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AquaCrop: A new model for crop prediction under water deficit conditions

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SUMMARY – Estimating attainable yield under water-limiting conditions remains central in arid, semi-arid and drought-prone environments. To address this need, FAO has been developing a yield-response to water model, *AquaCrop*, which simulates attainable yields of the major herbaceous crops. As compared to other crop models, *AquaCrop* has a significantly smaller number of parameters and a better balance between simplicity, accuracy and robustness. Root zone water content is simulated by keeping track of incoming and outgoing water fluxes at its boundaries, considering the soil as a water storage reservoir with different layers. Instead of leaf area index, *AquaCrop* uses canopy ground cover. Canopy development, stomatal conductance, canopy senescence and harvest index are the key physiological crop responses to water stress. Evapotranspiration is simulated as crop transpiration and soil evaporation and the daily transpiration is used to derive the daily biomass gain via the normalized *biomass water productivity* of the crop. The normalization is for reference evapotranspiration and CO_2 concentration to make different water management systems, including rainfed agriculture and supplemental, deficit, and full irrigation. Simulations can be carried out both on calendar and thermal time, and the developing versions will incorporate effects of nutrient regimes, particularly nitrogen, and of soil salinity. *AquaCrop* is mainly addressed to extension services practitioners, consulting engineers, governmental agencies, NGOs and farmers associations.

Key words: Crop modeling, yield simulation, water productivity, water stress.

RESUME – "AquaCrop : *Un nouveau modèle pour la prédiction de la production des cultures en conditions de limitation d'eau". L'estimation de la production qui peut être obtenue en conditions de limitation d'eau est capitale dans les environnements arides, semi-arides et sujets á la sécheresse. Afin de faire face à cette exigence, la FAO est en train de développer un logiciel pour la simulation de la réponse productive des cultures herbacées à la disponibilité hydrique, nommé* AquaCrop. *Par rapport à d'autres logiciels,* AquaCrop *nécessite un nombre significativement plus faible de paramètres, atteignant un équilibre entre simplicité, précision et robustesse. La teneur en eau dans la zone des racines est simulé à travers la quantification des flux d'eau en entrée et en sortie du système, considérant le sol comme un réservoir d'eau constitué par plusieurs couches.* AquaCrop *utilise le pourcentage de couverture du sol au lieu de l'indice foliaire. La réponse de la culture au stress hydrique est modulée par le développement de la couverture foliaire, la conductance stomatique, la sénescence et l'indice de récolte. La simulation de la transpiration détermine l'accumulation journalière de biomasse, au moyen de la productivité de l'eau de la culture. Ce dernier paramètre est normalisé pour l'evapotranspiration de référence et pour le* CO_2*, permettant de faire des simulations en zones et périodes différentes, ainsi que pour des scénarios climatiques futures.* AquaCrop *simule l'agriculture pluviale, l'irrigation supplémentaire, déficitaire et totale. Les simulations peuvent être conduites en jours ou sur la base du régime thermique. La version finale d'*AquaCrop *prendra en considération l'azote et la salinité du sol.* AquaCrop *s'adresse aux ingénieurs-conseil, organismes gouvernementaux, ONG et associations d'usagers.*

Mots-clés : *Modélisation des cultures, simulation des productions, productivité de l'eau, stress hydrique.*

Introduction

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

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

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.

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

The consultation led to a revision framework that treats separately field crops from tree crops. For the field crops, it was suggested to develop a model of proper structure and conceptualization that would evolve from Eq. (1) and be designed for planning, management and scenario simulations. For the tree-crops, it was recommended to formulate guidelines to determine on a relative basis their yield response to water relying on experts knowledge. This paper addresses only the development of the crop model, namely *AquaCrop*, which differs from the main existing models for its balance between accuracy, simplicity and robustness.

The conceptual framework, design, structure, algorithms and distinctive features of *AquaCrop* are herein described.

Model description

Model growth-engine and flowchart

AquaCrop evolves from the previous Doorenbos and Kassam (1979) approach (Eq. 1) by separating: (i) the ET_a into soil evaporation (E_s) and crop transpiration (T_a); and (ii) the final yield (Y) into biomass (B) and harvest index (HI). The separation of ET_a into E_s and T_a avoids the confounding effect of the non-productive consumptive use of water (E_s). This is important especially during incomplete ground cover. The separation of Y into B and HI allows the distinction of the basic functional relations between environment and B from those between environment and HI. These relations are in fact fundamentally different and their use avoids the confounding effects of water stress on B and on HI. The changes described led to the following equation at the core of the *AquaCrop* growth engine:

$$B = WP \cdot \Sigma T_a \quad (2)$$

where T_a is the crop transpiration (in mm) and WP is the water productivity parameter (kg of biomass per m^2 and per mm of cumulated water transpired over the time period in which the biomass is produced). This step from Eq. (1) to Eq. (2) has a fundamental implication for the robustness of the model due to the conservative behavior of WP (Steduto *et al.*, 2007). It is worth noticing, though, that both equations are different expressions of a *water-driven growth-engine* in terms of crop modeling design (Steduto, 2003). The other main change from Eq. (1) to *AquaCrop* is in the time scale used for each one. In the case of Eq. (1), the relationship is used seasonally or for long periods (of the order of months), while in the case of Eq. (2) the relationship is used for daily time steps, a period that is closer to the time scale of crop responses to water deficits.

A schematic representation of the evolution of *AquaCrop* from Eq. (1) is shown in Fig. 1.

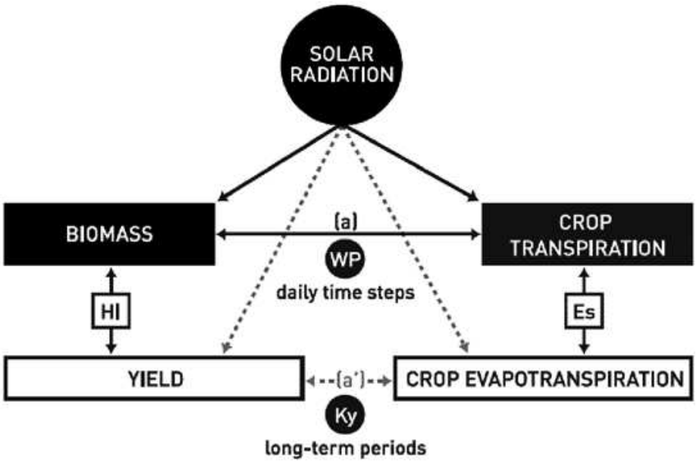

Fig. 1. Evolution of *AquaCrop* from Eq. (1), based on the introduction of two intermediary steps: the separation of soil evaporation (E_s) from crop transpiration (T_a) and the attainment of yield (Y) from Biomass (B) and harvest index (HI). The relationship *a'* linking Y to crop evapotranspiration is expressed through Eq. (1) via the k_y parameter and normally applies to long periods. The relationship *a* linking B to T_a is expressed through Eq. (2) via the WP parameter and has a daily time step.

To be functional, this growth engine (Eq. 2) needs to be inserted in a complete set of additional model components. In fact, similarly to many other models, *AquaCrop* has a structure that overarches the soil-plant-atmosphere continuum. It includes *the soil,* with its water balance; *the plant*, with its development, growth and yield processes; and *the atmosphere*, with its thermal regime, rainfall, evaporative demand and carbon dioxide concentration. Additionally, some *management* aspects are explicitly considered (e.g., irrigation, fertilization, etc.), as they will affect the soil water balance, crop development and therefore final yield. Pests, diseases, and weeds are not considered.

The functional relationships between the different model components are depicted in the flow chart of Fig. 2.

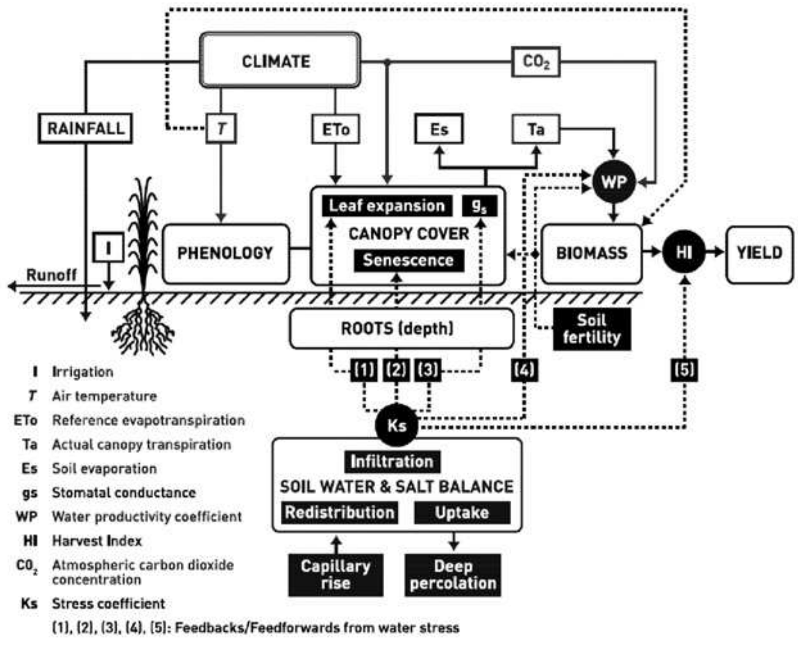

Fig. 2. Flowchart of *AquaCrop* indicating the main components of the soil-plant-atmosphere continuum.

While algorithms of *AquaCop* which are distinctive of this model are presented below, others that are common to other models are only mentioned here and the reader is referred to the literature for their description. For further insight into the model, the reader is referred to the *AquaCrop Calculation Procedure* (Raes *et al.*, 2008).

The atmosphere

The atmospheric environment of the crop is described in the *climate* component of *AquaCrop* and deals with key input meteorological variables (see Fig. 2). Five weather input variables are required to run *AquaCrop*: daily maximum and minimum air temperatures, daily rainfall, daily evaporative demand of the atmosphere expressed as reference evapotranspiration (ET_o), and the mean annual carbon dioxide concentration in the bulk atmosphere. While the first four are derived from typical agro-meteorological stations, the CO_2 concentration uses the Mauna Loa Observatory records in Hawaii.

ET_o is obtained following the procedures described in the FAO *Irrigation and Drainage Paper* 56 (Allen *et al.*, 1998). Where not all the required input variables for calculating ET_o are available, *Paper* 56 describes the methods to derive them. *AquaCrop* does not include the routines for calculating ET_o, but a separate software program (Raes *et al.*, 2008) based on the *Paper* 56 is provided to the user for such purpose.

Temperature (min and max), rainfall and ET_o may be provided at different time scales, specifically daily, 10-day, and monthly records. However, at run time *AquaCrop* processes the 10-day and monthly records into daily values. The calculation procedure to downscale the 10-day and the monthly records to daily values is described by Gommes (1983). This flexibility for different time scales of weather input variables is required to use *AquaCrop* in areas of limited weather records.

On a daily basis, the rainfall that infiltrates the soil is derived subtracting runoff from the total rainfall. When 10-day or monthly data are used, *AquaCrop* estimates the infiltrated rainfall through two options, the USDA Soil Conservation Service (SCS, 1993), or as a percentage of total rainfall.

As illustrated in Fig. 2, the temperature plays a role in influencing the crop development (phenology); the rainfall and ET_o are inputs for the water balance of the soil root zone; and the CO_2 concentration of the bulk atmosphere influences the crop growth rate and the WP.

The crop

In *AquaCrop*, the crop system has five major components and associated dynamic responses (see Fig. 2): phenology, aerial canopy, rooting depth, biomass production and harvestable yield. The crop grows and develops over its cycle by expanding its canopy and deepening its rooting system while at the same time the main developmental stages are established.

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

The canopy, thus, represents the source for actual transpiration that gets translated in a proportional amount of biomass produced through the WP (Eq. 2). The harvestable portion of such biomass (yield) is then determined via the HI, i.e.

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

Even though *AquaCrop* uses a HI parameter, it does not calculate the partitioning of biomass into various organs (e.g., leaves, roots, etc.), i.e., biomass production is decoupled from canopy expansion and root deepening. This choice avoids dealing with the complexity and uncertainties associated with the partitioning processes, which remain among the least understood and most difficult to model. The relationship between shoot and root is maintained through a functional balance between canopy development and root deepening.

Depending on the data availability, preference of the user and/or simulation modes, crop growth and development can be described dynamically either in *calendar* or in *thermal* time. *AquaCrop* uses Growing Degree Days (GDD) to compute thermal time, through the following equation

$$GDD = \frac{(T_{max} + T_{min})}{2} - T_{base} \tag{4}$$

where, GDD is the number of temperature degrees determining a proportional crop growth and development, T_{max} is the daily maximum air temperature, T_{min} is the daily minimum air temperature and T_{base} is the temperature below which crop development stops. *AquaCrop* incorporates an upper temperature (T_{upper}) threshold above which crop development no longer increase with an increase in air temperature. The actual calculation of the GDD, accounting for the base and upper threshold, follows the procedure described by McMaster and Wilhelm (1997).

Different crop developmental stages are completed once a given number of calendar days or GDD are reached. *AquaCrop* distinguishes three major crop types on the basis of their harvestable yields: (i) fruit or grain producing crops; (ii) roots and tubers producing crops; and (iii) leafy vegetable producing crops. Each of this crop type has its own corresponding developmental stages. The genetic variation among species and cultivars may be implemented in the model through the variation in timing and duration of the various developmental stages, as well as through the rate of canopy expansion, rate of root deepening, the water productivity parameter and other response factors to environmental conditions.

The canopy is a crucial feature of *AquaCrop* through its expansion, ageing, conductance and senescence (Fig. 2), as it determines the amount of water transpired, which in turn determines the amount of biomass produced.

The canopy expansion is expressed through the fraction of green canopy ground-cover (CC). For non stressed conditions, the expansion from emergence to full canopy development follows the exponential growth during the first half of the full development (Eq. 5), and follows an exponential decay (Eq. 6) during the second half:

$$CC = CC_o e^{CGC \cdot t} \tag{5}$$

$$\text{and, } CC = CC_x - (CC_x - CC_o) \cdot e^{-CGC \cdot t} \tag{6}$$

where CC is the canopy cover at time t, CC_o is the initial canopy cover, or canopy cover at t = 0, CGC is the canopy growth coefficient in fraction per day or per degree-day, CC_x is the maximum canopy cover, and t is the time in days or in degree-days.

After the full development, the canopy can have a variable duration period before entering the senescence phase. During this period, an ageing effect is allowed to account for a reduction of the overall photosynthetic capacity of the crop over time (but before senescence), and this is implemented through an ageing coefficient that decreases mildly the CC_x as time passes. Once the late season is reached, CC enters in a declining phase during senescence.

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

Because T_a is the basis for biomass production, the accurate simulation of the canopy is crucial to compute T_a separately from E_s. The calculation of crop transpiration in *AquaCrop* accounts also for effects deriving from sun angle, inter-row micro-advection and sheltering effect during partial ground cover and in presence of row crops.

In *AquaCrop*, the canopy responses to water deficit (see Fig. 2) occurs through: (i) the reduction in expansion rate, i.e., reducing the CGC of Eq. 5 and 6, (ii) the reduction in stomatal conductance (g_s); and (iii) the acceleration of senescence, i.e., increasing the canopy decline coefficient (CDC). Depending on crops and conditions, water stress can also induce acceleration of ageing through the increase of the ageing coefficient but this aspect is treated differently from the major three canopy responses.

All three major responses are formalized with the same conceptualization and algorithms. Water deficits are quantified through a water stress coefficient (K_s) that varies from 1 (no stress) to zero (full stress). Stress occurs when the depletion in the root zone relative soil water content reaches a threshold value, p varying between 0 and 1. When p reaches a threshold value for a specific response to water deficit, K_s is computed through the following equation:

$$K_s = 1 - \frac{\left(e^{p \cdot f_{shape}} - 1\right)}{\left(e^{f_{shape}} - 1\right)} \tag{7}$$

where the parameter f_{shape} influences the shape of the function K_s. Typical response functions of K_s are represented in Fig. 3.

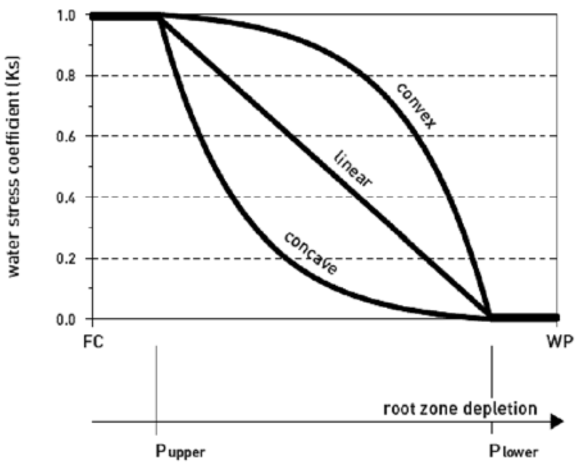

Fig. 3. Examples of K_s response function to the relative depletion in soil water content. The function assumes linear shape when f_{shape} = 1, concave shape when f_{shape} < 0, and convex shape when f_{shape} > 0.

The root system in *AquaCrop* is simulated through its *effective rooting depth* and its *water extraction pattern*. The *effective rooting depth* (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. A level of 90-95% of the water uptake is considered to be taken up within the effective rooting depth. Water extraction patterns follow by default the standard 40%, 30%, 20% and 10% for every quarter of the ERD. However, a specific extraction pattern can be established for different crops and soils by the user, in cases where different patterns are inferred from soil physical or chemical limitations.

As previously indicated, the growth engine of *AquaCrop* is water driven through Eq. (2). The model does not simulate lower hierarchical processes expressing the intermediary steps involved in the accumulation of biomass. The underlying processes are "summarized" and synthetically incorporated into one single coefficient defined biomass water productivity (WP). The basis for using Eq. (2) as the core of the model growth engine lies on the conservative behaviour of WP (Steduto and Albrizio, 2005; Steduto *et al.*, 2007). The WP parameter of *AquaCrop* is normalized for ET_o and the carbon dioxide (CO_2) concentration of the bulk atmosphere, it may vary moderately in response to the fertility regime, and remains constant under water deficits except when severe water stress is reached. The normalization of WP for climate makes the model applicable to diverse location and seasons, including future climate scenarios.

Once the biomass is obtained (Eq. 2), the crop yield is derived by multiplying B times the HI (Eq. 3). Starting from flowering, HI is simulated after a lag phase, by a linear increase with time for a given period during yield formation that depends on the crop species and cultivar. HI can be adjusted for water deficits depending on the timing and extent of the water stress during the crop cycle.

The soil

The soil component of *AquaCrop* is configured as a dispersed system of a variable depth allowing up to 5 layers of different texture composition along the profile. As default, the model includes all the classical textural classes present in the USDA triangle but the user can input its own specific value. For each texture class, the model associates a few hydraulic characteristics and it estimates them for the texture entered by the user through pedotransfer functions. Also in this case, though, specific values of the soil hydraulic characteristics can be entered by the user. The hydraulic characteristics include the drainage coefficient (τ), the hydraulic conductivity at saturation (k_{sat}), and the volumetric water content at saturation (θ_{sat}), field capacity (θ_{FC}), and wilting point (θ_{WP}).

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

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

The management

The management component of *AquaCrop* has two main categories: a more general *field* and a more specific *water* management.

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

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

Conclusions

The conceptual framework, design, structure and key algorithms of *AquaCrop* have been described to highlight its distinctive features and peculiarities.

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

The particular features that distinguishes *AquaCrop* from other crop models is its focus on water, the use of ground canopy cover instead of leaf area index, and the use of water productivity values normalized for atmospheric evaporative demand and of carbon dioxide concentration that confer the model an extended extrapolation capacity to diverse locations and seasons, including future climate scenarios. Moreover, although the model is simple, it gives particular attention to the fundamental processes involved in crop productivity and in the responses to water, from a physiological and agronomic background perspective. For further details on the specific algorithms and calculation procedure of *AquaCrop*, the reader is referred to Raes *et al*. (2008).

References

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998). Crop evapotranspiration: Guidelines for computing crop water requirements. *Irrigation and Drainage Paper* No. 56. FAO, Rome, Italy, 300 pp.

Doorenbos, J. and Kassam, A.H. (1979). Yield response to water. *Irrigation and Drainage Paper* No. 33. FAO, Rome, Italy, 193 pp.

Gommes, R.A. (1983). Pocket computers in agrometeorology. *Plant Production and Protection Paper* No. 45. FAO, Rome, Italy, 140 pp.

McMaster, G.S. and Wilhelm, W.W. (1997). Growing degree-days: One equation, two interpretations. *Agric. For. Meteorol.*, 87: 291-300.

Raes, D., Steduto, P., Hsiao, T.C., Fereres, E. and Heng, L. (2008). *AquaCrop Calculation Procedure, Prototype Version 2.3a*. FAO, Rome, Italy, 64 pp.

Ritchie, J.T. (1972). Model for predicting evaporation from a row crop with incomplete cover. *Water Res. Research*, 8: 1204-1213.

SCS (1993). Irrigation water requirements. National Engineering Handbook, part 623. *Soil Conservation Service*, US Dept. of Agriculture. Washington, USA, 284 pp.

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, Italy.

Steduto, P. and Albrizio, R. (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., Hsiao, T.C. and Fereres, E. (2007). On the conservative behaviour of biomass water productivity. *Irrig. Sci.*, 25: 189-207.