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AquaCrop: FAO'S crop water productivity and yield response model☆

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A B S T R A C T

With the help of relatively few conservative crop parameters, AquaCrop simulates final crop yield in four steps that are easy to understand, which makes the modeling approach transparent. The steps consist in the simulation of development of the green crop canopy cover, crop transpiration, above-ground biomass, and final crop yield. Temperature and water stresses directly affect one or more of the above processes. Nutrient deficiencies and salinity effects are simulated indirectly by moderating canopy cover development over the season, and by reducing crop transpiration and the normalized water productivity. The effect of CO_2 concentration on biomass is simulated by altering the normalized water productivity. The model requires a relatively small number of explicit parameter values and mostly intuitive input variables. The paper describes the essence of AquaCrop Version 4.0, applications and parameterization of crops, crop responses to elevated CO_2 concentration, soil fertility and salinity, and further model developments.

Software availability

The software ‘AquaCrop’ is freely available. The installation disk, installation guidelines and reference manual can be downloaded from the FAO website: http://www.fao.org/nr/water/aquacrop.html

AquaCrop is programmed in Delphi and operates under Windows. It was first released in January 2009 (Version 3). The current version 4.0 was released in August 2012. AquaCrop is developed by FAO (Rome, Italy). For further information contact Dirk RAES (dirk.raes@ees.kuleuven.be; Tel. +32 16 32 97 43; Fax: +32 16 32 97 60).

1. Introduction

Nowadays a multitude of environmental models exist. All have their own purpose and merit, and before a model is used, a critical evaluation of the most appropriate model for a study should be made, based on the model's scope and purpose (Bennett et al., 2013). For example, some models can be very good in providing seasonal estimates with a limited calibration, while others can provide daily or even hourly information that can be of relevance in detailed studies, on the condition of the availability of good data for model calibration. Ever more, individual models are also compared in the frame of large-scale projects (e.g. AgMIP, the Agricultural Model Intercomparison and Improvement Project; Rosenzweig et al., 2013; BioMA, Biophysical model applications; Donatelli et al., 2012) or form part of an integrated (environmental) modeling concept where multiple disciplines come together to formulate solutions for complex, real-world problems (Laniak et al., 2013). To make informed choices on which model(s) to apply, model users should have a good view on the broad range of models, and their scopes, that are available today. For good use, all these models share the necessity for appropriate parameter estimation, performance evaluation (Bennett et al., 2013) and uncertainty analysis of different steps of the modeling process (e.g. Refsgaard et al., 2007; Saltelli and Annoni, 2010; Vanuytrecht et al., 2014a; Warmink et al., 2010). Although diverse reasonable methods exist, these routines should be of minimum quality. Standard protocols can therefore be useful (Saltelli and Annoni, 2010; Warmink

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et al., 2010). At the same time, expert knowledge, which can have a fuzzy origin, is also valuable for environmental models and their parameterization (Krueger et al., 2012). In any case, transparency about the applied protocols is essential. With all this in mind, the essence, current status and future prospects of the crop productivity model AquaCrop are presented in this paper, five years after its release (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2009).

Facing growing water scarcity, declining water quality, and uncertainties of climate change and climate variability, improving efficiency and productivity of crop water use, with the simultaneous reduction of negative environmental impact, are of utmost importance to respond to the increasing food demand of the growing world population (Steduto et al., 2012). To address food security and assess crop production as affected by environment and management, a large number of crop simulation models were developed over the last four decades. These models often require a large number of input variables and parameter values that are not easily available for the diverse range of crops and environments worldwide. Usually, scientists are much more familiar with these variables and parameters than the model's end users. Furthermore, insufficient transparency is often a strong constraint for extension services practitioners, consulting engineers, governmental agencies, NGOs and farmer associations. To deal with these limitations, the Food and Agriculture Organization of the United Nations (FAO) has developed AquaCrop as a model that seek a balance among simplicity, accuracy and robustness. To facilitate wide application, this multi-crop model requires only a relatively small number of explicit parameter values and mostly intuitive input variables, which are obtainable by straightforward methods. Nonetheless, the calculated processes are based mostly on fundamental and often complex biophysical processes to ensure realistic simulation of crop responses to environment.

2. Essence of AquaCrop

AquaCrop simulates daily biomass production and final crop yield in relation to water supply and consumption and agronomic management, based on current plant physiological and soil water and salt budgeting concepts. Details of the simulated processes are provided in a set of three papers which were published at the model's release (Steduto et al., 2009; Raes et al., 2009; Hsiao et al., 2009), in the Irrigation and Drainage Paper No. 66 '*Crop Yield Response to Water*' (Steduto et al., 2012), and in the reference manual (Raes et al., 2012) that is updated regularly.

2.1. Soil water and salt budgeting concepts

2.1.1. Soil water balance

The model is water driven with biomass production tied to transpiration, so the soil water balance is a critical component. In a schematic way, the root zone is considered as a reservoir in which the water content fluctuates as a result of incoming (rainfall, irrigation and capillary rise) and outgoing (runoff, evaporation, transpiration, and deep percolation) water fluxes at the zone boundaries. To describe the balance and movement of water in the soil profile, AquaCrop divides the soil profile in compartments (Fig. 1). For deep soils, to simulate dynamics of the near-surface layers better, the thickness of the compartments increases exponentially with depth. The standard time step is daily, but fractions of a day are used when simulating soil evaporation. Each compartment has the hydraulic characteristics of the soil horizon to which it belongs. A soil profile can consist of up to five horizons, each with its specific physical characteristics.

Infiltration, water movement among the compartments, and drainage are simulated by a set of equations in terms of the

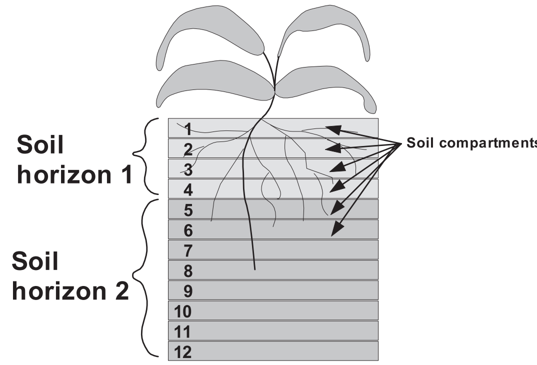

Fig. 1. Soil horizons, characterized by specific soil physical parameters, and soil compartments introduced to simulate the retention and movement of water and salts in the soil profile.

dependent variable (θ) using a dimensionless drainage coefficient derived from K_{sat} (Raes et al., 2006, 2009). The flow upwards from a shallow groundwater table to the root zone has been introduced in version 4.0 of the AquaCrop model (Raes et al., 2012). The maximum amount of water (CR_x) that can be transported upward is estimated according to the depth to the water table and the hydraulic characteristics of the soil layer(s) through which the water is transported (Janssens, 2006; Raes et al., 2012). Capillary rise is obtained by multiplying CR_x with a capillary rise factor (f_{CR}) that can vary between one (full strength) to zero (no water movement) depending on θ of the soil layer(s).

By adjusting the soil water content throughout the soil profile on a daily basis, AquaCrop keeps track of the soil water balance in the root zone. The various crop responses to water stress are modeled as dependent functions of θ, as described in a later section.

2.1.2. Salt balance

In version 4.0 (Raes et al., 2012), also incoming and outgoing salt fluxes are simulated. Salts enter and are leached out of the soil profile with downward water movement. Salts can also enter as a result of upward transport of saline water from a shallow water table. To simulate salt movement and retention, AquaCrop divides each soil compartment into a number of hypothetical cells where salts are stored (Raes, 2002; Raes et al., 2012). The inverse of K_{sat} is used to determine the number of cells (ranging from 2 up to 11). Since a cell represents a volume of pores with a particular mean diameter, most cells will be filled with solutes in a wet soil. In a dry soil, only the cells representing the small pores contain soil water. Since salts are held by cation exchange, a clayey horizon, with its higher cation exchange capacity, will contain more salts than a sandy horizon (given the higher volume of water held at field capacity (FC) in clayey horizons). Salts can diffuse horizontally and vertically from one cell to adjacent cells if there exists a concentration gradient. The diffusion not only depends on the gradient, but also on the ease of salt movement, which is expressed by a diffusion coefficient (f_{diff}). The coefficient varies between one for the macro pores (no limitation on salt diffusion) and close to zero for the smallest pores (salts can hardly diffuse between adjacent cells). Hence, movement is slow in clayey soils with its strong adsorption forces and low hydraulic conductivity, requiring much time before equilibrium is reached among cells.

2.2. Crop physiological concepts

In AquaCrop, a crop grows by developing a canopy and accumulating biomass in daily time steps. Crop phenology is simulated in terms of daily increments of growing degree days (GDD) that are accumulated over the season (McMaster and Wilhelm, 1997; Steduto et al., 2009), with the thermal time for the various phenological stages specified for a given crop cultivar. Crop canopy (CC) development, transpiration, biomass production, and yield are simulated in four steps (Fig. 2). Effects of environmental stresses on these steps are simulated with stress coefficients.

2.2.1. Stress coefficients (Ks) functions

The effect of any kind of environmental stress on the crop is simulated by stress coefficients (Ks). In essence, Ks is a modifier of its target model parameter, and varies in value from one (no stress) to zero (full stress) as function of a stress indicator. For water shortage, the stress indicator is not some measure of plant water status, but simply the relative root zone water depletion (Dr), which refers to the shortage of water for the crop with reference to the water amount at FC. Dr varies between zero at field capacity (0% depletion, Ks = 1) and one (100% depletion, Ks = 0) at permanent wilting point (PWP). For water logging, the stress indicator is the degree of excess water (i.e. the amount of water between the anaerobiotic point and saturation). For inhibition of biomass production at low temperatures, the stress indicator is GDD below a threshold value. For inhibition of pollination by extreme cold and heat, the indicators are respectively the daily minimum and maximum air temperature. For soil salinity, the stress indicator is the average electrical conductivity of saturation soil-paste extracts (ECe) from the root zone.

Ks is defined by specifying an upper and lower threshold in terms of the stress indicator and by selecting a curve shape for the Ks function. Above the upper threshold, stress is non-existent and Ks is one. At and below the lower threshold, the stress effect is maximum and Ks is zero. The shape of the Ks curve between the two thresholds can be linear or convex. Preliminary tests indicate that the thresholds and shapes of the curves may be conservative at least to a fair degree (Heng et al., 2009; Hsiao et al., 2009; Mebane et al., 2013). Generally the curve shapes are convex, though to varying extent. The Ks coefficients, which modify the rate of all kind of processes, are adjusted daily at the end of each time step, by checking how far the air temperature, GDD, Dr and salt content are below or above their thresholds on that day. Fractions of a day are only used for the simulation of the falling rate stage of soil evaporation, since the reduction coefficient decreases strongly with θ in the top soil.

2.2.2. Step 1 – simulation of crop development

AquaCrop does not simulate leaf area index. Instead, foliage development is expressed as green canopy cover (CC), the fraction of the soil surface covered by the canopy. CC varies between 0 (before emergence) to a maximum (CC_x) which can be close to 100% depending on crop type and planting density. The canopy is a crucial feature of AquaCrop. Its expansion, aging, conductance and senescence are key determinants of the amount of water transpired, which in turn determines the amount of biomass produced (Steduto et al., 2009). The canopy development for non-limiting conditions (CCpot) is modeled using three parameters: the initial canopy cover after emergence (CC_o), the maximum canopy cover reached (CC_x), and the canopy growth coefficient (CGC). First order kinetics equations are used to simulate canopy development (Bradford and Hsiao, 1982; Hsiao, 1982). Upon the start of canopy senescence, the decline in CC is simulated with a canopy decline coefficient (CDC). When Dr drops below the thresholds for water stress to affect canopy expansion, the Ks for canopy expansion (Ks_{exp}) begins to fall below one to reduce the effective CGC, and canopy development is slowed down. When Dr reaches the upper threshold for accelerated canopy senescence, CDC is increased by Ks_{sen}, leading to earlier and faster canopy decline. Since AquaCrop simulates crop development in GDD, the rate of canopy expansion and decline are modulated by temperature.

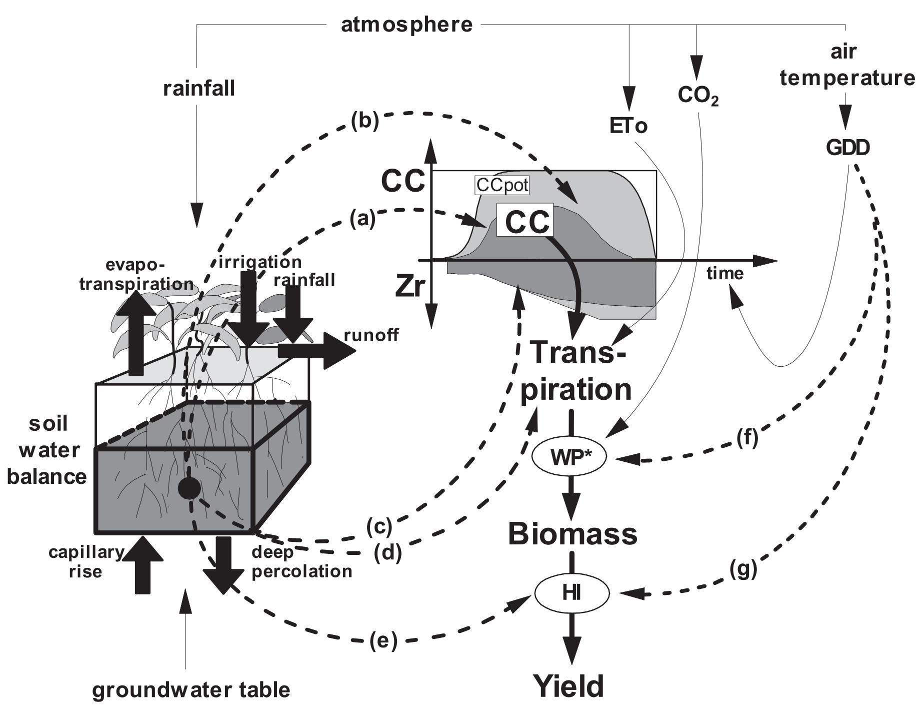

Fig. 2. Calculation scheme of AquaCrop with indication (dotted arrows) of the processes affected by water stress (a–e) and temperature stress (f to g). CC is green canopy cover; Zr, rooting depth; ETo, reference evapotranspiration; WP*, normalized biomass water productivity; HI, harvest index; and GDD, growing degree day. Water stress: (a) slows canopy expansion, (b) accelerates canopy senescence, (c) decreases root deepening but only if severe, (d) reduces stomatal opening and transpiration, and (e) affects harvest index. Cold temperature stress (f) reduces biomass productivity. Hot or cold temperature stress (g) inhibits pollination and reduces HI.

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2.2.3. Step 2 — simulation of crop transpiration (Tr)

Given CC and the weather at each daily step, crop transpiration (Tr) is calculated by multiplying ETo, the evaporating power of the atmosphere, by the crop coefficient Kc_{Tr} (Eq. (1)). ETo is preferably calculated by the Penman–Monteith equation as specified by FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998) and given to the model as input driving variable. The crop transpiration coefficient Kc_{Tr} is proportional to CC, but is additionally adjusted for interrow advection and the diurnal trend of radiation interception by the canopy (Villalobos and Fereres, 1990; Steduto et al., 2009). The maximum of the proportional factor ($Kc_{Tr,x}$) varies between 1.0 and 1.2 for different common agricultural crops. When Dr drops below the upper threshold for transpiration reduction, Tr is simulated with the Ks for stomatal closure (Ks_{sto}). The effect of water logging, also known to cause stomatal closure and reduce transpiration, is simulated similarly, with Ks_{aer}:

$$\mathrm{Tr} = \mathrm{Ks}\left(\mathrm{Kc}_{\mathrm{Tr,x}}\ \mathrm{CC}^*\right)\ \mathrm{ETo} \quad (1)$$

where Ks is the stress coefficient (either Ks_{sto} or Ks_{aer}), CC^* the adjusted green canopy cover, ($Kc_{Tr,x}$ CC^*) the crop coefficient, and ETo the evaporating power of the atmosphere.

2.2.4. Step 3 — simulation of above ground biomass production (B)

Using WP^*, the normalized biomass water productivity (Steduto et al., 2007), AquaCrop accumulates the daily biomass production (*B*) to the end of the season from daily Tr and the corresponding daily ETo (Eq. (2)). Except for root and tuber crops, simulated *B* accounts only for the aboveground portion, as extremely little quantitative data exist for root biomass in the field to allow testing and validation. Water stress, except in extremely severe cases, has a negligible effect on WP^* if nutrients are not limiting (Steduto and Albrizio, 2005), so the effect on *B* is fully accounted for by reduction in Tr. Empirical tests show a reducing effect of low temperature on WP^*. So a cold temperature stress coefficient for biomass (Ks_b) with GDD as the stress indicator is used to reduce biomass production. If GDD drops below its threshold value (which is likely to be conservative for a specific crop), Ks_b becomes smaller than 1 and biomass production decreases:

$$B = \mathrm{Ks_b}\ \mathrm{WP}^* \sum\left(\frac{\mathrm{Tr}}{\mathrm{ETo}}\right) \quad (2)$$

The normalization of WP involves two environmental factors: evaporative demand of the atmosphere as represented by ETo, and air carbon dioxide concentration ($[CO_2]$) for the reference year 2000. These two factors have major impact on water productivity, defined as the ratio of biomass produced (enhanced by increases in $[CO_2]$) to water transpired. Normalization makes WP^* applicable to diverse locations and seasons, accounting for ETo variations, and over a time span of years, accounting for rising $[CO_2]$. Normalization for evaporative demand is obtained by dividing the daily Tr by ETo for that day. Normalization for $[CO_2]$ applies a multiplier (f_{CO_2}), which depends on the ratio of and difference between $[CO_2]$ in the arbitrary reference year (year 2000) and in the year when the crop is grown. Actual $[CO_2]$ for each year is the average measured at the observatory station in Mauna Loa, Hawaii, USA. The adjustment of WP^* by f_{CO_2} is based on fundamental concepts for plant gas exchange and validated by a number of empirical data (Xu and Hsiao, 2004; Steduto et al., 2007). Its validity and associated uncertainties are discussed in Section 3.3.1.

2.2.5. Step 4 — simulation of crop yield (Y)

Crop yield (*Y*) is calculated as the product of final *B* and a harvest index (HI). The actual HI is obtained by adjusting, during simulation, the reference Harvest Index (HIo) with an adjustment factor (f_{HI}) for stress effects. HIo is the fraction of *B* that is harvestable as observed under non-stress conditions and is a cultivar-specific parameter. *Y* is calculated as:

$$Y = f_{\mathrm{HI}}\ \mathrm{HIo}\ B \quad (3)$$

f_{HI} depends on the timing and extent of water or temperature stress during the crop cycle. Water stress often reduces HI, but can also increase HI by inhibiting vegetative growth, which competes with grain or fruits for assimilates. Thus the value of f_{HI} can vary between a crop specific maximum (up to 1.6) and zero (complete failure). During yield formation, f_{HI} is modeled to rise above 1 when there is mild water stress that inhibits canopy expansion but that is not yet strong enough to trigger stomatal closure and reduce photosynthesis. So f_{HI} depends on Ks_{exp} and Ks_{sto}. During flowering, pollination can be hampered by water stress, cold or heat stress, each with its own Ks function, which results in a f_{HI} smaller than 1. Finally, a too short grain/fruit filling period or tuber formation stage, caused by stress-induced early senescence, will result in reductions in f_{HI} and HI because there is insufficient time for filling the grain, tuber or storage root.

2.3. Required conservative crop parameters and input variables

The simulation of the final crop yield in the four steps is transparent, simple to understand and requires only a relatively few conservative crop parameters (Table 1). The required input variables (Table 2) are widely used or require merely basic methods for their determination. Further-on, the well-developed user-interface makes the model easy to use.

3. Current status

Since the release of version 3.0 in 2009, (1) more crops have been calibrated and their conservative parameters added to the database, (2) the AquaCrop model has been tested, validated and applied by the global scientific community at field and regional scales, and (3) new concepts and model equations have been introduced or updated to improve simulation of expected yield and water use efficiency in diverse environments.

3.1. Parameterization of crops and validation

AquaCrop relies on a set of conservative parameters (Table 1), which are general and widely applicable without local calibration. Currently, conservative crop parameters are provided in the AquaCrop software for barley (*Hordeum vulgare* L.), cotton (*Gossypium hirsutum* L.), maize (*Zea mays* L.), potato (*Solanum tuberosum*), quinoa (*Chenopodium quinoa* Willd.), rice (*Oryza sativa* L.), soybean (*Glycine max* (L.) Merr.), sugar beet (*Beta vulgaris* L.), sugar cane (*Saccharum officinarum*), sorghum (*Sorghum bicolor* (L.) Moench), sunflower (*Helianthus annuus* L.), tef (*Eragrostis tef* (Zucc.) Trotter), tomato (*Solanum lycopersicum* L.), and wheat (*Triticum aestivum* L. and *Triticum turgidum durum*). The thoroughness of calibration and validation varies with crop. The reference manual (Raes et al., 2012) categorizes the degree of thoroughness with respect to well watered and water stress conditions, as well as coverage of the crop major production areas around the world.

Since the model release, interest in AquaCrop has grown, attracting an increasing number of users. Several recent papers describe calibration and testing of AquaCrop for crops for which the parameters are not yet included in the model (e.g. Coorevits, 2010; Karunatne et al., 2011; Kiptum et al., 2013; Wellens et al., 2013).

Table 1
Conservative crop parameters.

Crop parameter	Comments
Step 1. Simulation of green canopy cover (CC):	
- Canopy size of the average seedling at 90% emergence;	for determining initial canopy cover (CCo) with given (Table 2) plant density
- Canopy growth coefficient (CGC) and Canopy decline coefficient (CDC).	for simulating CC development and decline
Step 2. Simulation of crop transpiration (Tr) and root water uptake:	
- Maximum value of Kc_{Tr} ($Kc_{Tr,x}$) when canopy is complete (CC = 1), and decline of $Kc_{Tr,x}$ as a result of aging;	for simulating Tr (Eq. (1)) and root water uptake in soil profile
- Maximum root water extraction in top and bottom quarter of root zone.	
Step 3. Simulation of above-ground biomass production (*B*):	
- Water productivity (WP*) normalized for ETo and $[CO_2]$, for year 2000, and reduction coefficient describing the effect on WP* of the products synthesized during yield formation;	for simulating *B* (Eq. (2))
- Sink term, expressing crop performance under elevated atmospheric $[CO_2]$.	
Step 4. Simulation of final crop yield (*Y*):	
- Reference harvest index (HIo).	for simulating Y (Eq. (3))
Simulation of growing degree days (GDD):	
- Base temperature (T_{base}) and upper (T_{upper}) temperature.	GDD is calculated by subtracting T_{base} from average air temperature (T_{avg}). Several methods (Raes et al., 2012) are available to calculate T_{avg} (from minimum and maximum air temperature and by considering thresholds given by T_{base} and T_{upper})
Simulation of effect of water, temperature and soil salinity stress on CC, Tr, *B* and *Y*:	
- Thresholds of relative soil water depletion (Dr) for (i) canopy expansion and (ii) early canopy senescence and shapes of both stress curves;	for simulating effect of soil water stress on CC
- Anaerobiotic point and the threshold of relative soil water depletion (Dr) for stomatal closure and shape of the stress curve;	for simulating the effect of soil water stress on Tr (Ks in Eq. (1))
- Possible increase of harvest index (HI) due to water stress before flowering;	for simulating the effect of water stress on HI (f_{HI} in Eq. (3))
- Coefficient describing positive impact of restricted vegetative growth during yield formation on HI;	
- Coefficient describing negative impact of stomatal closure during yield formation on HI;	
- Threshold of relative soil water depletion (Dr) for failure of pollination and shape of the stress curve;	
- Minimum growing degrees required for full biomass production;	for simulating the effect of temperature stress on *B* (Ks_b in Eq. (2))
- Air temperature thresholds at which pollination starts to fail;	for simulating the effect of temperature stress on HI (f_{HI} in Eq. (3))
- Excess of potential fruits;	for estimating the effect of water and temperature stresses on pollination
- Maximum allowable increase of HIo due to water and/or temperature stress;	for determining f_{HI} in Eq. 3
- Thresholds for Electrical conductivity of the saturated soil-paste extract (ECe) at which *B* starts to be affected (ECe_n) and is completely halted (ECe_x).	for simulating effect of soil salinity stress on CC and Tr

These new crops and their parameters will only be added to the model if high quality data of several years and different locations are available those are required to determine the conservative crop parameters (essentially constant and applicable in diverse environments). Evett and Tolk (2009) demonstrated that simulations of yield and water use might be inadequate in some years, when calibration data are all for one location and under a narrow range of weather conditions. The reliance on conservative parameters of AquaCrop cannot be overemphasized. The initial and paradigm tests of AquaCrop (Hsiao et al., 2009; Heng et al., 2009), using maize as the crop, yielded a list of conservative parameters (Hsiao et al., 2009), which were shown to be applicable for maize in California, Texas, Florida, and Spain. The validity of this approach was attested further by three recent studies, which showed that these parameters, either exactly the same or with only very minor adjustments, allowed the realistic simulation of maize production in Serbia (Stricevic et al., 2011), Pennsylvania (Mebane et al., 2013), and Belgium (Vanuytrecht, 2013; Vanuytrecht et al., 2014b), locations different in climate, soil and water regimes from previous studies. Also different for all the locations were the maize cultivars.

3.2. Current applications of AquaCrop

AquaCrop has been applied in various regions around the world to characterize the crop response to water stress (e.g. Araya et al., 2010; Geerts et al., 2009; Todorovic et al., 2009), to develop deficit irrigation schedules (e.g. Geerts et al., 2010), to improve farm irrigation management (e.g. García-Vila and Fereres, 2012), to assess the potential increase in production by crop and field management (e.g. Abrha et al., 2012; Mhizha, 2010; Mhizha et al., 2014; Shrestha et al., 2013; Tsegay, 2012; Tsegay et al., 2012; Zinyengere et al., 2011), to assess the impact of climate change on crop production (e.g. Vanuytrecht et al., 2014b) and to develop decision support tools for farm operations (e.g. Cusicanqui et al., 2013). The applications and corresponding formulated guidelines in these examples can be considered as reliable since well calibrated crops, fine-tuned to the local environment, were used in the simulations.

Like most crop growth models, AquaCrop is designed to predict crop yield at the single field scale (point simulations). To scale up single simulations beyond a field or farm up to the regional level, high resolution input data of weather, crop, soil, and management practices are required (Soltani, 2013). The use of AquaCrop for these applications requires a large number of simulations runs, involving the generation of large amount of input and project files, and complex interpretation and analysis of the results. To facilitate these tasks, the AquaCrop plug-in program (FAO, 2012) and two tools for managing the inputs and outputs of AquaCrop, named AquaData and AquaGIS respectively (Lorite et al., 2013), were recently developed. AquaData, in combination with the AquaCrop plug-in program, facilitates in multiple runs of the pre-defined projects. AquaGIS enhances the interpretation of simulation outputs by linking them to a geospatial module to permit spatial analysis and improve visualization through mapping. AquaGIS requires the GIS programming tool MapObjects to be combined with AquaData in a single package. A full description of both software utilities and example applications at the regional scale are found in Lorite et al. (2013).

Table 2
Required input variables for simulations with AquaCrop.

Input variable	Comments
Climate (conditions at the upper boundary):	
- Daily, 10-daily or monthly maximum and minimum temperature and rainfall;	Daily data are generated at run time from 10-daily or monthly input data
- Daily, 10-day or monthly reference evapotranspiration (ETo);	A calculator (FAO, 2009), in which data can be given in a wide variety of units, is available to estimate ETo
- Mean annual CO_2 concentrations.	Historical data from Mauna Loa Observatory (Hawaii) and various sets (A1, A1B, …) of expected [CO_2] for future years are available
Crop parameters likely to require adjustments for cultivar and local environment and management:	
- Planting date;	Procedures are available to generate planting date from rainfall, air temperature data, or soil water content in top soil
- Plant density;	Procedures are available to estimate plant density from sowing rate or plant spacing
- Maximum canopy cover (CCx);	Depending on plant density and cultivar
- Time to crop emergence, flowering, start of canopy senescence and to maturity (length of crop cycle);	Cultivar specific
- Maximum effective rooting depth (Z_x) and time to reach Z_x.	Depends on conditions in root zone
Soil physical parameters of the distinctive (up to 5) soil horizons:	
- Soil water content (θ) at saturation, field capacity, and permanent wilting point; - Saturated hydraulic conductivity (K_{sat}); - Depth of layer restricting root deepening.	A hydraulic properties calculator (Saxton and Rawls, 2006) is available to estimate θ's and K_{sat} from soil texture. From θ_{SAT}, θ_{FC}, θ_{PWP} and K_{sat}, AquaCrop derives other physical parameters governing soil evaporation, internal drainage, deep percolation, surface runoff and capillary rise
Groundwater table (conditions at the lower boundary):	
- Depth and salinity of the groundwater table.	Can be constant or variable in time
Parameters describing field management practices:	
- Maximum relative dry aboveground biomass (B_{rel}) that can be expected in a fertility-stressed environment compared to stress-free conditions;	B_{rel} is the maximum B that can be produced under the governing local conditions in a field only affected by soil fertility stress in a good rainy year or under irrigation when there is no water stress. It may be available from statistical reports, indigenous farmer knowledge, or from nearby experimental fields.
- Cover and type of soil mulches;	
- Height of soil bunds;	
- Surface runoff: ON/OFF.	
Parameters describing irrigation management practices:	
- Irrigation method;	The method affects soil evaporation
- Application depth and time of irrigation events;	
- Salinity of the irrigation water.	
Parameters describing initial conditions at start of simulation period:	
- Initial soil water content and soil salinity at various depths in the soil profile.	

3.3. *Crop responses to various environments*

3.3.1. *Crop response to elevated [CO_2]*

During the last decades, the simulation of crop responses to CO_2 has gained interest given the imminent climatic changes (for an overview, see Tubiello and Ewert, 2002). The existing simulation procedure in AquaCrop for responses to CO_2 by means of f_{CO_2} has been recently tested against experimental data from free air CO_2 enrichment (FACE) experiments by Vanuytrecht et al. (2011, 2012). FACE experiments have been chosen as a reference because they are thought to provide the most realistic conditions for observations of crop responses to elevated [CO_2]. Nonetheless, controversy exists about the apparent differences between FACE and enclosure studies. Some authors are convinced that crop responses to CO_2 as observed in enclosure systems are an exaggeration of realistic field responses (e.g. Long et al., 2006). Others believe instead that responses in FACE experiments are underestimating real responses due to fluctuations in [CO_2] concentration treatments (e.g. Bunce, 2012). Still others claim quantitatively consistency between enclosure methodologies and FACE studies when properly scaled (e.g. Ziska and Bunce, 2007). The tests by Vanuytrecht et al. (2011, 2012) showed that AquaCrop tended to overestimate the biomass production response to elevated [CO_2] in comparison with FACE experiments. The original production response to [CO_2] of the model is based on a theoretical framework supported by field and pot experimental data (Steduto et al., 2007). However, there seems to be a discrepancy between theoretical crop productivity responses and those in enclosed systems on the one hand, and the responses observed in FACE fields on the other hand (e.g. Long et al., 2006). These differences could have been the result of differences in sink strength of the crop for assimilates (Stitt and Krapp, 1999). On the other hand, the limited sampling of biomass on the relatively small FACE fields, and the uncertainties in the maintenance of the desired [CO_2] level over the crop day and night raise questions about some of the FACE data. In the light of these uncertainties, the current version of AquaCrop now includes the option for users to adjust f_{CO_2} according to assumed sink strength. Before making such adjustments, users should be aware of evidence arguing against the need for these adjustments. In the initial parameterization (Hsiao et al., 2009) and validation (Heng et al., 2009) of AquaCrop for maize, a single value was assigned to WP* of maize for the reference year (year 2000), and WP* for all other years were adjusted by f_{CO_2} without a consideration of sink strength. The year for the crop's growth ranged from 1974 to 1996, with corresponding increase of [CO_2] from 330 ppm to 363 ppm, and a total increase of 10% in calculated WP*. The fact that the simulated B for those years matched well the field experimental data with no sign of overestimation for the late years argues for not making any sink strength adjustment. More recently, tests of AquaCrop to simulate maize production in years 1974, 1975 and 2005 were reported by Mebane et al. (2013) and in years 2000–2006 by Stricevic et al. (2011). By 2006 [CO_2] had increased to 383 ppm, a 16% increase from 1974. Yet B simulated with Eq. (2) matched well with the experimental data, again with no indication of overestimating the response to CO_2 in years 2005 or 2006. Although the experimental data for the later tests of the model were less comprehensive than those of Hsiao et al. (2009) and Heng et al. (2009), the results nonetheless do not support the need to adjust for sink strength for the current environmental conditions and years.

3.3.2. Crop response to soil fertility

With respect to stresses caused by low soil fertility (nutrient deficiencies), it is not possible to simulate the effects based on fundamental processes and concepts while keeping the model relatively simple. Therefore, AquaCrop employs an indirect approach by considering the effects on canopy development and WP*. The indirect approach is dependent on local calibration, and the user needs to have the total biomass data from well-watered, fully fertilized and low fertility treatments (see input variables, Table 2). The ratio of B of the low fertility treatment to the B of the fully fertilized treatment (B_{rel}) determines the shape of a set of four Ks coefficient curves with the constraint that the simulated B_{rel} always remain the same as the observed. Upon specification of B_{rel}, AquaCrop searches for a setting of the four stress coefficients, in the absence of any other stress, targeting (i) WP*, (ii) CC_x, (iii) CGC and (iv) the decline of CC once CC_x is reached. The settings alter the simulated CC and water productivity, hence B, and mimic thereby the effect of soil fertility stress on canopy development pattern and crop production. The user needs to vary the balance between the four Ks curves to ensure that the pattern of CC progression over time is realistic. Of course the best approach is to match the simulated CC with the observed CC (Raes et al., 2012).

In the absence of stresses other than soil fertility stress, the simulated B and Y for the low fertility treatment would be perfect (since B_{rel} is given as input). The advantage is that once the Ks curves are so calibrated, rough estimates may be made for other categories of fertility stress expressed in terms of relative reduction in biomass. Further, some tests reveal that the procedure can also give good results when water stresses occur in addition to fertility stress (Van Gaelen et al., 2014). After calibration with the B ratio from well watered fields and ensuring that the observed patterns of CC for the fertility deficient field relative to that for the fully fertilized field were well simulated, Shrestha et al. (2013) and Van Gaelen et al. (2014) obtained good estimates of the soil water content, canopy cover, biomass and yield for maize, wheat, tef and quinoa cultivated in different environments and years, for water stressed situations (rainfed agriculture and deficit irrigation) and various soil fertility levels.

3.3.3. Crop response to soil salinity

Similarly to what occurs under water deficits, high salt concentration in the soil water elicits many different plant responses. Two major effects have been described, one caused by the decrease in soil water potential due to the osmotic effects, and another due to the toxicity of certain ions such as sodium. The impact of such effects on crop yield depends on a myriad of factors which require complex procedures and an extensive set of parameters and variables to simulate in a mechanistic fashion (Addiscott and Wagenet, 1985; Šimůnek et al., 1996). In line with the simulation of the crop response to soil fertility, AquaCrop opts for a simple model that relates seasonal yield decline to salinity. Following the empirical model of Maas and Hoffman (1977), the reduction in biomass is given by:

$$B_{rel} = 100\ Ks_{salt} \tag{4}$$

Similar to the case of fertility stress, B_{rel} expresses the expected biomass production under a given salinity stress relative to the biomass that can be produced in the absence of any stress. The average electrical conductivity of saturation soil-paste extracts (ECe) from the root zone, which is the stress indicator for soil salinity stress, determines the value for the soil salinity stress coefficient (Ks_{salt}). Values for the lower (ECe_n) and upper threshold (ECe_x) for many crops are given by Ayers and Westcot (1985). The values might be too conservative and overestimate the salinity impact due to the steady state assumptions of the model, which might result in an inefficient use of limited water resources (Letey et al., 2011). Although in AquaCrop (i) the plant root water extraction pattern is dynamic and adjusted when the soil water and salt profile change as a result of incoming and outgoing fluxes (transient state solution), and (ii) Ks_{salt} is adjusted daily to the average ECe in the root zone, crop response to salinity is not yet thoroughly tested. In the absence of a reliable validation, the user can adjust the ECe thresholds and alter the shape of the Ks-ECe curve if specific information on the response is available. The shape may be linear (Maas and Hoffman, 1977), convex or logistic (Van Genuchten, 1983; Cardon and Letey, 1992).

Similar to what was undertaken in the simulation of soil fertility, AquaCrop reduces the canopy development resulting in a reduction of B (Eq. (4)). Soil salinity stress also reduces Tr. To mimic those effects, the model uses four different Ks coefficients targeting Tr, CC_x, CGC and the decline of CC once CC_x is reached. As for soil fertility stress, AquaCrop adjusts the values of the four stress coefficients to ensure that the simulated relative biomass is equal to the B_{rel} (Eq. (4)) in the absence of other stresses. If in a simulation run, other stresses (next to soil salinity stress) affect canopy development, the most limiting factor at that moment determines the reduction in CC.

Simulations with the BUDGET model (Raes, 2002), which served as the basis of the soil water and salt balance model in AquaCrop, showed that salt accumulation in the soil profile can be predicted well. The accumulation of salts in the root zone after a number of years of irrigation with low quality water in 27 fields in the Khanasser Valley (Northwest Syria) and 6 fields in the Gaza Strip (Palestinian Autonomous Regions) was well in line with the measured salt accumulation (Raes et al., 2001). The two locations differed in soil type, crops, irrigation method and irrigation water quality.

While the model component in AquaCrop describing the accumulation of salts in the soil profile is robust and tested, translating the salinity levels to yield predictions should be exercised with caution. Reasons include (i) assumptions of the steady state modeling approach, (ii) missing understanding of the crop response to heterogeneous salinity profiles, common in the field, (iii) cultivar dependency of the model of Maas and Hoffman (1977), (iv) irrigation water with an atypical chemical composition, and (v) absence of simulating toxicity effects on yield.

4. Future prospects

Through its website and training activities, FAO gathers questions continuously and comments from AquaCrop users. Collected shortcomings and reflections, additional crops to be modeled and parameterized, and requests for further development are discussed regularly by the core group. The attention of the group is primarily focused on high-impact routines that might need to be improved, while respecting the required balance among simplicity, accuracy and robustness. Given that the model is intended mainly to assist practitioners end-users, the challenge is to keep the user interface simple and to restrict the input to a relatively small number of explicit parameters and largely-intuitive input variables.

4.1. Additional crops and calibration

AquaCrop currently simulates fruit/grain crops, leafy vegetables, and root and tuber crops, but is restricted to herbaceous species. A missing group is forage crops, which are usually perennial and are harvested or grazed several or more times over a season. The modeling of forage crops is underway. The chosen model crop for now is alfalfa (*Medicago sativa* L.), as good experimental data are available for testing and calibration. Challenging aspects are the movement of assimilates between the shoot and root systems at the start of the winter dormancy and the beginning of spring regrowth, and stand thinning during cold winters (Moot et al., 2012).

Crop responses to periods of low temperature and cold damage are likewise critical for the simulation of winter cereals. Currently, the AquaCrop model is only applicable for wheat for mild winter conditions due to the absence of vernalization and photoperiod responses, which are crucial for the correct simulation of regrowth of winter cereals after a cold period (e.g. Butterfield and Morison, 1992; McMaster et al., 2008; Ottman et al., 2013). Simulations for winter wheat in temperate climates (e.g. Vanuytrecht, 2013) have shown that the model overestimates the regrowth of canopy after cold winters. The option to include the physiological crop responses of winter cereals in a simple way to avoid many extra parameters is currently being investigated. Efforts are directed at making the model applicable to cold winter conditions by incorporating stand thinning and cold induced leaf senescence.

To accelerate further calibration and validation of crop parameters, access to high quality experimental data, collected in a wide variety of environments, is required. This may be accessible through an active involvement of modelers in projects such as AGMIP (Rosenzweig et al., 2013), the Agricultural Model Intercomparison and Improvement Project.

4.2. Further development of root zone soil water balance

Since the simulation of final crop yield is sensitive to the timing and magnitude of water stress in the root zone, the root deepening and soil physical characteristics (e.g. water retention, hydraulic conductivity, and runoff) need to be carefully described and calibrated (Vanuytrecht et al., 2014a). To perfect the simulation of the soil water balance, efforts are made to improve the simulation of root deepening and surface runoff, and to describe the soil better by extending the required input of soil characteristics and field management practices. The current version of AquaCrop estimates the amount of rainfall lost by surface runoff with the Curve Number (CN) method (USDA, 1964; Steenhuis et al., 1995). Although this is sufficient for many applications, this type of static approach cannot capture all aspects. Run-off depends not only on wetness of the top soil, but also on slope of the land, land use, and infiltration rate. The latter varies over the season and can vary with the extent of canopy cover, which protects the soil against the force of rain drops destroying soil aggregates and causing sealing of the soil. Attempts will be made to account for these variations in the model. AquaCrop currently accounts for stoppage of root deepening by an impeding layer at a specified depth in a soil, but it cannot simulate reduced root deepening rate through a restricting layer. Also the effect of stones in soil layers on the total available soil water should be accounted for. Additional efforts are planned to improve the description of tillage practices (including conservation tillage) and the simulation of their effects.

4.3. Improving the modeling of effects of various stresses on crop development and production

AquaCrop simulates the reduction of water biomass productivity by cold temperature with the temperature stress coefficient for biomass Ks_b (Eq. (2)). The first large study of AquaCrop in a temperate climate (Belgium) with cool temperature regimes (Vanuytrecht, 2013) revealed that the effect of cold stress on biomass production could be simulated. Although the parameter could be calibrated and validated for different crops in the climate of Belgium, the validity of the calibrated Ks_b function should be verified in other locations at different latitudes.

There remains scope to further improve the simulation of the effects of elevated [CO_2] on WP* and possibly, on other aspects of crop production. As already discussed, the main obstacle is the limited amount of experimental data, especially for crops grown in open fields. The lack of full response of various crops to elevated [CO_2] under different circumstances is well known and some or much of it could be due to variations in sink strength for assimilates or in nitrogen nutrition. The model now does provide the means for a user to adjust WP*, either for assumed sink strength difference or for other reasons. Due to the complexity of quantifying sink strength and its likely changing nature as plants progress through their life cycles, the prospect of much improvement in this component of the model is slim.

AquaCrop now simulates the crop under rising atmospheric [CO_2] only by considering effects of CO_2 on WP*. Currently the ubiquitous reduction in stomatal conductance as [CO_2] increases, and the resultant reduction in Tr, are not considered. In attempts to keep the model relatively simple, it was judged that the effect of stomatal conductance on Tr of crops in open fields is much reduced by interactions with aerodynamic conductance, especially when canopy cover is substantial (Hsiao, 1990) and there is little or no water stress. Also considered was the fact that in a span of several decades, the change in [CO_2] would not be large enough to induce large changes in crop transpiration. Now with the model better developed and tested, it would be the opportune time to reevaluate the need to incorporate stomatal response to [CO_2] in the model. Also to be considered is the incorporation of the beneficial effect of higher [CO_2] on leaf growth rate and hence on canopy development (Vanuytrecht et al., 2012). Similar to the response to [CO_2], potential stomatal response to vapor pressure gradient (e.g. Ocheltree et al., 2014) is ignored in the model, again to maintain simplicity. For some crop species this response is stronger than the response to [CO_2], so this is also an appropriate time to reevaluate the inclusion of a humidity response.

The current model version uses saturation soil-paste extract (ECe) as the salt stress indicator. Although the salinity of the soil water increases between irrigation events, as more and more water is extracted from the root zone, ECe remains constant. The use of the EC of the soil water (EC_{sw}) as an indicator might remove some of the shortcomings of the static model approach, since EC_{sw} changes continuously in time and depth in response to salt and water fluxes in and out of the soil profile. Also Maas and Hoffman (1977) and Ingvalson et al. (1976), suggested that EC_{sw} might be a more appropriate stress indicator, since its change is more in line with the variation in strength of soil salinity stress. Preliminary tests by Jacobs (2013) indicated that time-integrated EC_{sw} was able to simulate better the effects of soil salinity on canopy development and transpiration than ECe.

The soil water and temperature status required for seed germination and emergence are treated very simply in the model. Field data are currently being collected to test the validity of the conceptual description and model equations to improve the simulation of dry sowing.

Weeds can reduce crop yields significantly by competing with the crop for nutrients, soil water, space and light (Kropff, 1993). Several empirical and mechanistic models have been developed by different researchers (Cousens, 1985; Kropff and Spitters, 1991; Lotz et al., 1994; Kropff et al., 1995). At this stage, the incorporation of some of these models in AquaCrop is being explored.

4.4. Further development of the user interface

In the present model interface, simulation results are plotted in different graphs, which are updated at the end of each daily time step. From such plots the user can follow throughout the simulation of the soil water balance, the inhibitive effects of stresses on CC, Tr and *B*, and alteration of HI. The building up of salts in the root zone also can be viewed. The capacity of simulating in short time steps and switching between several graphs is particularly useful to study the effect of particular events on a specific parameter (Raes et al., 2009). This type of output is essential for understanding the crop responses to environmental changes. However, to transfer results to extension services practitioners, NGO's, policy makers and farmer associations, efforts are needed to develop the user interface further to give end-users the information they require in a usable and understandable format. This will enhance sound decision making in often complex environments.

5. Conclusion

AquaCrop is a water-driven dynamic model that is able to simulate the attainable yield of herbaceous crops under various management and environmental conditions by using relative few conservative crop parameters and a small number of input variables. Although the model has already been tested and applied in various regions, efforts are continuously made to further improve the simulations of yield and water use by introducing new concepts and model equations, without jeopardizing the simple approach of the model and the transparency of the simulation.

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