Concepts and Applications of AquaCrop: The FAO Crop Water Productivity Model

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Abstract: Predicting attainable yield under water-limiting conditions is an important goal in arid, semi-arid and drought-prone environments. To address this task, FAO has developed a model, *AquaCrop,* which simulates attainable yields of the major herbaceous crops in response to water. Compared to other models, *AquaCrop* has a significantly smaller number of parameters and attempts to strike a balance between simplicity, accuracy, and robustness. Root zone water content is simulated by keeping track of incoming and outgoing water fluxes. Instead of leaf area index, *AquaCrop* uses canopy ground cover. Canopy expansion, stomatal conductance, canopy senescence, and harvest index are the key physiological processes which respond to water stress. Low and high temperature stresses on pollination and harvestable yield are considered, as is cold temperature stress on biomass production. Evapotranspiration is simulated separately as crop transpiration and soil evaporation and the daily transpiration is used to calculate the biomass gain via the normalized *biomass water productivity*. The normalization is for atmospheric evaporative demand and carbon dioxide concentration, to make the model applicable to diverse locations and seasons, including future climate scenarios. *AquaCrop* accommodates fertility levels and water management systems, including rainfed, supplemental, deficit, and full irrigation. Simulations are routinely in thermal time, but can be carried out in calendar time. Future versions will incorporate salt balance and capillary raise. *AquaCrop* is aimed at users in extension services, consulting firms, governmental agencies, NGOs, farmers associations and irrigation districts, as well as economists and policy analysts in need of crop models for planning and assessing water needs and use of projects and regions.

Keywords: crop modeling, water-driven growth-engine, transpiration and biomass, water stress

1 Introduction

The complexity of crop responses to water deficits has often led to the use of empirical production functions as the most practical option to assess crop yield response to water. Among the empirical function approach, FAO *Irrigation & Drainage Paper* 33 (Doorenbos and Kassam, 1979) has been a landmark in predicting the yield response to water of annual and perennial crops, through the following equation:

$$\left(\frac{Y_x - Y_a}{Y_x}\right) = k_y \left(\frac{\mathrm{ET}_x - \mathrm{ET}_a}{\mathrm{ET}_x}\right) \tag{1}$$

Where Y_x and Y_a are the maximum and actual yields, 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. Different forms of Eq. (1) may be found in the literature (Stewart et al., 1974; Tanner and Sinclair, 1983).

Theoretical and experimental advances in crop-water relations from 1979 to date, along with the strong demand for improving water productivity as one of the major approaches to cope with water scarcity, have prompted FAO to revise its *Paper* 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 field and vegetable crops separately from tree crops because of the different level of knowledge and the additional complexities involved in yield determination of the latter. For herbaceous crops, the decision was to develop a simulation model of proper structure based on concepts traceable to Eq. (1), for use in planning, management and scenario analysis. The model is named *AquaCrop*, which attempts to strike a balance between accuracy, simplicity, robustness, and ease of use.

This paper describes the conceptual framework, structure, algorithms, and distinctive features of *AquaCrop*, along with the performance evaluation for a few crops grown under variable water availability.

2 Model Description

2.1 Model Growth-Engine and Flowchart

Conceptually, *AquaCrop* is an expression of Eq. (1) but with refinements. The crop evapotranspiration (ET) is separated into soil evaporation (E) and crop transpiration (Tr) to avoid the confounding effect of the non-productive consumptive use of water (E). This is particularly important when canopy cover of the ground is incomplete and soil E may be the major component of ET. The harvestable yield (Y) is expressed as a function of biomass (B) and harvest index (HI) to distinguish between environmental stress effects on B from those on HI. The separation of these two kinds of effects, which differ fundamentally, makes it possible to introduce functional links based on underlying physiological processes. The changes described led to the following equations at the core of the *AquaCrop* growth engine:

$$B = \mathrm{WP} \cdot \Sigma\mathrm{Tr} \tag{2}$$

And,

$$Y = B \cdot \mathrm{HI} \tag{3}$$

Where WP is the water productivity parameter in units of kg (biomass) m^{-2} (land area) mm^{-1} (water transpired). Stepping from Eq. (1) to Eq. (2) makes the model more robust and more applicable, due to the conservative behavior of WP when normalized for climatic conditions (Steduto et al., 2007), although both equations are expressions of a *water-driven growth-engine* in terms of crop model design (Steduto, 2003). In Eq. (2), *AquaCrop* introduces daily time steps to account for dynamic changes in water supply, soil evaporation, crop transpiration and air temperature, in contrast to the use of Eq. (1) to compute production over long periods (weeks to months).

Other important refinements include a novel way to simulate canopy growth, the separation of effects of stress on canopy growth, stomatal conductance, canopy senescence, and pollination and other aspects of HI, as will be described below.

Similarly to 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. In terms of *management*, the model emphasizes irrigation, but also considers soil fertility, especially nitrogen, and aspects related to water such as soil bounds and mulches, as they affect the soil water balance, crop development and growth. Cuttings of forage crops are also specified under management. Pests, diseases, and weeds are not considered.

The functional relationships between the different model components are depicted in Fig. 1.

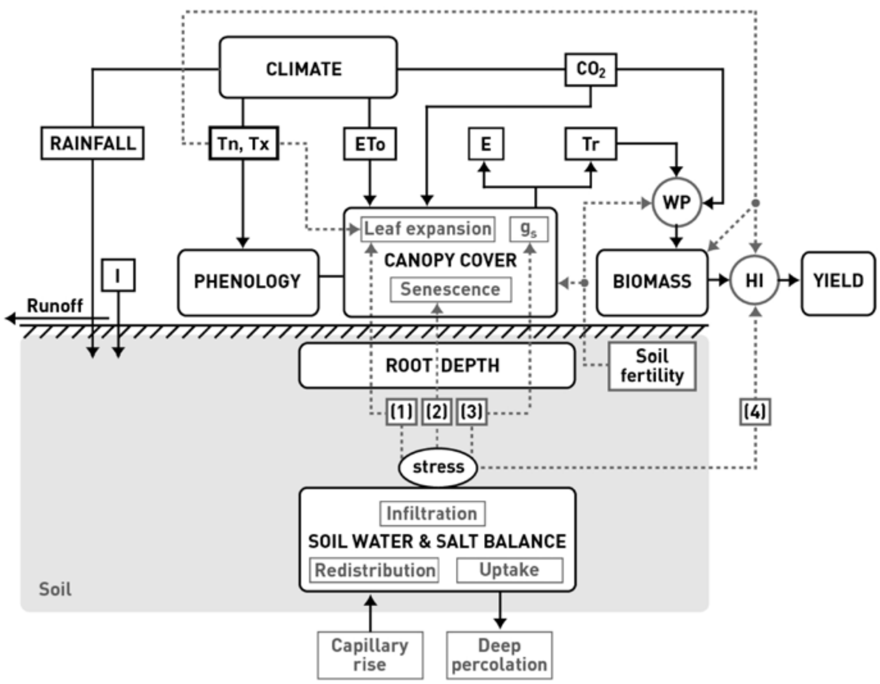

Figure 1 Chart of AquaCrop indicating the main components of the soil-plant-atmosphere continuum and the parameters driving phenology, canopy cover, transpiration, biomass production and final yield (I – Irrigation; Tn – Min air temperature; Tx – Max air temperature; ETo – Reference evapotranspiration; 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) – different water stress response functions). Continuous lines indicate direct links between variables and processes. Dashed lines indicate feedbacks. For explanation, see processes description

Following is a brief description of the model, which consists of 4 components: the atmosphere, the crop, the soil, and management. Only algorithms largely distinctive to *AquaCrop* are presented, while those in common with existing models are only mentioned, with reference to the literature. For further insight into the model components and software, the reader is referred to Steduto et al. (2008) and Raes et al. (2008a,b).

2.2 The Atmosphere

The atmospheric environment of the crop is described in the *climate* component of *AquaCrop* (Fig. 1) as 5 weather input variables: daily maximum and minimum air temperatures, daily rainfall, daily evaporative demand of the atmosphere, expressed as ET_o, and the mean annual carbon dioxide concentration in the bulk atmosphere. While the first 4 are obtained or derived from data of agro-meteorological stations, the CO_2 concentration uses the Mauna Loa Observatory records in Hawaii.

ET_o should be calculated from daily solar radiation, temperature, humidity, and wind data following the procedures described in the FAO *Paper* 56 (Allen et al., 1998). When not all the required input variables for ET_o are available, *Paper* 56 describes the methods for their estimation. *AquaCrop* does not include the routines for calculating ET_o, but a separate software program (named *ETo Calculator*) based on *Paper 56* is provided for such purposes. When daily weather data are not available, 10-day or monthly records are processed by *AquaCrop* into daily values using the downscaling procedure of Gommes (1983). This flexibility allows the use of *AquaCrop* in areas of limited weather records. The model also has a sub-routine to estimate *effective* rainfall from 10-day or monthly data through two options, the USDA Soil Conservation Service method (SCS, 1993), or by setting effective rainfall as a percentage of total rainfall.

As illustrated in Fig. 1, temperature plays a role in influencing crop development (phenology, biomass production and pollination); the rainfall and ET_o are inputs for the water balance of the soil root zone; and the CO_2 concentration of the atmosphere influences the canopy growth rate and the water productivity (WP).

2.3 The Crop

The crop system has 5 major components (Fig. 1): phenology, green canopy cover, rooting depth, biomass production and harvestable yield. The crop grows and develops through the ontogenetic stages of its cycle by expanding, maintaining, and senescing its canopy, deepening its rooting system, flowering, and accumulating above-ground biomass, partly in the yield organ. The dynamic responses to water stress associated to the various crops components are discussed later.

2.4 Canopy Development

The canopy is a crucial feature of *AquaCrop*. Through its expansion, ageing, changes in conductance, and senescence (Fig. 1), it determines the amount of water transpired, which in turn determines the amount of biomass produced. One of the key features of *AquaCrop* distinguishing it from existing models is the expression of crop surface for transpiration (hence for biomass production) as the fractional green canopy ground cover (CC) and not via leaf area index (LAI). This simplifies the simulation significantly, reducing the overall canopy expansion to a growth function and allowing the user to enter actual values of CC, even those estimated by eye. Moreover, CC may be easily obtained also via remote sensing. One important feature of the equations developed to simulate CC is that they account directly for the effects of plant density, within the commonly encountered density range. Beyond CC, where differences due to canopy architecture and height may exert influence, the effects are implicitly incorporated when parameterizing the crop coefficient for transpiration of each crop species.

For non-stress conditions, the canopy expansion from emergence to full canopy development follows a sigmoid-type curve constructed with an exponential function for the first half of the development, and an exponential decay function for the second half, according to the equations:

$$CC = CC_o e^{CGC \cdot t} \tag{4}$$

$$CC = CC_x - (CC_x - CC_o) \cdot e^{-CGC \cdot t} \tag{5}$$

Where CC is the canopy cover at time t in growing degree day (GDD) or calendar day, CC_o is the initial canopy cover (CC at t=0), CGC is the canopy growth coefficient in fraction per GDD (or per day), and CC_x is the maximum canopy cover, or canopy cover at t=∞. CC_o represents the initial canopy cover once the seedlings are established and is equal to the plant density times the mean initial canopy cover per seedling. The latter is a crop-specific parameter provided in *AquaCrop* for each of the major crops.

After its full development, the canopy can have a variable duration before entering the senescence phase. For the fully developed canopy and before senescence, an ageing effect is applied to account for the slight reduction in the overall canopy transpiration capacity over time (e.g., 0.3% reduction per day). Once senescence starts in the late season, CC enters a declining phase following the equation:

$$CC = CC_x \left[1 - 0.05 \left(\exp^{\frac{CDC_t}{CC_x}} - 1 \right) \right] \tag{6}$$

Where t is time since the start of canopy senescence, and CDC is a canopy decline coefficient that reflects the speed of decline up to maturity.

2.5 Biomass and Yield

The green canopy represents the source for transpiration, which is translated into a proportional amount of biomass produced through the normalized WP. The choice of a water-driven engine instead of the more common radiation-driven engine now used by most established crop simulation models (e.g., Keating et al., 2003; Jones et al., 2003) is based on a recent analysis of the conservativeness of normalized WP (Steduto et al., 2007), and on the focus that AquaCrop has on simulating attainable yields in response to water. Because WP is strongly influenced by evaporative demand, its normalization for different climates is critical. In *AquaCrop*, the normalization is achieved through ET_o, which was found to be more consistent than through the atmospheric Vapor Pressure Deficit (VPD) (Steduto and Albrizio, 2005; Steduto et al., 2007), and the theoretical basis for this has been elaborated (Asseng and Hsiao, 2000). The CO_2 concentration normalization procedure is based on gas exchange principles and supporting data (Hsiao, 1993; Steduto et al., 2007; Xu and Hsiao, 2004). To account for the higher energy content of the biomass produced during yield formation of seed crops high in oil content (Penning de Vries et al., 1983; Azam-Ali and Squire, 2002), WP is adjustable in *AquaCrop* for the yield formation (reproductive) phase. After calculating B, its harvestable portion, the yield (Y), is determined via harvest index (HI), using Eq. (3).

Though *AquaCrop* uses HI as a key parameter, it does not calculate the partitioning of biomass into various organs (e.g., leaves, roots, etc.), i.e., biomass production is decoupled from its allocation to leaves and roots. This choice avoids dealing with the complexity and uncertainties associated with the partitioning processes, which remain among the least understood in crop physiology and are most difficult to model. In *AquaCrop*, a reference HI must be provided for each crop (and cultivar when warranted). HI increases linearly after a lag-phase, starting from the time of anthesis or the beginning of yield formation period, similarly to the approach followed by Amir and Sinclair (1991) and Wheeler et al (1996). Water deficits may affect the final HI value, as discussed below. The relationship between shoot and root is maintained by empirical procedures which are based on the functional balance between canopy development and root deepening (Raes et al., 2008a).

AquaCrop uses thermal time (GDD) as the default driver, and offers calendar time as an alternative when data are not available to derive GDD. GDD is computed following the procedure of McMaster and Wilhelm (1997), with the additional incorporation of an upper temperature threshold above which crop development no longer increases with increases in air temperature. In addition, a special procedure is found to be necessary for the computation when dealing with winter crops that go through a period of freezing weather. The genetic variation among species and cultivars is implemented in the model through the variation in timing and duration of the various developmental stages, the initial canopy size per seedling, canopy growth and decline coefficients, rate of root deepening and potential maximum depth, normalized WP, and the response factors to environmental conditions.

2.6 Transpiration

As the canopy develops, transpiration (Tr) is simulated separated from soil evaporation (E) because it is the basis for biomass production (Eq. (2)). The model attempts to provide accurate estimations of Tr by accounting for the extent of CC, effects of inter-row micro-advection, and effects on stomata.

Transpiration is calculated as a function of a specific crop coefficient Kc_{tr}, which is the Tr/ET_o ratio of the full canopy of the crop under optimal conditions ($Kc_{tr\,x}$), adjusted for effects of stresses on stomata and for canopy aging and senescence, as follows:

$$Tr = Ks_{sto} * Kc_{tr} * CC_{adj} * ET_o \tag{7}$$

Where CC_{adj} is CC adjusted to account for the interactions between Tr and E, which are particularly relevant under partial canopy cover (Ritchie 1983) and enhances Tr, and Ks_{sto} is the water stress coefficient for stomatal closure. After CC_x is reached, $Kc_{tr\,x}$ is adjusted slightly downward per day as the canopy ages until the onset of senescence. When senescence starts and CC declines following the trend indicated by Eq. (6), $Kc_{tr\,x}$ is adjusted further downward. If water stress affects Tr by reducing stomatal opening, then Ks_{sto} becomes smaller than 1.

For specifics on all the adjustments, see Raes et al., (2008a). Water stress also may affect Tr indirectly by reducing CC, as discussed below.

2.7 Responses to Water Stress

Since the focus of *AquaCrop* is the simulation of water-limited yield, efforts were made to include all the responses underpinning the effects of water stress on crop yield. Other models dealing with water stress have placed more emphasis on simulating stress effects on photosynthesis than on canopy expansion or senescence (van Ittersum et al., 2003; Jones and Kiniry, 1986). *AquaCrop* presents a novel approach by segregating the canopy response to water deficits (Fig. 1) into three components, namely, ① reduction in expansion rate, i.e., reducing the canopy growth coefficient (CGC), ② reduction in stomatal conductance (g_s), and ③ acceleration of senescence, i.e., triggering the early start of senescence and adjusting the canopy decline coefficient (CDC) to the level of water stress. All three major canopy responses are formalized with the same conceptualization and algorithms. Water deficits are quantified through a water stress coefficient (*Ks*) for each response that varies from 1 (no stress) to zero (full stress). Stress occurs when the depletion in the relative soil water content of the root zone reaches an upper threshold value, p, varying between 0 and 1. When that threshold value for a specific response is reached, *Ks* for that response is computed through the following equation:

$$Ks = 1 - \frac{(e^{D_{rel} \cdot f_{shape}} - 1)}{(e^{f_{shape}} - 1)} \tag{8}$$

Where the parameter f_{shape} influences the shape of the function Ks and D_{rel} is the relative depletion between the upper and lower threshold. A sample of response functions of Ks is presented in Fig. 2.

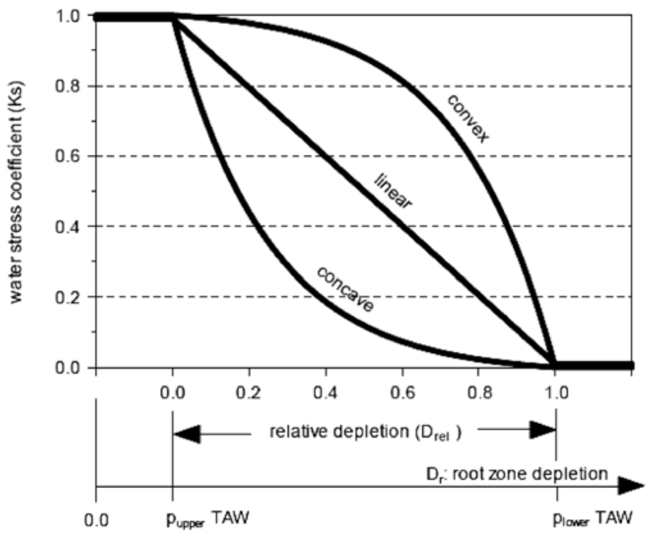

Figure 2 Examples of K_s response function to the relative depletion in soil water content. The function assumes linear shape when f_{shape}=1, concave shape when f_{shape}<0, and convex shape when f_{shape} >0. The initial and final values of p are arbitrarily taken at 0 and 1, respectively just as examples

This relatively high level of refinement for a simple model in the simulation of canopy responses to water stress is extended to the modeling of the responses of HI to water deficits. Empirical equations, but based on the competition between vegetative and reproductive growth, are used in *AquaCrop* to simulate the changes in HI when water deficits occur during the vegetative and/or the reproductive phases. Additionally, the well-known detrimental effects on HI of severe water stress during pollination and fruit set are simulated in a novel way. Pollination failure is calculated according to the fraction of total flowers that would be pollinated each day when stress of a certain level occurs, but its impact on HI is modulated by the extent that excessive potential fruits are present. This model component is still under testing against the limited datasets that exist on this important response. For further insight on the algorithms for simulating the HI responses to water deficits, the reader is referred to Raes et al (2008a).

2.8 The Soil-Root System

The root system in *AquaCrop* is simulated through the *effective rooting depth* (ERD) and its *water extraction pattern*. ERD 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. Water extraction pattern follows by default the standard 40%, 30%, 20%, and 10% for each quarter of the ERD starting with the top quarter, and may be established by the user in cases where different patterns are inferred from soil physical or chemical limitations. For the soil profile explored by the root system, the model performs a water balance that includes the processes of infiltration, runoff, drainage within the root zone, deep percolation, plant uptake, evaporation, and transpiration. Capillary rise is not yet included in the current version of *AquaCrop*. A daily soil water balance keeps track of the incoming and outgoing water fluxes at the boundaries of the root zone and of the water retained within it.

The distinctive features of the soil model component of *AquaCrop* are the adaptation of the *BUDGET* (Raes et al., 2006) approach to compute the soil water balance, and the procedures followed to simulate soil E. Briefly, the soil is divided into 12 compartments of variable depth, a requirement for the detailed simulation of E and of root water uptake. A set of finite differential equations compute the water movement between compartments, while crop water uptake is calculated with a root extraction term (Belmans et al., 1983). The model simulates unsaturated flow by comparing the drainage ability of the different soil horizons (Raes et al., 2006).

The simulation of E from soil is based on the principle of Stage I and Stage II drying (Philip, 1957; Ritchie, 1983) often used by models but relies on a new equation to simulate E during the Stage II drying phase (Raes et al., 2008a) with soil water content of the surface layer as the driver of the E process, instead of using the more common time function (Ritchie, 1972).

2.9 The Management

The management component of *AquaCrop* has two main categories: one on the more general *field* management, and one more specifically on *water* management. Under *field* management are options to select or define the fertility level or regime of the soil, to select and define field-surface practices of mulching to reduce soil E, or the use of soil bunds to control run-off and infiltration, and to define the time of cuttings of forage crops. The model does not compute nutrient balances; instead, parameterization is done for several fertility levels, ranging from optimal to poor. In addition the user may parameterize and define his/her own fertility level. These fertility levels affect CGC, CC_x, the onset of canopy senescence and rate of decline in CC, and the normalized WP. In addition, fertility may also affect stomata. Thus, *AquaCrop* provides general options to account for variations in fertility regime on the overall yield response, but does not simulate the nutrient cycles and dynamics.

Under *water* management are options to select ① rainfed-agriculture (no irrigation) or ② irrigation. Under irrigation one selects the application method (sprinkler, drip, or surface either by furrow or flood irrigation). The user can define his/her own schedule on the basis of applied water depth, or timing criteria, or let the model automatically generate the scheduling on the basis of fixed interval, fixed depth, or fixed percentage of soil water content criteria. With weather data as input, the model can either run the simulation automatically over the whole season, or run in time steps of 1 day or longer as defined by the user. The latter option is particularly suitable for trying out different irrigation schedules by adding water of selected amounts at selected times over the crop development cycle. The user interface offers several options of instant display of the simulated results in terms of crop production parameters or soil water balance. Thus, *AquaCrop* is particularly suited for optimizing a schedule of supplemental or deficit irrigation.

3 Model Performance

AquaCrop has recently been parameterized and calibrated for several crops, and validated against experimental data obtained either in other locations under different climate and water treatments, or in other years. We report here some results of *AquaCrop* performance to show its predictive capabilities for maize, cotton, soybean, and quinoa. In all the results presented here, the "measured" canopy cover was derived from the measured LAI, using a regression equation based on a number of data sets where both CC and LAI were measured.

3.1 Maize

The most extensive efforts on calibration and validation of *AquaCrop* have been carried out in maize (Hsiao et al., 2008; Heng et al., 2008). The maize crop parameters of *AquaCrop* were initially calibrated with an extensive dataset obtained in 6 field experiments conducted at the University of

California, Davis in 6 different years (Hsiao et al., 2008). Instead of calibrating the model with 1 or 2 years of measured data and then test the calibrated model with data measured in other years, the calibration was performed to fit the simulations of all 6 years of Davis data (Hsiao et al., 2008). The soil of the experimental area is dominantly Yolo silty clay loam, high in water holding capacity, deep and with no restrictive layers, allowing roots to reach 2.7 m depth near the end of the season. The climate is Mediterranean, with an annual average rainfall of 440 mm confined mostly to the winter-early-spring period. The 6 experiments involved 4 different cultivars. In the simulation, it was assumed that the cultivars differed only in their phenology, i.e., in their time to flower, senescence and maximum rooting depth, and physiological maturity. The same stress response functions were used regardless of the cultivar or year, or the stress treatment.

All treatments were irrigated around planting time. Thereafter the control treatment was irrigated regularly to ensure maximum production. The stress treatments were rainfed, irrigated regularly only for the first 40% or only for the last 55% of the life cycle, or irrigated lightly 2 or 3 times during the season. Model calibration was performed by comparing the simulated against the measured results for each simulation run, and a common set of parameters were selected which fitted best all the 6 years of experimental data used in this calibration. These parameters were then used to simulate maize data sets collected from 3 locations in other parts of the world, 2 of which were climatically very different from that of Davis (Heng et al., 2008). The parameters values obtained in the calibration of AquaCrop with the experiments conducted in Davis are given in Hsiao et al., (2008).

Model validation for maize was carried out with datasets from Bushland, Texas, Gainsville, Florida, and Zaragoza, Spain, largely differing in soil and climatic conditions (Heng et al., 2008). The Gainsville and Zaragoza datasets were obtained from ICASA Data Exchange (IDE) at http://www.icasa.net, while the Bushland datasets were originally reported by Howell et al (1996). An example of the degree of agreement between measured and simulated values with *AquaCrop* is shown in Fig. 3 for the canopy development and biomass accumulation collected in three experiments in Bushland. *AquaCrop* simulated very well the canopy cover development of 1989 and both the full and short seasons irrigated treatments in 1994 (Fig. 3). In 1990 the simulation of CC was also very good, although the maximum canopy cover in the irrigated treatment was slightly under-estimated (Fig. 3). On the other hand, the CC of the non-irrigated short-season treatment in 1994 was not well simulated after day 70; the simulated canopy cover declined faster than the measured values (Fig. 3).

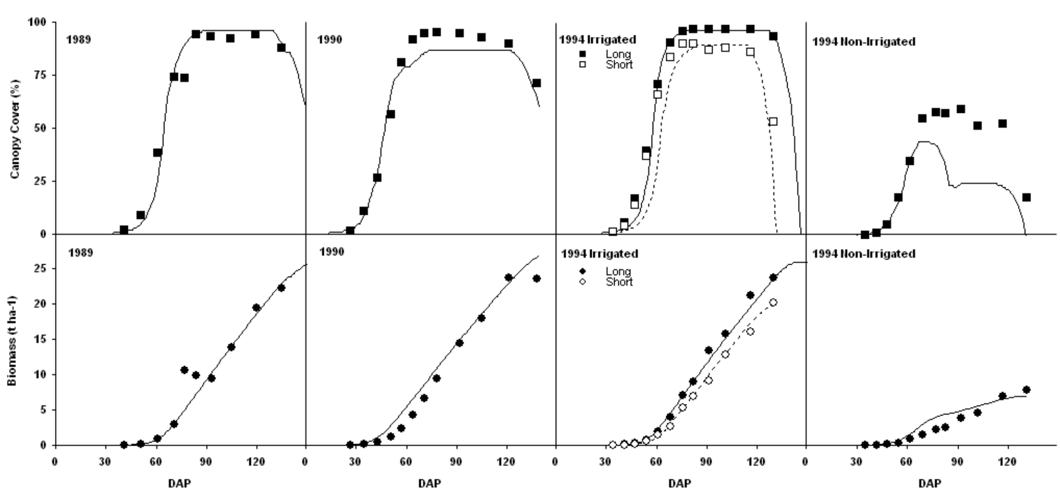

Figure 3 Simulated (line) and measured canopy cover (■) (top) and biomass (●) (bottom) accumulation of maize for the 1989, 1990 and the 1994 fully irrigated and non-irrigated treatments in Bushland, Texas

The time course of biomass production for the three seasons' irrigated treatments in Bushland was simulated accurately (Fig. 3b). The model was able to properly simulate the 1989, 1990 and both the full and short seasons irrigated biomass in 1994. Contrary to the under-prediction in the canopy cover in the non-irrigated short-season treatment in 1994 (Fig. 3a), the model simulated the biomass production that year fairly well (Fig. 3b). The values of simulated and observed total biomass and grain yield are given in Table 1. The biomass comparison shows that the majority of values had a deviation of less than 5%, while the comparison between measured and simulated grain yield was also within 3% in three out of the four cases (no grain yield was given in the non-irrigated treatment in 1994). Excellent match in grain yield was observed in 1989 while grain yield simulation was off by 12.4% in the 1994 irrigated full-season hybrid, even though final biomass was accurately simulated.

Table 1 Comparison between measured and simulated total biomass, grain yield and seasonal evapotranspiration (ET) for Bushland, Texas

Treatment	Final Biomass (Mg ha^{-1})		Grain Yield (Mg ha^{-1})		Total ET (mm)	
	Measured	Simulated	Measured	Simulated	Measured	Simulated
1989 – FI	22.3	25.6	12.4	12.1	625.0	598.0
1990 – FI	26.2	26.8	13.1	12.7	730.8	778.3
1994 – FI (Full Season)	27.8	26.2	13.2	12.3	882.1	808.0
1994 – FI (Short Season)	20.4	19.9	11.3	9.5	696.0	687.0
1994 – NI (Short Season)	7.8	7.0	NA	3.4	NA	—

Model validation results for the experiments located in Gainesville (Florida) and Zaragoza, (Spain), were also quite good, although with less satisfactory results when simulating severe water-stress treatments, especially when stress occurred during senescence (Heng et al., 2008). Overall, considering that parameterization and calibration was done using data collected only in Davis, California, the results of the validation in Texas, Spain and Florida were quite satisfactory.

3.2 Cotton

Parameterization and calibration of *AquaCrop* for cotton under full and deficit irrigation was performed by Farahani et al., (2008) in the eastern Mediterranean environment of northern Syria. The experimental site (Tel-Hadya) is characterized by an annual average rainfall of 350 mm concentrated in the fall to early spring, with no rainfall during the hot and windy summer. Soil at the site is over 1.5 m deep, well-drained, and of clay texture. Experimental results from 3 sequential years (2004 to 2006) were used for the investigation.

The short season cotton cultivar *Aleppo-118* was sown beginning May. Cotton was drip irrigated. Four levels of irrigation were applied and measured by flow meters, namely 40, 60, 80, and 100% of the estimated full water requirements.

AquaCrop was parameterized for cotton using data of 2006 and the parameters were then used to validate the model for the 2004 and 2005 experiments. The model was used to predict ET and seed yield. Validation results for 2004 and 2005 are shown in Fig. 4. *AquaCrop* simulated total ET across irrigation treatments and years with a RMSE of 38 mm, and cotton seed yield with a RMSE of 0.36 t ha^{-1}.

Cotton, being an indeterminate crop with a detrimental tendency to go highly vegetative when water supply is ample, has a complex response to the environment variations and its behavior is difficult to simulate. Current cotton simulation models such as *GOSSYM* (Baker et al., 1983; Whisler et al., 1986) are amongst the more elaborate mechanistic crop simulation models. The results from Farahani et al. (2008) with *AquaCrop* provide a set of first estimates for the difficult-to-determine parameters for further testing of the model for cotton at other locations. Obviously, this parameterization and testing are preliminary and further work is needed at other geographical locations and under different water deficit regimes. *AquaCrop* has been used to develop optimal strategies for deficit irrigation of cotton under conditions of Southern Spain (Garcia-Vila et al., 2008).

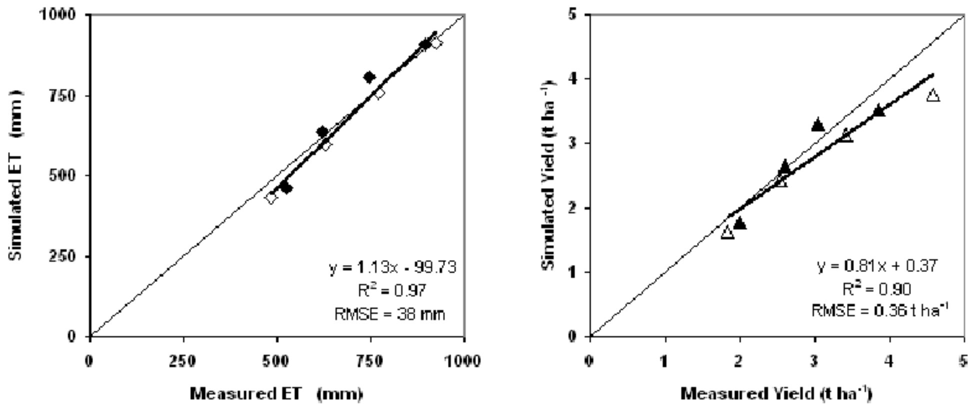

Figure 4 Simulated (line) and measured evapotranspiration (♦) and seed yield (▲) of cotton for the 2004 (solid) and 2005 (open) growing seasons in Tel Hadya, Syria

3.3 Soybean

The evaluation of *AquaCrop* for simulating soybean growth, development and yield was conducted using data from experiments over a seven-year period (1995 – 2001), conducted on a 4.7 ha watershed at the ICRISAT Center, Patancheru, Andhra Pradesh in India. The cropping system was a sequence of soybean-chickpea rotated every year on the same field, with soybean sown during the rainy season and chickpea during the post-rainy season. The soybean cultivar PK 472 was planted with a density of 30 plants/m^2 around 25 June each year, depending on the onset of rainy season. The soil is a Vertic Inceptisol with depth varying between 110 and 125 cm and a extractable soil water around 150 mm/m. Five replicated plant samples were collected over an area of 0.5 m^2 every 7 to ten days throughout the season. Leaf area index and biomass, separated into stems, leaves and pods, were measured on each sample. Final yield was determined on a 45 m^2 area per plot.

The phenology, growth and productivity data of 1996 were used to calibrate the model. Using the planting density, sowing date and measured initial soil water content for that year to initiate the model, WP* was parameterized as 12 g m^{-2} before anthesis, and was reduced by 20% during yield formation, because of the high lipid and protein content of soybean seeds. The model parameters calibrated with the 1996 data were then used to validate *AquaCrop* using the independent dataset from the other six years. A summary of the results comparing the simulated and measured trends of biomass and seed weight for 1996 through 2001 is given in Fig. 5.

Good agreement was observed between measured and simulated values. This result was particularly significant given the variability in rainfall observed over the six years of validation (Fig. 6).

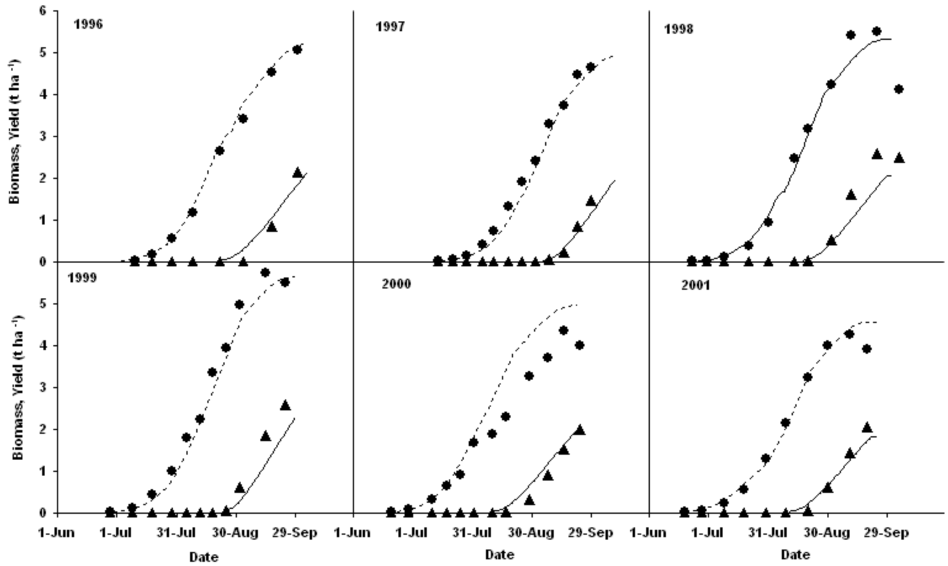

Figure 5 Simulated (line) and measured biomass (●) and yield (▲) of soybean for the 1996 – 2001 crop seasons in Patancheru, India

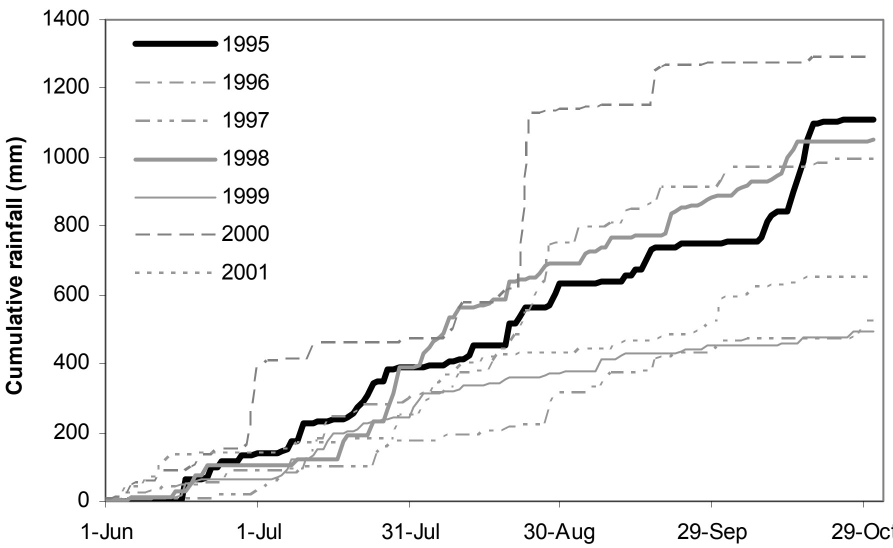

Figure 6 Cumulative rainfall during soybean cropping cycles for the 1995 – 2001 seasons in Patancheru, India

In 2000, *AquaCrop* over-predicted biomass in the second half of the crop cycle. The reason for the apparent over-estimation is not clear. It is possible that due to the unusually high rainfall recorded in that particular season (over 1200 mm between June and September) there might have been some problems either with experimental data collection or with the crop behavior. In fact, close examination of the measured trend reveals a downward shift in biomass production starting from the middle of August up to harvest. The simulations of canopy cover for the six years (Fig. 7) were also satisfactory, except during the early parts of some years when the simulations delayed emergence by 3-5 days as compared to the measured data. That resulted in a discrepancy in the predicted date of maximum canopy cover, as showed in Fig. 7.

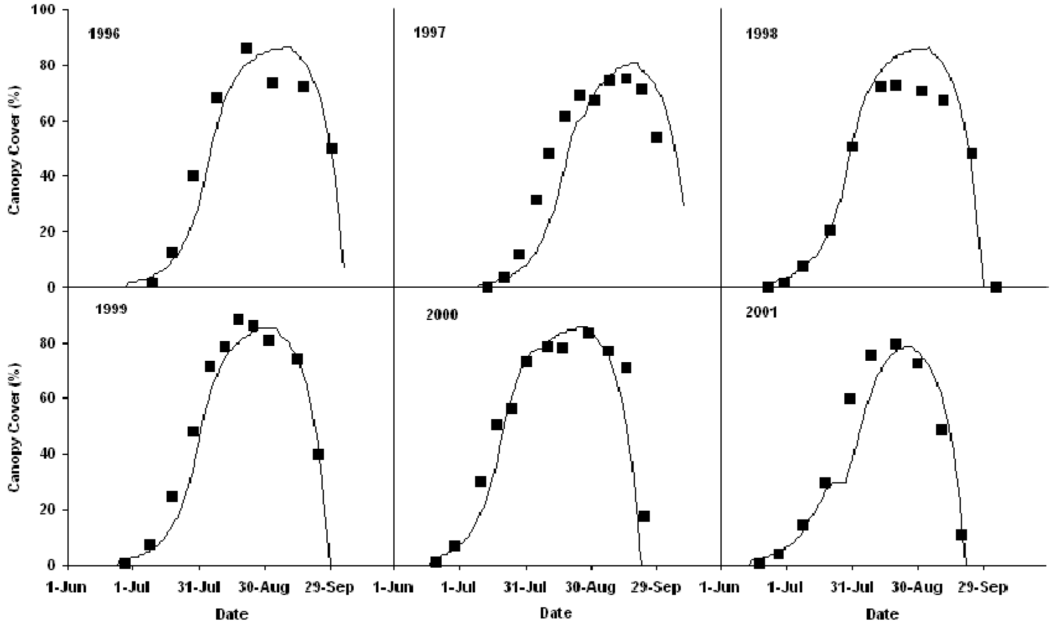

Figure 7 Comparison of AquaCrop simulated (lines) and observed (symbols) canopy cover of soybean during the 1996 – 2001 crop seasons in Patancheru, India

The comparison of simulated against observed biomass and grain yield for the six soybean seasons were in close agreement (Table 2). The excellent overall performance of *AquaCrop* in this case is demonstrated by the fact that only 1 in 6 predictions of biomass and grain yields was outside the 5% deviation of the observed values.

Table 2 Measured and simulated final grain and biomass yields, absolute difference between simulated and measured, maximum and minimum absolute difference, and Root Mean Square Error (RMSE) of soybean during the 1996 – 2001 crop seasons in Patancheru, India

	Biomass at Harvest (t ha^{-1})			Yield (t ha^{-1})		
	Measured	Simulated	|Δ|	Measured	Simulated	|Δ|
1996	5.1	5.2	0.1	2.4	2.1	0.3
1997	4.6	4.9	0.3	1.5	2.0	0.5
1998	5.5	5.3	0.2	2.6	2.1	0.5
1999	5.7	5.6	0.1	2.6	2.3	0.3
2000	5.1	5.8	0.7	2.3	2.3	0.0
2001	4.3	4.6	0.3	2.1	1.8	0.3
Δmax	—	—	0.7	—	—	0.5
Δmin	—	—	0.1	—	—	0.0
RMSE	—	—	0.3	—	—	0.4

AquaCrop has shown sensitivity to initial soil moisture conditions. These were quite variable and difficult to characterize in this case due to the cracking features of the soils of the experimental field (Vertisols and Vertic intergrades). While the very good performance of *AquaCrop* for this dataset is quite encouraging, there is a need to verify the validity of the soybean crop parameters, derived in the semi-arid tropics of India, in other regions.

3.4 Quinoa

AquaCrop has also been calibrated and validated by Geerts et al (2008) for the simulation of ① the soil water balance, ② biomass and ③ seed yield of quinoa (Chenopodium quinoa Willd.) in the Bolivian Altiplano. To calibrate and validate *AquaCrop*, the data of a mini-lysimeter experiment (2004 – 2005) and several field experiments (2005 – 2006 and 2006 – 2007) in 4 locations in the Central and Southern Bolivian Altiplano, described in Geerts et al (2006 and 2008), were used. In each location, the irrigation treatments included: rainfed, different strategies of deficit irrigation, and full irrigation. Quinoa land races fitting best the eco-regions in the study area were selected. The crop parameters of quinoa were calibrated using data from 8 out of the 22 monitored fields, in different years and locations, in order to obtain various environmental and boundary conditions. Excellent results were obtained for the simulation of the soil water balance transpiration, biomass and final yield, as reported in Geerts et al. (2008). An example of the simulation of the soil water content is shown in Fig. 8, where simulated values agreed very well with the measurements throughout the crop cycle. For the 14 validation fields the relation between simulated and observed biomass yielded a coefficient of determination (R^2) of 0.87, a Nash efficiency (EF) of 0.83 and a relative root mean square error (RRMSE) of 16 %. For the relation between simulated and observed yield, the statistics are R^2 = 0.82, EF = 0.79, and RRMSE = 18% (Geerts et al 2008).

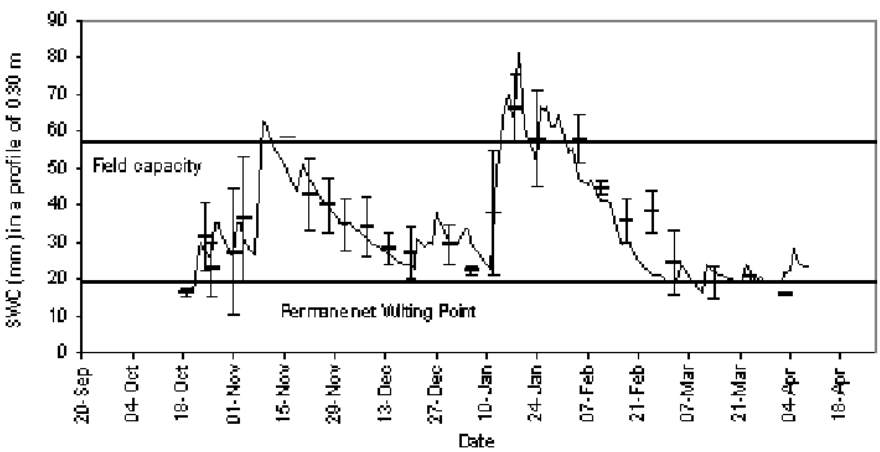

Figure 8 Simulated (line) and observed (▬ with error bars) soil water content (SWC) for quinoa under deficit irrigation during the 2005-2006 growing season in Patacamaya, Bolivia

4 Concluding Discussion

The conceptual framework, design, structure and key algorithms of *AquaCrop* have been described to highlight its distinctive features. *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 major field and vegetable crops cultivated worldwide. When compared to other crop simulation models, its parameters are explicit and mostly intuitive and the model was built to achieve a balance between accuracy, simplicity, and robustness. The goal was to make the model as transparent as possible to users that generally do not belong to the research community and are not very familiar with the discipline of crop physiology. Since the development of the first simulation models several decades ago, modelers have attempted to incorporate all the relevant advances in crop physiology and that has resulted in relatively complex, research oriented tools that have a significantly higher number of parameters than *AquaCrop*. For instance, one of the models of the Wageningen school, uses 27 crop-specific parameters to simulate aboveground growth and production, plus ten genetic coefficients to deal with specific traits (Yin and Van Laar, 2005). The main simulation models currently in use have also been designed to incorporate many physiological processes at a level that requires the use of a relatively large number of parameters (Wang et al., 2002).

Hammer et al. (2002) reviewed the contributions of crop modeling and focused on two areas where models may contribute in the future. One area dealt with improving the understanding of genetic regulation, and with simulating the role of different genetic traits in determining crop productivity (Hammer et al., 2002). For that purpose, crop models require the highest possible level of process physiology, and to be as mechanistic as feasible. The other area where new developments were anticipated is an enhanced role for models in assisting in management decisions, policy actions, and in education and research (Hammer et al., 2002). *AquaCrop* clearly attempts to contribute in this second area. 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. Even though *AquaCrop* uses a limited number of parameters, it represents an effort to incorporate current knowledge of crop physiological responses to water deficits 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 the water productivity levels (benchmarking tool). It can also be used by economists, water agencies, and managers for scenario analysis and for planning purposes. It is suited for prospective studies such as those of future climate change scenarios. Overall, it is particularly suited to develop agricultural water management strategies for a variety of objectives and applications.

The particular features that distinguishes *AquaCrop* from other crop models are 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 for 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 relatively simple, it gives particular attention to the fundamental processes involved in crop productivity and in its responses to water deficits, both from physiological and agronomic background perspectives. The fact that the simulated results agreed generally well with the measured data in the examples presented suggests that *AquaCrop* may be successful in achieving a good balance in simplicity, robustness, accuracy, and ease of use. These findings are particularly promising as they have been obtained with only limited calibration of the model. For further details on the conceptual design of the model, and for the specific algorithms and calculation procedures of *AquaCrop*, the reader is referred to Steduto et al. (2008), and to Raes et al. (2008b).

Acknowledgements

The Authors would like to acknowledge: Arianna Facchi, V. Nageswara Rao, and Piara Singh, for their contribution of the soybean data for *AquaCrop* calibration; Magali Garcia, Roberto Miranda, Jorge A. Cusicanqui, Cristal Taboada, Richard Mamani, Jorge Mendoza, Ruben Huanca, and Teddious Mhizha for their contribution to the quinoa *AquaCrop* calibration and testing.

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