTRACT

This article introduces the FAO crop model AquaCrop. It simulates attainable yields of major herbaceous crops as a function of water consumption under rainfed, supplemental, deficit, and full irrigation conditions. The growth engine of AquaCrop is *water-driven*, in that transpiration is calculated first and translated into biomass using a conservative, crop-specific parameter: the biomass water productivity, normalized for atmospheric evaporative demand and air CO₂ concentration. The normalization is to make AquaCrop applicable to diverse locations and seasons. Simulations are performed on thermal time, but can be on calendar time, in daily time-steps. The model uses canopy ground cover instead of leaf area index (LAI) as the basis to calculate transpiration and to separate out soil evaporation from transpiration. Crop yield is calculated as the product of biomass and harvest index (HI). At the start of yield formation period, HI increases linearly with time after a lag phase, until near physiological maturity. Other than for the yield, there is no biomass partitioning into the various organs. Crop responses to water deficits are simulated with four modifiers that are functions of fractional available soil water modulated by evaporative demand, based on the differential sensitivity to water stress of four key plant processes: canopy expansion, stomatal control of transpiration, canopy senescence, and HI. The HI can be modified negatively or positively, depending on stress level, timing, and canopy duration. AquaCrop uses a relatively small number of parameters (explicit and mostly intuitive) and attempts to balance simplicity, accuracy, and robustness. The model is aimed mainly at practitioner-type end-users such as those working for extension services, consulting engineers, governmental agencies, nongovernmental organizations, and various kinds of farmers associations. It is also designed to fit the need of economists and policy specialists who use simple models for planning and scenario analysis.

MODELS ARE GENERALLY DEFINED as simplification or abstraction of a real system (Loomis et al., 1979). This is particularly the case for models of biological systems like crops, where the reality is composed of a vast number of components and processes interacting over a wide range of organizational levels (Sinclair and Seligman, 1996). Specifically, a crop model can be described as a quantitative scheme for predicting the growth, development, and yield of a crop, given a set of genetic features and relevant environmental variables (Monteith, 1996).

Crop models can be useful for different purposes; primarily, crop models interpret experimental results and work as agronomic research tools for research knowledge synthesis. Lengthy and expensive field experiments, especially with a high number of treatments, can be preevaluated through a well-proven model to sharpen the field tests and to lower their overall costs (Whisler et al., 1986). Another application of crop models is to use them as decision support tools for system

management. Optimum management practices, either strategic or tactic, such as planting date, cultivar selection, fertilization, or water and pesticides usage, can be assessed through proven models for making seasonal or within-season decisions (Boote et al., 1996). Other uses, such as planning and policy analysis, can benefit from modeling as well.

Efforts in crop simulation modeling, aimed primarily at the integration of physiological knowledge, were started in the late 1960s by several research groups; among them that of de Wit and co-workers (Brouwer and de Wit, 1969). Subsequent efforts led to the development of more advanced models, some of them more oriented toward the single-plant scale, such as CERES (Jones and Kiniry, 1986); and others more oriented toward canopy-level scale and as management tools to assist in decision making, such as EPIC (Williams et al., 1989), its derivation ALMANAC (Kiniry et al., 1992), CropSyst (Stockle et al., 2003), the DSSAT cropping system model (Jones et al., 2003), the Wageningen models (van Ittersum et al., 2003) and the APSIM models (Keating et al., 2003). Scientists, graduate students, and advanced users in highly commercial farming represent the typical users of these models.

Depending on the purpose and objectives of the crop model, we can distinguish two main modeling approaches: *scientific* and *engineering*. The first mainly aims at improving our understanding of crop behavior, its physiology, and its responses to environmental changes. The second attempts to provide sound management advice to farmers or predictions to policymakers

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Abbreviations: ERD, effective rooting depth; ET_o, reference evapotranspiration; FC, field capacity; GDD, growing degree day; HI, harvest index; LAI, leaf area index; PWP, permanent wilting point; Tr, crop transpiration; WP, water productivity.

(Passioura, 1996). Scientific modeling is also meant to be more mechanistic, based on laws and theory on how the system functions, while engineering modeling is meant to be functional, based on a mixture of well-established theory and robust empirical relationships, as termed by Addiscott and Wagenet (1985).

The model presented in this paper is a canopy-level and engineering type of model, mainly focused on simulating the attainable crop biomass and harvestable yield in response to the water available. The model focuses on water because it is a key driver of agricultural production, and because recent growth in human population and increased industrialization and living standards around the world are demanding a greater share of our finite water resources, making water an increasingly critical factor limiting crop production. Additionally, the crop response to water deficit remains among the most difficult responses to capture in crop modeling, as water deficits vary in intensity, duration, and time of occurrence (Hsiao, 1973; Hsiao et al., 1976; Bradford and Hsiao, 1982).

The complexity of crop responses to water deficits led earlier to the use of empirical production functions as the most practical option to assess crop yield as related to water. Among the methods based on this approach, FAO Irrigation & Drainage Paper no. 33, *Yield Response to Water* (Doorenbos and Kassam, 1979) stands out. For decades, this paper has been widely adopted and used to estimate yield response to water of numerous crops, particularly by planners, economists, and engineers (e.g., Vaux and Pruitt, 1983; Howell et al., 1990). Other software developed by FAO, such as the irrigation scheduling model CROPWAT (Smith, 1992), uses this approach to simulate water-limited yield. Central to the approach is the following equation, relating yield to water consumed:

$$\left(\frac{Y_x - Y_a}{Y_x} \right) = K_y \left(\frac{ET_x - ET_a}{ET_x} \right) \quad [1]$$

where Y_x and Y_a are the maximum and actual yield, ET_x and ET_a are the maximum and actual evapotranspiration, and K_y is the proportionality factor between relative yield loss and relative reduction in evapotranspiration.

Understanding of soil–water–yield relations has improved markedly since 1979; this, along with the strong demand for improving water productivity as a means to cope with water scarcity, prompted FAO to reassess and restructure its Paper no. 33. This was done through consultation with experts from major scientific and academic institutions and governmental organizations worldwide. The consultation led to the decision of developing a simulation model for field and vegetable crops that would evolve from Eq. [1], to remain water-driven and retain the original capacity of Paper no. 33 for broad-spectrum applications, and at the same time achieve significant improvements in accuracy while maintaining adequate simplicity and robustness. This paper reports the concepts and principles of the resultant crop model.

At the start, the main existing crop models were evaluated since many of them already could simulate yield response to water. These models, however, presented substantial complexity for the majority of targeted users, such as extension personnel, water user associations, consulting engineers, irrigation and farm managers, and economists. Furthermore, they required an

extended number of variables and input parameters not easily available for the diverse range of crops and sites around the world. Usually, these variables are much more familiar to scientists than to end users (e.g., LAI or leaf water potential). Lastly, the insufficient transparency and simplicity of model structure for the end user are considered a strong constraint. To address all these concerns, and in trying to achieve an optimum balance between accuracy, simplicity, and robustness, a new crop model, named AquaCrop, has been developed by FAO. The conceptual framework, underlying principles, and distinctive components and features of AquaCrop are herein described, while in companion papers of this symposium the structural details and algorithms are reported by Raes et al. (2009) and the calibration and performance evaluation for several crops are presented by others.

MODEL DESCRIPTION

Model Growth-Engine and Structural Components

AquaCrop evolves from the previous Doorenbos and Kassam (1979) approach (Eq. [1]), where relative ET is pivotal in calculating Y . AquaCrop progressed by (i) separating the ET into crop transpiration (Tr) and soil evaporation (E), (ii) developing a simple canopy growth and senescence model as the basis for the estimate of Tr and its separation from E , (iii) treating the final yield (Y) as a function of final biomass (B) and HI, and (iv) segregating effects of water stress into four components: canopy growth, canopy senescence, Tr , and HI. The separation of ET into Tr and E avoids the confounding effect of the nonproductive consumptive use of water (E), which is important especially during incomplete ground cover, and led to the conceptual equation at the core of the AquaCrop growth engine:

$$B = WP \times \Sigma Tr \quad [2]$$

where WP is the water productivity (biomass per unit of cumulative transpiration), which tends to be constant for a given climatic condition (de Wit, 1958; Hanks, 1983; Tanner and Sinclair, 1983). By normalizing appropriately for different climatic conditions, WP becomes a conservative parameter (Steduto et al., 2007). Thus, stepping from Eq. [1] to Eq. [2] has a fundamental implication for the robustness and generality of the model. It is worth noting though, that both equations are expressions of a *water-driven growth-engine* in terms of crop model design (Steduto, 2003). The other improvement from Eq. [1] to AquaCrop is the time scale used. In the case of Eq. [1], the relationship is used seasonally or for different phases of the crop lasting weeks or months, while in the case of Eq. [2] the relationship is used for daily time steps, a period closer to and approaching the time scale of crop responses to water deficits (Acevedo et al., 1971).

As in other models, AquaCrop structures its soil–crop–atmosphere continuum by including (i) the soil, with its water balance; (ii) the plant, with its growth, development, and yield processes; and (iii) the atmosphere, with its thermal regime, rainfall, evaporative demand, and carbon dioxide concentration. Additionally, some management aspects are explicit, with emphasis on irrigation, but also the levels of soil fertility as they

affect crop development, water productivity, and crop adjustments to stresses, and therefore final yield. Pests and diseases are not considered.

The functional relationships between the different AquaCrop components are depicted in Fig. 1. The atmosphere and the soil components are largely in common with many other models. The plant component and its relations to soil water status and evaporative demand of the atmosphere are more distinctive, with effects of water stress separated into four elements, that on leaf and hence canopy growth, on stomatal opening and hence transpiration, on canopy senescence and on HI, as elaborated on later. The main concepts of AquaCrop, together with their mathematical formulation distinctive of this model, are presented below. Processes and algorithms common or similar to those used in other models are only addressed briefly here, with the appropriate citations. For further insight into model software, algorithms and operation, see Raes et al. (2009).

Atmospheric and Soil Environments

The atmospheric environment of the crop is specified in the *climate* component of AquaCrop (Fig. 1), with five daily weather input variables required to run the model: maximum and minimum air temperatures, rainfall, evaporative demand of the atmosphere expressed as reference evapotranspiration (ET_o), and the mean annual carbon dioxide concentration (CO_2) in the atmosphere. Temperature affects crop development (phenology), and when limiting, growth and biomass accumulation. Rainfall and ET_o are determinants of water balance of the soil root zone and air CO_2 concentration affects WP and leaf growth.

The first four weather variables are derived from typical records of agrometeorological stations, and the CO_2

concentration is the annual mean measured by the Mauna Loa Observatory in Hawaii. The past and current CO_2 concentration values are stored in AquaCrop, while that for future years need to be entered by the user. The ET_o is calculated by the Penman–Monteith equation following the procedures of FAO Paper no. 56 (Allen et al., 1998). When necessary, input temperature, rainfall, and ET_o can be mean decade or monthly values, with the model invoking built-in approximation procedures to derive daily values (Raes et al., 2009).

The soil of AquaCrop is configured as horizons of variable depth, allowing up to five layers of different texture along the profile, which usually would be specified by the user. The hydraulic characteristics considered are: field capacity (FC) or the upper limit of volumetric water holding capacity, permanent wilting point (PWP), taken as the lower limit of water holding capacity, drainage coefficient (τ), and hydraulic conductivity at saturation (K_{sat}). The model includes all the textural classes in the USDA triangle (Soil Conservation Service, 1991), and can estimate the hydraulic characteristics according to textural class through pedotransfer functions (Saxton et al., 1986). There is no doubt, however, that user specified values would be more applicable for specific locations.

For the soil profile explored by the root system, the model performs a daily water balance that includes the processes of infiltration, runoff, internal drainage within the root zone, root extraction in different depth layers, deep percolation, evaporation, transpiration and, in a later version, also capillary rise. The model keeps track of the incoming and outgoing water fluxes and changes in soil water content within the boundaries of the root zone, as described by Raes (1982). Water uptake is simulated by computing a root extraction term S (Feddes et al., 1978). Other details are found in Raes et al. (2009).

AquaCrop separates soil E from Tr according to the extent of green canopy cover. Soil E is taken to be basically proportional to the area of soil not covered by the canopy, but adjusted empirically for effects of microadvection, as detailed in Raes et al. (2009). Soil evaporation is based on Ritchie's approach (Ritchie, 1972), following the classical theory of bare-soil evaporation (Philip, 1957; Ritchie, 1972) in which only Stage I (the energy limited phase) and Stage II (the declining phase limited by the transport of water to the soil surface) are considered. However, instead of the time-dependent function used in many other models for Stage II evaporation, AquaCrop uses a function that is dependent on water content of the thin top soil layer for this purpose, to better reflect E under conditions of low as well as high evaporative demand. Although the model operates in daily time steps, Stage I evaporation is calculated in fractions of a day. Details on soil E, including effects of mulch and shading of the soil by senescent and nontranspiring canopy, are described in the next paper of this symposium (Raes et al., 2009).

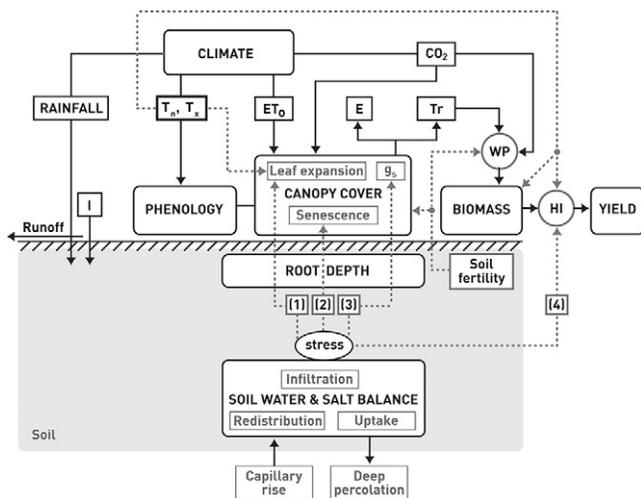


Fig. 1. Chart of AquaCrop indicating the main components of the soil–plant–atmosphere continuum and the parameters driving phenology, canopy cover, transpiration, biomass production, and final yield [I, irrigation; T_n , minimum air temperature; T_x , Max air temperature; ET_o , reference evapotranspiration; 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), different water stress response functions]. Continuous lines indicate direct links between variables and processes. Dashed lines indicate feedbacks. For explanation, see processes description.

Crop

Biomass of the crop is simulated to accumulate over time as a function of the water transpired. Water deficit may develop any time during life cycle of the crop, affecting Tr and hence biomass accumulation, depending on timing, severity, and duration of the stress. For grain, fruit, and tuber and root crops, only a part of the biomass is partitioned to the harvested organs to give yield. The HI can be affected by water stress

in rather complicated ways, depending on stress severity and timing relative to the reproductive process (Hsiao et al., 1976; Bradford and Hsiao, 1982; Sadras and Connor, 1991; Hsiao, 1993a; Hammer and Muchow, 1994; Kemanian et al., 2007). These principles serve as the background framework for the crop component of this model.

In AquaCrop, the crop system has five major components and associated dynamic responses (Fig. 1): phenology, foliage 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 progressing through its phenological stages. Crop responds to water stress, which can occur at any time, through four major control links via stress coefficients (K_s , see Fig. 1): reduction of canopy expansion rate (typically during initial growth), closure of stomata (throughout the life cycle), acceleration of canopy senescence (typically during late growth), and changes in HI (after the start of reproductive growth). Green canopy cover and duration represent the source for transpiration, and the amount of water transpired translates into a proportional amount of biomass produced through WP (Eq. [2]). The harvestable portion of the biomass, the yield, is then determined as $B \times HI$.

It is important to note that in AquaCrop, beyond the partitioning of B into Y , there is no partitioning of B 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. In AquaCrop, the interdependence between shoot and root is not tight and mostly indirect. Canopy is linked to root depth via the effect of water deficit in the rooting volume on canopy expansion and senescence. Root deepening rate is linked to canopy via its growth and an empirical function tied to stress effects on stomata. Raes et al. (2009) should be consulted for details.

Phenology and Crop Type

With phenology being determined largely by cultivar characteristics and temperature regimes, AquaCrop, similarly to many other models, uses thermal time, that is, growing degree day (GDD), as the default clock, but runs only in daily (calendar) time step. Calendar time clock is an option for the user. The GDD is calculated following Method 2 as described by McMaster and Wilhelm (1997), with an important modification, that no adjustment is made of the minimum temperature when it drops below the base temperature. This allows the more realistic consideration of the damage caused by air temperature below the base temperature and should make simulation of winter crops more realistic. Details of the GDD calculations are given by Raes et al. (2009).

AquaCrop addresses four major crop types: fruit or grain crops; root and tuber crops; leafy vegetable crops, and forage crops typically subjected to several cuttings per season. For all crops, the key developmental stages are: emergence, start of flowering (anthesis) or root/tuber initiation, maximum rooting depth, start of canopy senescence, and physiological maturity. Maximum canopy size is an important parameter of AquaCrop but in addition to phenology, it is equally dependent on planting density and canopy growth rate as modulated by stresses. Therefore, it is simulated in terms of these variables by the model.

Canopy size as a function of time also depends on the determinacy of the crop, and determinacy can be varied by the user. These aspects are more fully described in Raes et al. (2009).

The genetic variation among species dictates that AquaCrop be calibrated for each species. Once extensively calibrated, the expectation (see Hsiao et al., 2009) is that a number of the fundamental parameters would be widely applicable even to different cultivars. Cultivars usually vary in timing and duration of the various developmental stages, and possibly other parameters taken to be conservative. Thus, a specific cultivar needs to be evaluated in terms of the calibrated parameters listed for the generic crop in the crop-file database of AquaCrop, and adjustments made when necessary.

Water Productivity and Aboveground Biomass

Biomass WP is central to the operation of AquaCrop, since its growth engine is water driven through Eq. [2]. The model does not simulate lower hierarchical processes, those intermediary steps involved in the accumulation of biomass. The underlying processes are “summarized” and integrated into a single coefficient, WP. The basis for using Eq. [2] as the core of the model growth engine lies on the conservative behavior of WP, first demonstrated in studies at the start of the 20th Century, summarized and analyzed insightfully by de Wit (1958). de Wit also showed that normalization for different evaporative demands of the environment is necessary to generalize WP and keep it conservative for application in different environments. Further advance was made in a subsequent analysis by Tanner and Sinclair (1983). Hsiao and Bradford (1983) and Steduto et al. (2007) discussed the basic physiological features conferring constancy to the relationship between photosynthetic CO_2 assimilation or biomass production and transpiration. Experimental evidence of the conservative behavior of WP for many crop species is quite exhaustive (e.g., Fisher and Turner, 1978; Tanner and Sinclair, 1983; Hanks, 1983). Moreover, WP has been shown to be conservative under water and salinity stress, along with a low sensitivity to nutrient deficiency (e.g., Steduto et al., 2000; Steduto and Albrizio, 2005).

The WP parameter of AquaCrop is normalized for climate and can be taken as a near constant for a given crop not limited by mineral nutrients, regardless of water stress except for extremely severe cases. For nutrient-limited situations, the model provides categories ranging from slight to severe deficiencies corresponding to lower and lower WP. For many crop species, WP increases slightly with increased air CO_2 concentrations, as will be discussed below.

The normalization of WP for climate in AquaCrop is based on the atmospheric evaporative demand as defined by ET_o and the CO_2 concentration of the atmosphere. The goal is to make the WP value in the model specific for each crop applicable to diverse location and seasons, including future climate scenarios. The equation for calculating normalized water productivity (WP*) is the following:

$$WP^* = \left[\frac{B}{\sum \left(\frac{Tr}{ET_o} \right) } \right]_{[CO_2]} \quad [3]$$

with the summation taken over the sequential time intervals spanning the period when B is produced. The $[\text{CO}_2]$ outside the bracket indicates that the normalization is for a given year with its specific mean annual CO_2 concentration. The equation for adjusting WP^* as the CO_2 concentration varies is described in Raes et al. (2009). The theoretical basis for using ET_o instead of vapor pressure deficit (VPD) to normalize is discussed in Asseng and Hsiao (2000); the experimental data demonstrating the superiority of normalization by ET_o instead of VPD are presented in Steduto et al. (2007); and the normalization for different air CO_2 concentration is described in Steduto et al. (2007). Additional background information on the ET_o normalization is found in Steduto and Albrizio (2005), and on the CO_2 normalization, in Hsiao (1993b). The normalization, in addition to making the WP^* applicable over a range of evaporative demand, also coalesces different crops grown at different times of the year into classes having similar WP^* . Cumulative B and cumulative Tr/ET_o over the season are plotted in Fig. 2 for wheat, sweet sorghum, sunflower, and chickpea as examples of this coalescence. Other evidence of the conservative nature of WP^* is found in Steduto et al. (2007), which also gives more details on the normalization procedure.

Using WP^* , AquaCrop calculates daily aboveground biomass production (B_i , with i as running number designating a particular day) from daily transpiration (Tr_i) and the corresponding daily evaporative demand of the atmosphere expressed as $\text{ET}_{o,i}$:

$$B_i = \text{WP}^* \left(\frac{\text{Tr}_i}{\text{ET}_{o,i}} \right) \quad [4]$$

The single value of the normalized WP^* (the slope of the relationships in Fig. 2b) is generally used for the entire crop cycle. However, in crops where the harvestable yield has a high proportion of lipids and protein, more energy is required per unit of dry weight produced (Penning de Vries et al., 1974, 1983; Azam-Ali and Squire, 2002) after the grain/fruit begin to grow than before. Therefore, AquaCrop separates the preanthesis and postanthesis WP^* by providing an adjustment that reduces WP^* by a chosen fraction.

Biomass production may be hampered by low temperatures beyond the restriction accounted for by GDD and irrespective of Tr and ET_o . This temperature limitation is simulated with an adjustment factor that reduces WP^* below normal values as a function of GDD, as discussed in Raes et al. (2009).

Responses to Water Stress

Water stress can have major impact on productivity and yield depending on timing, severity, and duration as outlined previously. The model distinguishes four stress effects: on leaf growth, stomata conductance, canopy senescence, and HI. With the exception of HI, these effects are manifested through their individual stress coefficient K_s , an indicator of the relative intensity of the effect. In essence, K_s is a modifier of its target model parameter, and varies in value from one, when the effect is non-existent, to zero when the effect is maximum. For water stress, K_s is a function of water content in the root zone, expressed as a fractional depletion (p) of the total available water (TAW, the volume of water the soil can hold between FC and PWP), and its values span a range corresponding to the upper and lower threshold in soil water content specific for a crop.

The upper and lower thresholds are for average evaporation conditions. It is well known, however, that as the middle part of the soil–plant–atmosphere continuum, leaf and shoot water status are also affected by the rate of transpiration, and hence, by evaporative demand (Denmead and Shaw, 1962; Hsiao, 1990). This effect of transpiration or evaporative demand on leaf expansion has been documented under laboratory (Hsiao et al., 1970) and field conditions (Sadras et al., 1993). To account for this, the upper and lower thresholds are adjusted according to ET_o of the day relative to a reference ET_o (typically set at 5 mm per day), being higher (wetter soil) for days of high evaporative demand and lower (drier soil) for days of low evaporative demand. For details on this adjustment see Raes et al. (2009).

The relation of K_s vs. p is usually not linear due to plant acclimation and adaptation to the stress, and to the nonlinearity of the matric potential vs. volumetric soil water content relationships. As described in Raes et al. (2009), a range of shapes for K_s vs. p curves (stress response curves) are provided in AquaCrop to select from. Three of the shapes are shown in Fig. 3.

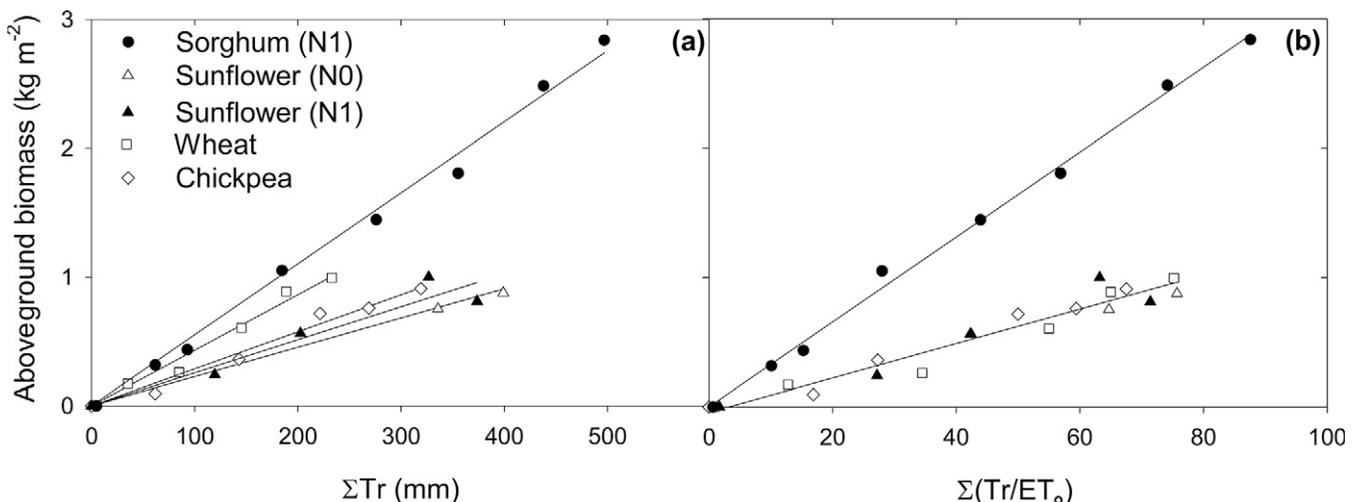


Fig. 2. Relationships (a) between aboveground biomass and cumulative transpiration (ΣTr) and (b) between aboveground biomass and cumulative normalized transpiration for reference-crop evapotranspiration [$\Sigma(\text{Tr}/\text{ET}_o)$], during the crop cycle of sunflower (under two N levels and up to anthesis), sorghum, wheat, and chickpea (redrawn from Steduto and Albrizio, 2005).

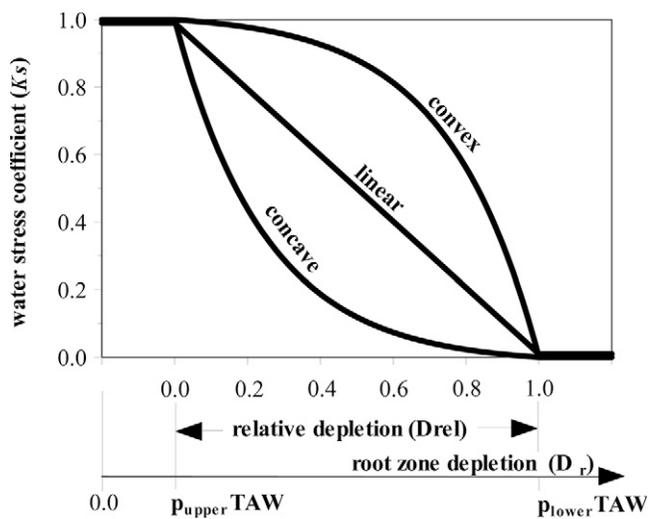


Fig. 3. Examples of stress coefficients (K_s) response function to the relative depletion in soil water content. The function assumes linear shape when $f_{\text{shape}} = 1$, concave shape when $f_{\text{shape}} < 0$, and convex shape when $f_{\text{shape}} > 0$. The initial and final values of fractional depletion (p) are arbitrarily taken at 0 and 1, respectively, as examples.

It has long been established in the plant–water relations literature that leaf expansive growth is the most sensitive of plant processes to water stress, and that stomatal conductance and senescence acceleration are considerably less sensitive in comparison (Boyer, 1970; Hsiao, 1973; Bradford and Hsiao, 1982; Sadras and Milroy, 1996). The general guideline is then to set the stress thresholds for K_s in AquaCrop accordingly, as exemplified in Fig. 4.

Note that for stomata and senescence the lower threshold is fixed at $p = 1$ (i.e., at PWP) in AquaCrop, while that for leaf growth is adjustable and should be set at a p value substantially less than one. For all three K_s curves in Fig. 4, the shape is convex, but the degree of curvature differs among the three. The convex nature is largely the consequence of adjustments by the crop to cope with the developing water stress that improve with time its resistance to stress. Also significant is the fact that generally for most soils the drop in matric potential (increase in soil water tension) becomes more and more steep as soil water content depletes near and approaches its PWP. The opposite curve shape, concave, is out of the range of norm. AquaCrop, however, provides those shapes too (Raes et al., 2009) for possible use in truly exceptional cases. One should not attribute much functional significance to the difference in the degree of curvature among the three curves in Fig. 4 as the algorithms translating the impact of K_s on canopy growth and stomatal conductance are largely functional based, whereas that for senescence is arbitrary and totally empirical.

The response of HI to soil water depletion is not depicted in Fig. 4 because it is more complex and involves more than one component. There is no K_s for HI in AquaCrop, as stress effects on HI are linked to K_s for leaf growth and stomata, and indirectly to K_s for senescence when the effect is due to a reduction in green canopy duration, as is elaborated on in the following sections.

Canopy Component

The canopy is a crucial feature of AquaCrop. Through its expansion, aging, conductance, and senescence, it determines

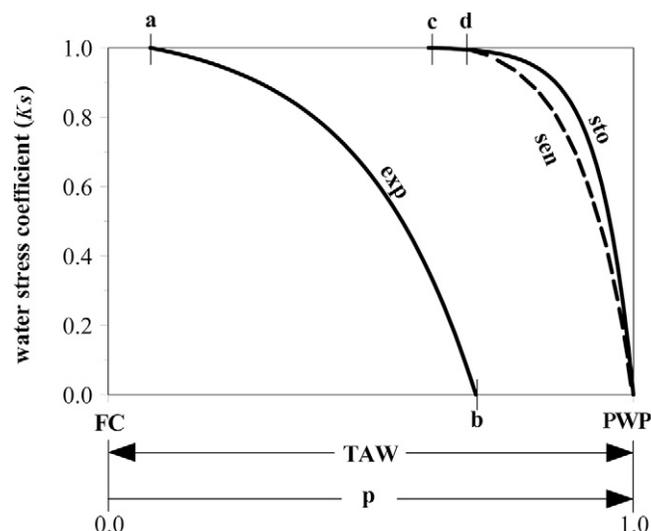


Fig. 4. Stress coefficients (K_s) for leaf expansion (exp), stomatal conductance (sto) and canopy senescence (sen) as functions of soil water depletion, exemplified by functions used in the simulation of maize productivity and yield. TAW (total available water) is the amount of water a soil can hold between field capacity (FC) and permanent wilting point (PWP). p is the relative depletion of soil water expressed as fractional TAW. As indicated by their locations on the horizontal axis, point a and point b are, respectively, the upper and lower threshold for leaf expansion, point c is the upper threshold for stomatal conductance, and point d is the upper threshold for senescence. Note that the lower thresholds for stomata and for senescence are fixed at PWP.

the amount of water transpired, which in turn determines the amount of biomass produced (Fig. 1). Having foliage development of the crop expressed through canopy cover (CC) and not via LAI is one of the distinctive features of AquaCrop. It introduces significant simplification in the simulation, consolidating leaf expansive growth, angle, and distribution to an overall growth function and allowing the user to enter actual values of CC, even that estimated by eye. Further, there is the advantage that CC may be easily obtained from remote sensing sources either to check the simulated CC or as input for AquaCrop.

As conceptualized (Hsiao, 1982; Bradford and Hsiao, 1982), when green canopy cover is sparse, the growth of canopy, being dependent on the existing canopy size for photosynthesis, follows first order kinetics (or has a constant relative growth rate). This led to the use of an exponential growth equation to simulate canopy development for the first half of the growth curve under nonstress conditions:

$$CC = CC_0 e^{CGC \times t} \quad [5]$$

where CC is the canopy cover at time t and is expressed in fraction of ground covered, CC_0 is initial canopy size (at $t = 0$) in fraction, and CGC is canopy growth coefficient in fraction per GDD or per day, a constant for a crop under optimal conditions but modulated by stresses. The CC_0 is proportional to plant density and the mean initial canopy size per seedling (cc_0), and this feature is used by the model to account for variations in plant density.

In principle, exponential growth of canopy should be expected only after crop seedlings become autotrophic and not before, as first-order kinetics applies only if canopy growth rate

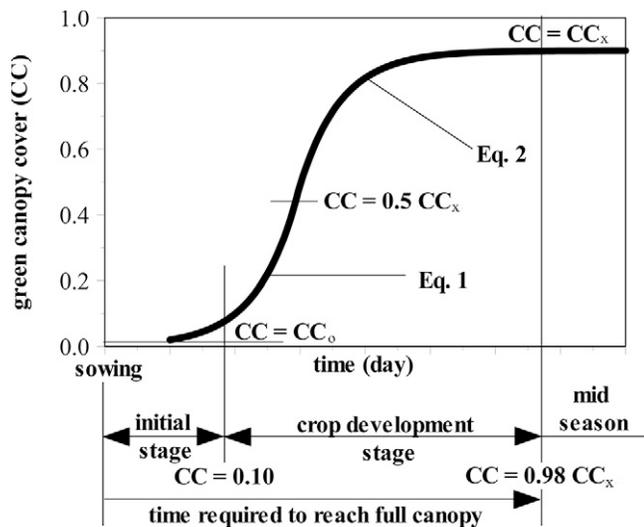


Fig. 5. Schematic representation of canopy development during the exponential growth and the exponential decay stages. CC_o and CC_x are the initial and maximum green canopy cover, respectively.

is proportional to the existing CC size (Bradford and Hsiao, 1982; Hsiao, 1993b). After emergence and before they become autotrophic, seedlings' growth is determined first completely and then partially by the rate of mobilization of seed reserve. Only after the first leaf or leaf pair turns fully green and the seed reserve is exhausted is Eq. [5] applicable. Based on field data with a number of crop species and taken into account typical heterogeneity of germination, it was decided that foliage canopy cover by seedlings at the time of 90% seedling emergence can be taken as CC_o . Obviously, at this time the early seedlings have passed the start of autotrophy for one or more days, and the late seedlings have yet to become autotrophic or only beginning to emerge. The assumption is that the 90% seedling emergence is representative of the whole population. It follows that CC_o is obtained by multiplying plant density and cc_o , the canopy size for the average seedling at the time of 90% emergence.

For a number of crop species the value of cc_o has already been assessed and found to be conservative (e.g., Hsiao et al., 2009, for maize). The intent is to have a well-tested value of cc_o for most of the important crop species as default in AquaCrop and the user only has to enter the plant density. Although cc_o is a conservative crop-species parameter, small adjustments may be required for specific varieties.

For the second half of the CC curve, because the plants begin to shade each other more and more, canopy growth no longer is proportional to existing canopy size. Hence, for the second half, CC follows an exponential decay, that is,

$$CC = CC_x - (CC_x - CC_o) \times e^{-CGC \times t} \quad [6]$$

where CC_x is the maximum canopy cover for optimal conditions. Mathematics dictates that true maximum canopy cover is at $t = \infty$. AquaCrop, however, approximates by taking 98% of the theoretical maximum as CC_x . For extensively studied crops, CC_x is assessed from the literature and default values are provided by AquaCrop. Since CC_x is determined also by plant density, a farm management option, the user should adjust

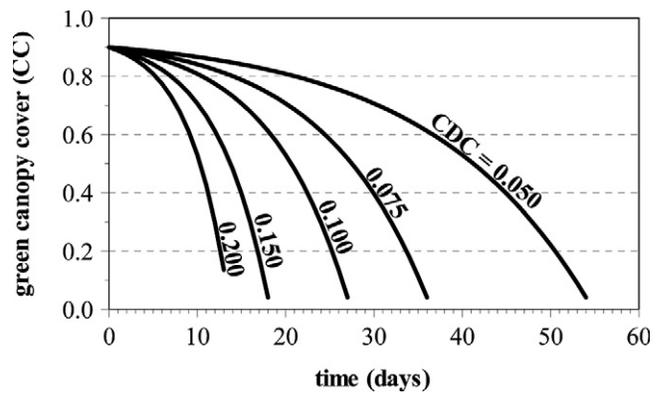


Fig. 6. Decline of green canopy cover during senescence for various canopy decline coefficients (CDC) as described by Eq. [8]. All lines have initial green canopy cover at 0.9 and starting time at 0.

the default CC_x to the actual field conditions. The graphical representation of the canopy expansion is shown in Fig. 5.

During its development phase canopy size can be easily modulated by water stress since leaf growth is very sensitive to water stress and may be slowed when only a small fraction of the available water is depleted in the soil, that is, the upper threshold for the water stress coefficient of expansive growth (Ks_{exp}) is reached at a low p value. This effect is computed by multiplying CGC by Ks_{exp} :

$$CGC_{adj} = Ks_{exp} CGC \quad [7]$$

With Ks_{exp} confined in the range of 1 to 0, the canopy growth begins to slow below the maximum rate when soil water depletion reaches the upper threshold, and stops completely when the depletion reaches the lower threshold. In this way, water stress may prevent CC_x to be reached and results in a smaller final canopy size, especially in determinant crops because in the model canopy growth is permitted only to the middle of the flowering period. In addition to its growth rate, the canopy can begin to senesce even during its development phase if water stress becomes severe enough.

As the crop approaches maturity, CC enters in a declining phase due to leaf senescence. The decline in green canopy cover in AquaCrop is described by

$$CC = CC_x \left[1 - 0.05 \left(\exp \frac{CDC}{CC_x t} - 1 \right) \right] \quad [8]$$

where CDC is canopy decline coefficient (in fraction reduction per GDD or per day), and t is time since the start of canopy senescence. The manifestation of different CDC on the rate of CC decline is illustrated in Fig. 6.

The starting time for canopy decline in AquaCrop is considered to be later than the starting time of leaf senescence. That is because senescence starts generally in the oldest leaf located at the shaded bottom of the canopy that contributes little to transpiration or photosynthesis. The start of canopy senescence in AquaCrop is functional at the time when canopy transpiration and photosynthesis start declining as maturity is approached.

Calibration of senescence requires accurate field observation as there is no simple way to assess green canopy cover during this phase due to interference by the yellow or dead leaves.

Combining Fig. 5 with one of the lines in Fig. 6 gives the CC progression over a full crop cycle, as depicted in Fig. 7 for nonstress conditions.

Senescence of the canopy can be accelerated by water stress any time during the life cycle, provided the stress is severe enough. This is simulated by adjusting CDC through the water stress coefficient for the acceleration of senescence ($K_{s_{sen}}$), with the following equation:

$$CDC_{adj} = (1 - K_{s_{sen}}^8) \times CDC \quad [9]$$

Transpiration

In AquaCrop, Tr is basically proportional to CC when there is no stress-induced stomata closure, but with an adjustment for interrow microadvection and sheltering effect by partial canopy cover. These effects cause Tr to be more than just being proportional to the CC and soil E less than being proportional to $(1 - CC)$. The adjustment is based on the studies of Adams et al. (1976) and Villalobos and Fereres (1990), who measured E of wet soil in microlysimeters under a range of CC values. The empirical equation generalized from their data and used by AquaCrop is given in Raes et al. (2009). The adjusted green canopy cover is denoted by CC^* and used to calculate transpiration.

In the absence of water stress, Tr in AquaCrop is proportional to CC^* , that is,

$$Tr = Kcb ET_0 \quad [10]$$

$$\text{with } Kcb = (CC^* \times Kcb_x) \quad [11]$$

where Kcb_x is the crop coefficient when the canopy cover has just fully developed ($CC = 1$), approximately equivalent to the basal crop coefficient at midseason as described in Allen et al. (1998), but only for cases of full canopy cover; and ET_0 is calculated according to the FAO Penman–Monteith equation (Allen et al., 1998).

After CC_x is reached and before 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 Kc_x by a constant and slight fraction (e.g., 0.3%) per day. When senescence is triggered, the transpiration and photosynthetic capacity of the green portion of the canopy drops more markedly with time. Then, Tr is decreased through a specific reduction coefficient (f_{sen}) which declines from 1 at the start of senescence ($CC = CC_x$) to 0 when no green canopy cover remains ($CC = 0$).

Of course, whenever water stress intensifies so that any of the three thresholds (for leaf growth, for stomatal conductance, for acceleration of senescence) is reached during the crop cycle, Tr is further reduced. The full calculation procedure to simulate Tr is detailed in Raes et al. (2009).

The major challenge in AquaCrop is to simulate correctly transpiration, which depends on the fraction of CC , stomatal opening, and the evaporative demand of the atmosphere. It is therefore essential that the CC and crop responses to

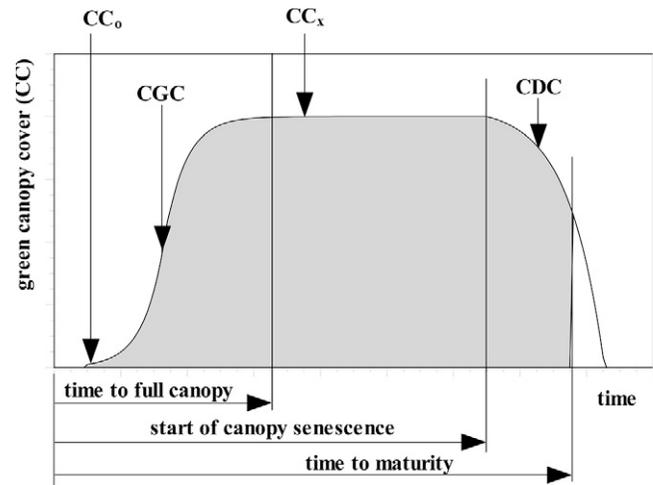


Fig. 7. An example of variation of green canopy cover throughout a crop cycle under non-stress conditions. CC_0 and CC_x are the initial and maximum green canopy cover, respectively; CGC is the green canopy growth coefficient; CDC is the green canopy decline coefficient.

environmental stress (mainly water stress) are properly simulated. Once Tr is calculated, biomass production per day (B_d) is computed with Eq. [4].

Water logging also affects growth in AquaCrop, triggered by the soil water content (between FC and saturation) at which root zone aeration is limited and affects transpiration (anaerobiosis point). The effect of water logging on transpiration is simulated by multiplying a water stress coefficient for water logging ($K_{s_{aer}}$) and the maximum Tr to obtain actual transpiration. To account for the resistance of the crops to short periods of water logging, the response is activated after a specified number of days (see Raes et al., 2009).

Root System Extension and Water Extraction

The root system in AquaCrop is simulated through its effective rooting depth (ERD) and its water extraction pattern. The ERD is defined as the soil depth where root proliferation is sufficient to enable significant crop water uptake. Water extraction follows by default the standard 40, 30, 20, and 10% pattern for the upper to the lower quarter of the ERD when water content is adequate. A different pattern can be established by the user, in cases warranted by specific physical or chemical limitations of the soil making up the different quarters. The capacity for water extraction is modulated using an extraction term S_i (Feddes et al., 1978; Belmans et al., 1983) that expresses the volume of water extracted at the i depth per unit soil volume per day. Details on the use of S_i are found in Raes et al. (2009).

The deepening dynamics of ERD, from planting until it reaches maximum depth, is described by the empirical equation

$$Z = Z_{ini} + (Z_x - Z_{ini}) \sqrt{\frac{\left(\frac{t - t_0}{2}\right)}{\left(t_x - \frac{t_0}{2}\right)}} \quad [12]$$

where Z is the effective rooting depth at time t (in days) after planting, Z_{ini} is the sowing depth, Z_x is the maximum effective rooting depth, t_0 is the time from planting to effective (85–90%) emergence of the crop, t_x is the time after planting when

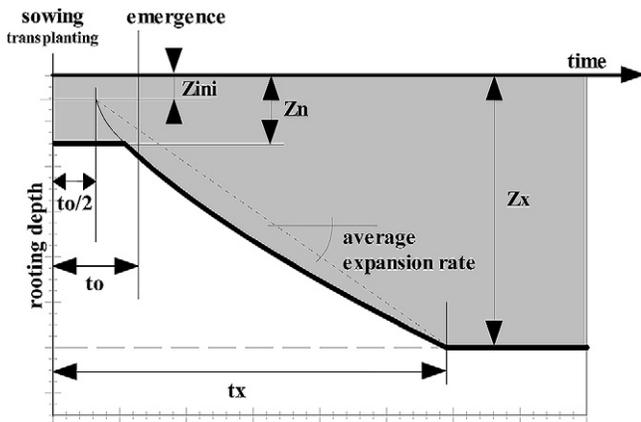


Fig. 8. Schematic representation of a generalized rooting depth development with time. The effectiveness for water balance calculation is highlighted by the shaded area (see text for explanation).

Z_x is reached, and n is a shape factor of the function. As usual, the time is in GDD (or day).

Although root development starts when half of the time required for crop emergence ($t_o/2$) has passed, its effectiveness in the soil water balance calculations occurs only when the minimum ERD (Z_n) is exceeded. A generalized development of the ERD along the crop cycle is shown in Fig. 8.

Under optimal conditions with no soil restrictions, root deepening rate should be at its maximum and Z_x is expected to be reached near the end of the crop's life cycle. If there is at a certain depth a layer of soil restrictive to root growth, roots should deepen normally until the restrictive layer is reached, and then either slows or stops deepening completely.

Because root growth is more resistant to water stress than leaf growth (Bradford and Hsiao, 1982; Hsiao and Xu, 2000), canopy expansion would be reduced as root zone water depletes to and beyond the upper threshold, while root deepening continues unabated. In AquaCrop, root deepening is programmed to be reduced only after the depletion exceeds the threshold for stomatal closure. At that point, the incremental daily root deepening (ΔZ) under normal conditions is adjusted (ΔZ_{adj}) by multiplying with the ratio of actual to potential transpiration of the existing canopy cover.

Harvest Index and Yield

Once biomass is calculated by accumulation using Eq. [4], crop yield is then obtained by multiplying $B \times HI$. Starting from flowering (or tuber initiation), HI is simulated by a linear increase with time (Moot et al., 1996; Bindi et al., 1999; Ferris et al., 1999) after a lag (slowing increasing) phase, up to physiological maturity. This approach is also employed in EPIC (Williams et al., 1989) and ALMANAC (Kiniry et al., 1992).

From the literature a commonly observed HI is chosen as the reference (HI_o) to serve as the target end point for the linear increase. At the user's discretion, this end point can be moved from physiological maturity to earlier for a given crop or cultivar, or the HI increase can be stop earlier by specifying a minimum fractional green canopy remaining as a threshold below which the HI increase stops.

The adjustment of HI to water deficits depends on the timing and extent of water stress during the crop cycle. In AquaCrop, HI is adjusted in four ways for the more common

stress levels, plus another adjustment for pollination failure caused by severe stress. The first four adjustments are for inhibition of leaf growth, for inhibition of stomata, for reduction in green canopy duration due to accelerated senescence, and for effect of preanthesis stress related to reduction in biomass.

As illustrated with the extensive data on cotton (e.g., Hearn, 1980; Jordan, 1983) and limited data on other crops (e.g., Hsiao, 1993a), for many crops HI is reduced by overly luxurious vegetative (leaf) growth during the reproductive phase, while mild to moderate restrictions of vegetative growth by mild water (and nitrogen; Sinclair, 1998) stress are known to enhance HI. This presumably results from the competition for assimilates, with too much diverted to the vegetative organs when their growth is excessive and the potential flowers or nascent fruits drop off the crop. Because leaf growth is much more sensitive to water deficit than the growth of roots (Hsiao and Xu, 2000) and presumably reproductive organs, and with stomata being less sensitive to water stress than leaf growth, AquaCrop relies on the K_s functions for leaf growth and for stomata to modulate HI, with the rate of HI increase being enhanced as K_s for leaf declines, and being reduced as K_s for stomata inhibition declines. The algorithms for pre- and postanthesis stress effects on HI are given in Raes et al. (2009). In operation, because the threshold soil water content for leaf growth inhibition is much higher than that for stomata inhibition, as stress develops the rate of HI rise is first enhanced more and more by the intensifying stress, and the enhancement then lessens as stomata begin to close restricting photosynthesis. At some level of stress severity, the HI increase with time is at the normal rate because the positive effect of leaf growth inhibition is counter balanced by the negative effect of stomata closure. As stress intensifies beyond this level, the overall effects would switch to negative with proper program setting parameters.

Logic dictates that HI should stop increasing when the crop reaches maturity and its canopy is fully senescent. Consequently, AquaCrop limits the increase in HI to the point when the green canopy is reduced to either zero or some chosen small value. This automatically reduces HI when the duration of green canopy is cut short by stress-accelerated senescence. This effect can be dramatic if canopy duration is shortened substantially.

According to a review (Feres and Soriano, 2007), water stress before the reproductive phase can enhance HI in some cases, and the effect is correlated with the reduction in the biomass accumulation. AquaCrop includes an algorithm 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 at the midpoint of the range.

Pollination failure due to severe water stress, cold, or high temperature is simulated in terms of impact on HI. The failure is quantified as the fraction of the total number of flowers that failed to pollinate when stress of a certain level occurs, for each day, modulated by the number of excessive potential fruits present, which differs from species to species. For details on all the simulated effects of stress on HI, see Raes et al. (2009).

The influence of water stress on HI of grain crops in pre-anthesis and postanthesis is simulated also in ALMANAC

(Kiniry et al., 1992). In this model, preanthesis water stress increases simulated HI up to 10% of the potential value, while water stress during anthesis and grain filling decreases simulated HI down to 15% of the potential HI. The approach of AquaCrop, though, is more elaborate as compared with ALMANAC, as it accommodates also indeterminate crops like cotton, allowing for HI enhancement due to restriction of vegetative growth during and after anthesis, and marked reduction in HI when stress is severe enough to drastically suppress pollination. Further insights on the HI response to water stress in postanthesis are given in Sadras and Connor (1991).

Management

The management component of AquaCrop has two main categories: one is *field* management, a broad category, and the other is more specific, *water* management.

Field management offers options to select or define (i) the fertility level, or regime, the crop is exposed to during its cycle, (ii) field-surface practices such as mulching to reduce soil evaporation, or the use of soil bunds (small dykes) to control surface run-off and infiltration, and (iii) the time for cutting of forage crops. The broad fertility categories range from non-limiting to poor, with increasing reductions in WP*, CGC, and CC_x, and acceleration in green canopy senescence as the fertility level decreases. Thus, AquaCrop does not compute nutrient balances, but offers the semiquantitative options to assess the effects of the fertility regime on the biomass and yield response. Mulching is simply considered as the fraction of soil surface that is covered and evaporation prevented. The height of soil bunds can be specified to allow retention of water on the soil surface, and may be useful when simulating rice (*Oryza sativa* L.) production.

The water management offers options of (i) rainfed agriculture (no irrigation), and (ii) irrigation. Under irrigation, the user selects the application method (sprinkler, drip, or surface) and defines the schedule by specifying the time and depth of each application, or let the model generate automatically the schedule on the basis of fixed time interval, fixed depth (amount) per application, or fixed percentage of allowable water depletion, similar to what is done in few other models, including IRSIS (Raes et al., 1988) and CROPWAT (Smith, 1992). The user defined time/depth option, along with the option to run the simulation manually day by day and applying irrigation at will in chosen amounts while seeing immediately the effect on crop canopy and transpiration, are particularly suited for analyzing and developing optimal supplemental or deficit irrigation schedules and analyzing the yield responses.

User Interface

To target a broad range of users, the user interface of AquaCrop is designed in layers, with the first layer aimed at users of minimal experience in model simulation, and deeper layers for the more and more experienced users with more and more expertise in subject areas underlying components of the model. The plan is to calibrate the model for each important crop species using data from diverse climate and geographic locations to set default values for most of the key parameters of the model. This makes it easy for the novice users, while the more advanced users can adjust these parameters by going to

the deeper layers. The key parameters that are location dependent (e.g., soil water characteristics, planting dates, cultivar season length) are left for the user to enter, although some default values are provided.

CONCLUSIONS

The aim of FAO is to have a functional canopy-level water-driven crop simulation model of yield response to water that can be used in the diverse agricultural systems that exist worldwide. It is therefore imperative that model calibration and validation, specific for each crop, are performed as extensively as possible. The current version of AquaCrop simulates several main crops (see Hsiao et al., 2009 and Heng et al., 2009 for maize; García-Vila et al., 2009 and Farahani et al., 2009 for cotton; Geerts et al., 2009 for quinoa). Additionally, wheat is being calibrated with data from several locations around the world. The network of partners in this endeavor is growing and contributing to either further testing of the model calibrated already for specific crops or to parameterize and calibrate the model for additional crops (e.g., forages, oil and protein crops, tuber and root crops, and few major underutilized crops).

Relative to other simulation models, AquaCrop requires a low number of parameters and input data to simulate the yield response to water, hopefully for most of the major field and vegetable crops cultivated worldwide. Its parameters are explicit and mostly intuitive, and the model has been built to maintain an adequate balance between accuracy, simplicity, and robustness. The model is aimed at a broad range of users, from engineers, economists, 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. AquaCrop incorporates 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 attainable against actual yields for a field, farm, or a region, to identify the constraints limiting crop production and water productivity, serving as a benchmarking tool. Economists, water administrators, and managers may find it very useful for scenario simulations and for planning purposes. It is also suited for perspective studies such as those under future climate change scenarios. The particular features that distinguishes AquaCrop from other crop models is its focus on water, the use of CC instead of LAI, and the use of WP values normalized for atmospheric evaporative demand and CO₂ concentration that confer the model an extended extrapolation capacity, to diverse locations, seasons, and climate, including future climate scenarios. Although the model is 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.

Further improvements of AquaCrop are planned, including the complete implementation of some of the features described above as well as effects of salinity and routines to simulate crop rotations and different cropping patterns and sequences. Moreover, after sufficient development, AquaCrop is expected to be inserted in GIS and decision support systems that will account for spatial variability of soils and weather and that will also make use of FAO already available software products such

as Terrastat, ClimWat, or ClimaAgri, to scale up crop productivity and water use from a portion of a field to whole fields, up through farms, landscapes, and water sheds.

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REFERENCES

- Acevedo, E., T.C. Hsiao, and D.W. Henderson. 1971. Immediate and subsequent growth responses of maize leaves to changes in water status. *Plant Physiol.* 48:631–636.
- Adams, J.E., G.F. Arkin, and J.T. Ritchie. 1976. Influence of row spacing and straw mulch on first stage drying. *Soil Sci. Soc. Am. J.* 40:436–442.
- Addiscott, T.M., and R.J. Wagenet. 1985. Concepts of solute leaching in soils: A review of modeling approaches. *J. Soil Sci.* 36:411–424.
- Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. *Irrig. and Drainage Paper no. 56.* FAO, Rome.
- Asseng, S., and T.C. Hsiao. 2000. Canopy CO₂ assimilation, energy balance, and water use efficiency of an alfalfa crop before and after cutting. *Field Crops Res.* 67:191–206.
- Azam-Ali, S.N., and G.R. Squire. 2002. *Principles of Tropical Agronomy.* CABI Publ., Wallingford, UK.
- Belmans, C., J.G. Wesseling, and R.A. Feddes. 1983. Simulation of the water balance of a cropped soil: SWATRE. *J. Hydrol.* 63:271–286.
- Bindi, M., T.R. Sinclair, and J. Harrison. 1999. Analysis of seed growth by linear increase in Harvest Index. *Crop Sci.* 39:486–493.
- Boote, K.J., J.W. Jones, and N.B. Pickering. 1996. Potential uses and limitations of crop models. *Agron. J.* 88:704–716.
- Boyer, J.S. 1970. Leaf enlargement and metabolic rates in corn, soybean and sunflower at various leaf area water potentials. *Plant Physiol.* 46:233–235.
- Bradford, K.J., and T.C. Hsiao. 1982. Physiological responses to moderate water stress. p. 263–324. *In* O.L. Lange et al. (ed.) *Physiological plant ecology. II. Water relations and carbon assimilation.* Encyclopedia of Plant Physiology, New Series. Vol. 12B. Springer-Verlag, New York.
- Brouwer, R., and C.T. de Wit. 1969. A simulation model of plant growth with special attention to root growth and its consequences. p. 224–244. *In* W.J. Whittington (ed.) *Root growth.* Proc. 15th Easter School in Agric. Sci. Butterworths, London.
- Denmead, O.T., and R.H. Shaw. 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. *Agron. J.* 54:385–390.
- de Wit, C.T. 1958. Transpiration and crop yields. *Agric. Res. Rep.* 64(6). Pudoc, Wageningen, The Netherlands.
- Doorenbos, J., and A.H. Kassam. 1979. Yield response to water. *Irrig. and Drainage Paper no. 33.* FAO, Rome.
- Farahani, H.J., G. Izzi, P. Steduto, and T.Y. Oweis. 2009. Parameterization and evaluation of AquaCrop for full and deficit irrigated cotton. *Agron. J.* 101:469–476 (this issue).
- Feddes, R.A., P.J. Kowalik, and H. Zaradny. 1978. Simulation of field water use and crop yield. Pudoc, Simulation Monographs, Wageningen, the Netherlands.
- Fereres, E., and M.A. Soriano. 2007. Deficit irrigation for reducing agricultural water use. *J. Exp. Bot.* 58:145–159.
- Ferris, R., T.R. Wheeler, R.H. Ellis, and P. Hadley. 1999. Seed yield after environmental stress in soybean grown under elevated CO₂. *Crop Sci.* 39:710–718.
- Fisher, R.A., and N.C. Turner. 1978. Plant productivity in the arid and semi-arid zones. *Annu. Rev. Plant Physiol.* 29:277–317.
- García-Vila, M., E. Fereres, L. Mateos, F. Orgaz, and P. Steduto. 2009. Deficit irrigation optimization of cotton with AquaCrop. *Agron. J.* 101:477–487 (this issue).
- Geerts, S., D. Raes, M. Garcia, R. Miranda, J.A. Cusicanqui, C. Taboada, J. Mendoza, R. Huanca, A. Mamani, O. Condori, J. Mamani, B. Morales, V. Osco, and P. Steduto. 2009. Simulating Yield Response to Water of Quinoa (*Chenopodium quinoa* Willd.) with FAO-AquaCrop. *Agron. J.* 101:499–508 (this issue).
- Hammer, G.L., and R.C. Muchow. 1994. Assessing climatic risk to sorghum production in water-limited subtropical environments I. Development and testing of a simulation model. *Field Crops Res.* 36(3):221–234.
- Hanks, R.J. 1983. Yield and water-use relationships. p. 393–411. *In* H.M. Taylor, W.R. Jordan, and T.R. Sinclair (ed.) *Limitations to efficient water use in crop production.* ASA, CSSA, and SSSA, Madison, WI.
- Hearn, A.B. 1980. Water relationships in cotton. *Outlook Agric.* 10:159–166.
- Heng, L.K., S.R. Evett, T.A. Howell, and T.C. Hsiao. 2009. Calibration and testing of FAO AquaCrop model for maize in several locations. *Agron. J.* 101:488–498 (this issue).
- Howell, T.A., R.H. Cuenca, and K.H. Solomon. 1990. Crop yield response. p. 93–122. *In* G.J. Hoffman et al. (ed.) *Management of farm irrigation systems.* Am. Soc. of Agric. Eng., St. Joseph, MI.
- Hsiao, T.C. 1973. Plant responses to water stress. *Annu. Rev. Plant Physiol.* 24:519–570.
- Hsiao, T.C. 1982. The soil-plant-atmosphere continuum in relation to drought and crop production. p. 39–52. *In* *Drought resistance in crops, with emphasis on rice.* IRRRI, Los Baños, the Philippines.
- Hsiao, T.C. 1990. Plant-atmosphere interactions, evapotranspiration, and irrigation scheduling. *Acta Hort.* 278:55–66.
- Hsiao, T.C. 1993a. Growth and productivity of crops in relation to water status. *Acta Hort.* 335:137–148.
- Hsiao, T.C. 1993b. Effects of drought and elevated CO₂ on plant water use efficiency and productivity. p. 435–465. *In* M.D. Jackson and C.R. Black (ed.) *Global environmental change. Interacting stresses on plants in a changing climate.* NATO ASI Series. Springer-Verlag, New York.
- Hsiao, T.C., and K.J. Bradford. 1983. Physiological consequences of cellular water deficits. p. 227–265. *In* H.M. Taylor, W.R. Jordan, and T.R. Sinclair (ed.) *Limitations to efficient water use in crop production.* ASA, CSSA, and SSSA, Madison, WI.
- Hsiao, T.C., and L.K. Xu. 2000. Sensitivity of growth of roots vs. leaves to water stress: Biophysical analysis and relation to water transport. *J. Exp. Bot.* 51:1595–1616.
- Hsiao, T.C., E. Acevedo, and D.W. Henderson. 1970. Maize leaf elongation: Continuous measurements and close dependence on plant-water status. *Science* 168:590–591.
- Hsiao, T.C., E. Fereres, E. Acevedo, and D.W. Henderson. 1976. Water stress and dynamics of growth and yield of crop plants. p. 281–305. *In* O. L. Lange, L. Kappen, and E. D. Schulze (ed.) *Ecological Studies. Analysis and Synthesis.* Water and Plant Life. Vol. 19. Springer-Verlag, Berlin.
- Hsiao, T.C., L.K. Heng, P. Steduto, D. Raes, and E. Fereres. 2009. AquaCrop—Model parameterization and testing for maize. *Agron. J.* 101:448–459 (this issue).
- Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens, U. Singh, A.J. Gijsman, and J.T. Ritchie. 2003. The DSSAT cropping system model. *Eur. J. Agron.* 18:235–265.
- Jones, J.W., and J.R. Kiniry (ed.) 1986. *CERES-Maize: A simulation model of maize growth and development.* Texas A&M Univ. Press, College Station.
- Jordan, W.R. 1983. Cotton. p. 213–254. *In* I.D. Teare and M.M. Peat (ed.) *Crop-water relations.* J. Wiley & Sons, New York.
- Keating, B.A., P.S. Carberry, G.L. Hammer, M.E. Probert, M.J. Robertson, D. Holzworth, N.I. Huth, J.N.G. Hargreaves, H. Meinke, Z. Hochman, G. McLean, K. Verburg, V. Snow, J.P. Dimes, M. Silburn, E. Wang, S. Brown, K.L. Bristow, S. Asseng, S. Chapman, R.L. McCown, D.M. Freebairn, and C.J. Smith. 2003. An overview of APSIM; a model designed for farming systems simulation. *Eur. J. Agron.* 18:267–288.
- Kemarian, A.R., C.O. Stockle, D.R. Huggins, and L.M. Viega. 2007. A simple method to estimate harvest index in grain crops. *Field Crops Res.* 103:208–216.
- Kiniry, J.R., J.R. Williams, P.W. Gassman, and P. Debaeke. 1992. A general, process-oriented model for two competing plant species. *Trans. ASAE* 35:801–810.
- Loomis, R.S., R. Rabbinge, and E. Ng. 1979. Explanatory models in crop physiology. *Annu. Rev. Plant Physiol.* 30:339–367.

- McMaster, G.S., and W.W. Wilhelm. 1997. Growing degree-days: One equation, two interpretations. *Agric. For. Meteorol.* 87:291–300.
- Monteith, J.L. 1996. The quest for balance in crop modelling. *Agron. J.* 88:695–697.
- Moot, D.J., P.D. Jamienson, A.L. Henderson, M.A. Ford, and J.R. Porter. 1996. Rate of change in harvest index during grain-filling of wheat. *J. Agric. Sci.* 126:387–395.
- Passioura, J.B. 1996. Simulation models: Science, snake oil, or engineering? *Agron. J.* 88:690–694.
- Penning de Vries, F.W.T., A.H.M. Brunsting, and van H.H. Laar. 1974. Products, requirements and efficiency of biosynthesis: A quantitative approach. *J. Theor. Biol.* 45:339–377.
- Penning de Vries, F.W.T., H.H. van Laar, and M.C.M. Chardon. 1983. Bioenergetics of growth of seeds, fruits and storage organs. p. 37–59. *In* W.H. Smith and S.J. Banta (ed.) *Productivity of field crops under different environments*. IRRRI, Los Baños, the Philippines.
- Philip, J.R. 1957. Evaporation, moisture and heat fields in the soil. *J. Meteorol.* 14:354–366.
- Raes, D. 1982. A summary simulation model of the water budget of a cropped soil. *Dissertationes de Agricultura* no. 122. K.U. Leuven Univ., Leuven, Belgium.
- Raes, D., H. Lemmens, P. Van Aelst, M. Vanden Bulcke, and M. Smith. 1988. IRSIS—Irrigation scheduling information system. Volume 1. Manual, Reference Manual 3. Dep. Land Management, K.U. Leuven Univ., Leuven, Belgium.
- Raes, D., P. Steduto, T.C. Hsiao, and E. Fereres. 2009. AquaCrop—The FAO crop model for predicting yield response to water: II. Main algorithms and software description. *Agron. J.* 101:438–447 (this issue).
- Ritchie, J.T. 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resour. Res.* 8:1204–1213.
- Sadras, V.O., and D.J. Connor. 1991. Physiological basis of the response of harvest index to the fraction of water transpired after anthesis: A simple model to estimate harvest index for determinate species. *Field Crops Res.* 26:227–239.
- Sadras, V.O., and S.P. Milroy. 1996. Soil-water thresholds for the responses of leaf expansion and gas exchange: A review. *Field Crops Res.* 47:253–266.
- Sadras, V.O., F.J. Villalobos, E. Fereres, and D.W. Wolfe. 1993. Leaf responses to soil water deficits: Comparative sensitivity of leaf expansion rate and leaf conductance in field-grown sunflower (*Helianthus annuus* L.). *Plant Soil* 153:189–194.
- Saxton, K.E., W.J. Rawls, J.S. Romberger, and R.I. Papendick. 1986. Estimating generalized soil-water characteristics from texture. *Soil Sci. Soc. Am. J.* 50:1031–1036.
- Sinclair, T.R. 1998. Historical changes in harvest index and crop nitrogen accumulation. *Crop Sci.* 38:638–643.
- Sinclair, T.R., and N.G. Seligman. 1996. Crop modelling: From infancy to maturity. *Agron. J.* 88:698–704.
- Smith, M. 1992. CROPWAT—A computer program for irrigation planning and management. FAO Irrigation and Drainage Paper No. 46. FAO, Rome.
- Soil Conservation Service. 1991. Soil–Plant–Water Relationships. Irrigation. Section 15 Chapter 1. p. 1-1 to 1-56. *In* National Engineering Handbook, Soil Conservation Service, USDA, Washington, DC.
- Steduto, P. 2003. Biomass water-productivity. Comparing the growth-engines of crop models. FAO Expert Consultation on Crop Water Productivity Under Deficient Water Supply, 26–28 February 2003, Rome. FAO, Rome.
- Steduto, P., and R. Albrizio. 2005. Resource use efficiency of field-grown sunflower, sorghum, wheat and chickpea. II. Water Use Efficiency and comparison with Radiation Use Efficiency. *Agric. For. Meteorol.* 130:269–281.
- Steduto, P., R. Albrizio, P. Giorio, and G. Sorrentino. 2000. Gas-exchange and stomatal and non-stomatal limitations to carbon assimilation of sunflower under salinity. *Environ. Exp. Bot.* 44:243–255.
- Steduto, P., T.C. Hsiao, and E. Fereres. 2007. On the conservative behavior of biomass water productivity. *Irrig. Sci.* 25:189–207.
- Stockle, C.O., M. Donatelli, and R. Nelson. 2003. CropSyst, a cropping systems simulation model. *Eur. J. Agron.* 18:289–307.
- Tanner, C.B., and T.R. Sinclair. 1983. Efficient water use in crop production: Research or re-search? p. 1–27. *In* H.M. Taylor, W.R. Jordan, and T.R. Sinclair (ed.) *Limitations to efficient water use in crop production*. ASA, CSSA, and SSSA, Madison, WI.
- van Ittersum, M.K., P.A. Leffelaar, H. van Keulen, M.J. Kropff, L. Bastiaans, and J. Goudriaan. 2003. On approaches and applications of the Wageningen crop models. *Eur. J. Agron.* 18:201–234.
- Vaux, H.J., Jr., and W.O. Pruitt. 1983. Crop-water production functions. *Adv. Irrig.* 2:61–97.
- Villalobos, F.J., and E. Fereres. 1990. Evaporation measurements beneath corn, cotton, and sunflower canopies. *Agron. J.* 82:1153–1159.
- Whisler, F.D., B. Acock, D.N. Baker, R.E. Fye, H.F. Hodges, J.R. Lambert, H.E. Lemmon, J.M. McKinion, and V.R. Reddy. 1986. Crop simulation models in agronomic systems. *Adv. Agron.* 40:141–208.
- Williams, J.R., C.A. Jones, and P.T. Dyke. 1989. EPIC—Erosion/productivity impact calculator. I. The EPIC model. USDA-ARS, Temple, TX.