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The AquaCrop model

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1 Origin and initial development

The response of crop yield to variations in the water supply has been a topic of great interest in agricultural sciences for a long time. A major contribution to the quantification of such response was the development of empirical water production functions in the 1960s and 1970s, which related yield to crop consumptive use as linear functions. Such information was fitted by Stewart (Stewart and Hagan, 1973) to a linear model which was then used by Doorenbos and Kassam to compile all the information available on various crops into a FAO (the Food and Agriculture Organisation of the United Nations) publication, the Irrigation & Drainage no. 33 paper (ID33; Doorenbos and Kassam, 1979).

In 2002, Martin Smith, senior officer of the Land and Water division of FAO, called an expert consultation to discuss the possible revision of ID33

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and whether there could be approaches that were different from the empirical production functions. Two options were discussed: the use of existing crop simulation models (e.g. DSSAT) and the development of a new simulation model focused on crop yield response to water. Following several international meetings in FAO, Rome, Pasquale Steduto, then recently appointed head of the water division, decided to develop a new water-driven crop simulation model with a minimum of variables but with solid foundations on the relations between crop production and water use. For the development of such a model, called AquaCrop, a core group of four was formed, namely, P. Steduto, T. C. Hsiao, E. Fereres, and D. Raes, who designed and tested different versions of the model from its inception. Finally, a working version of the model was presented officially at the American Society of Agronomy meetings of 2008 and was published in 2009 (Steduto et al., 2009; Raes et al., 2009; Hsiao et al., 2009).

With the contribution of several scientists worldwide, the model has been calibrated and partially validated to simulate a broad range of field crops, and it has been regularly updated and expanded with additional crops and new features (e.g. Vanuytrecht et al., 2014a; Van Gaelen et al., 2016; Raes et al., 2023a). AquaCrop is freely available, and key documents, training material, reference manuals, and software can be downloaded from the FAO AquaCrop website (https://www.fao.org/aquacrop/en/).

2 Calculation scheme

AquaCrop differs from other crop models, which are driven by the intercepted solar radiation in that it has a ‘water-driven’ growth engine that simulates crop production based on the conservative relation between crop transpiration and biomass production (Steduto et al., 2007). To take into consideration the differential sensitivity of key physiological processes affected by water stress, AquaCrop uses three different levels of soil water content for the onset of the reduction of canopy expansion and stomatal conductance, and for the triggering of early senescence (Hsiao, 1973; Bradford and Hsiao, 1982).

AquaCrop successively simulates on each day of the growing cycle, the (1) green canopy cover, (2) crop transpiration, (3) above-ground biomass, and (4) crop yield, as schematically depicted in the infographic (Fig. 1) and described in detail in the AquaCrop Reference Manual (Raes et al., 2023b).

Briefly, in each daily time step the model starts with the simulation of the degree of the green canopy cover (CC_i), which is affected by the prevailing water, fertility, and salinity stress (Fig. 1). This leads to the calculation of crop transpiration (Tr_i), which transpiration coefficient (Kc_i) is proportional to the simulated CC_i. Next, a normalized water productivity (WP*) is introduced to convert the amount of water transpired that day into biomass production

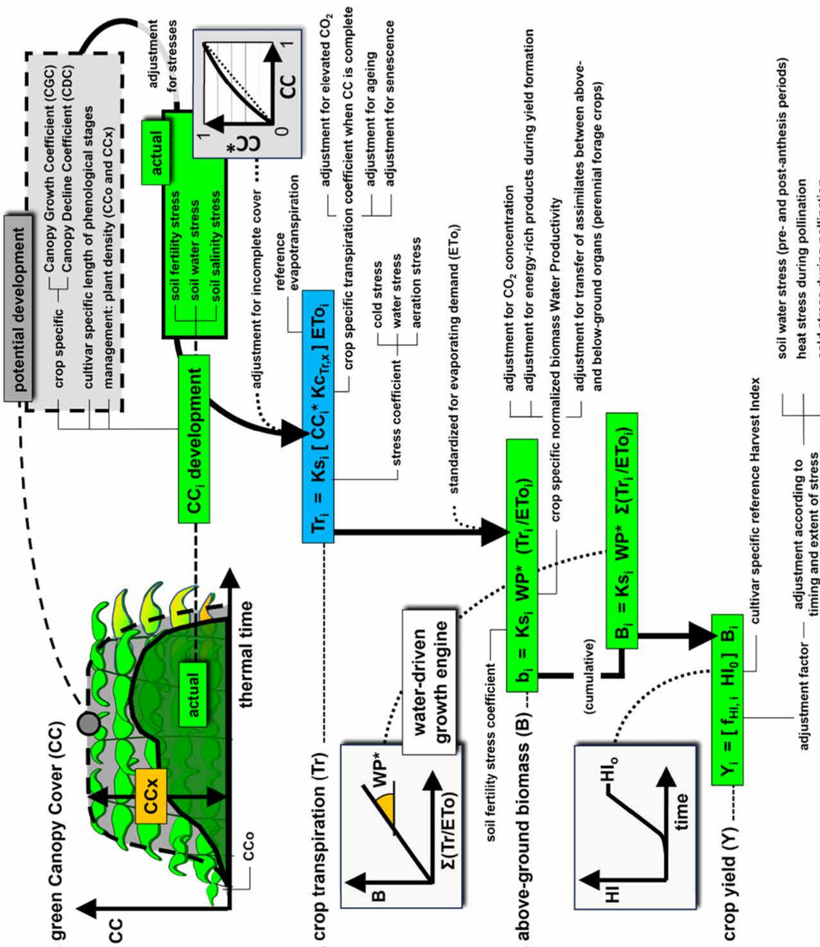

Figure 1 Infographic of the calculation scheme of AquaCrop. For details, see text or consult the Reference Manual (Raes et al., 2023b).

(b_i). Finally, a daily estimate of crop yield (Y_i) is obtained by considering the cumulative amount of biomass produced to date ($B = \Sigma b_i$), and the effect of water and temperature stresses on the harvest index (HI).

The effect of stress is described in AquaCrop by a stress coefficient (Ks) which varies in value from one (no stress) above an upper threshold to zero (full stress) below a lower threshold of the stress indicator (Fig. 2). Between the two thresholds, Ks follows a curve whose shape determines the impact on the simulated process for the various degrees of stress. AquaCrop considers air temperature, soil water, soil salinity, and soil fertility stress coefficients. The stress indicator (abscissa) for soil water stress is depletion (shortage versus field capacity), which is expressed as a fraction (p) of the total available soil water (TAW). The indicator for air temperature stress is growing degrees (affecting crop transpiration) or a minimum or maximum air temperature (affecting pollination). For soil salinity, the indicator is the electrical conductivity of the saturated soil-paste extract (EC_e).

The two presented Ks coefficients in Fig. 2 illustrate the differential sensitivity of physiological processes to water stress. Leaf growth by area expansion (expansive growth) and, therefore, canopy development are the highest in sensitivity to water stress among all the plant processes described by the model (Hsiao, 1973; Bradford and Hsiao, 1982). The decrease in canopy expansion is simulated by multiplying the Canopy Growth Coefficient (CGC) by Ks_{exp}. Stomata have been shown to be much less sensitive to water stress in comparison to leaf expansive growth. The multiplication of the crop transpiration coefficient ($Kc_{Tr,x}$) by Ks_{sto} simulates stomatal closure.

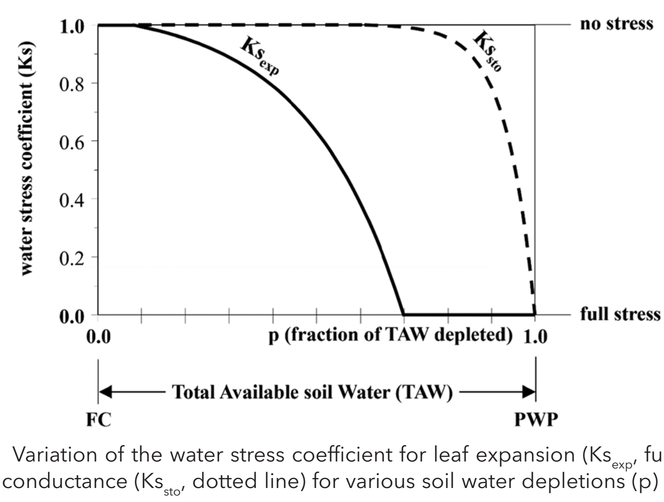

Figure 2 Variation of the water stress coefficient for leaf expansion (Ks_{exp}, full line) and stomatal conductance (Ks_{sto}, dotted line) for various soil water depletions (p) in the root zone.

2.1 Green Canopy Cover (CC)

The green Canopy Cover (CC) is the fraction of the soil surface covered by the green part of the canopy. In the absence of stress (potential development), the canopy development increases from a minimum value at emergence (CCo) to a maximum canopy cover (CCx), both of which are determined by the plant density. The potential canopy development, which is driven by thermal time (expressed in Growing Degree Days), is simulated by two equations, one describing the exponential growth from emergence till half of CCx, and the other the decelerating growth till CCx is reached. The Canopy Growth Coefficient (CGC) determines the development rate in both equations, while the Canopy Decline Coefficient (CDC) determines the rate of the green canopy decline in the late season stage. Both coefficients are conservative crop parameters and are crop specific. Contrary to other models, AquaCrop does not make use of the leaf area index (LAI) as a measure of canopy development, but CC and LAI have been shown to be closely related (e.g. Hsiao et al., 2009).

Soil water, soil fertility, and soil salinity stress affect canopy expansion. As a result, the expected CCx might not be achieved or might be achieved much later in the season. Severe soil water stress can even result in early canopy senescence as simulated in the model (Fig. 1).

2.2 Crop transpiration (Tr)

In the absence of stress, crop transpiration (Tr) is calculated by multiplying the reference evapotranspiration (ETo) with a crop transpiration coefficient (Kc_{Tr}, Eq.1), which considers (i) the fraction by which the green canopy covers the ground ($0 \le CC \le 1$) and (ii) specific characteristics that distinguish the crop from the reference grass ($Kc_{Tr,x}$):

$$Kc_{Tr} = CC^{*} Kc_{Tr,x} \qquad \text{(Eq.1)}$$

where $Kc_{Tr,x}$ is the crop coefficient for maximum crop transpiration (when CC = 1), and CC* the green canopy cover adjusted for incomplete cover. To estimate crop transpiration, the green canopy cover when incomplete (CC < 1) is increased to a CC* (see insert in Fig. 1), accounting for interrow micro-advection and sheltering effect by partial canopy cover (Adams et al., 1976; Villalobos and Fereres, 1990).

Transpiration is reduced when $Kc_{Tr,x}$ declines (i) under elevated CO_2 concentrations, (ii) with the ageing of the canopy, and (iii) once senescence is triggered. Further on, crop transpiration is restricted (by several Ks stress coefficients targeting $Kc_{Tr,x}$) when there are insufficient growing degrees for full crop transpiration (cold stress) and when there is too much (aeration stress) or too little water in the root zone (soil water stress).

2.3 Above-ground biomass (B)

The above-ground biomass (B) is derived from crop transpiration by means of the normalized biomass water productivity WP* (see insert in Fig. 1), which has been shown to be conservative under water and salinity stress, along with a low sensitivity to nutrient deficiency (Steduto et al., 2000; Steduto and Albrizio, 2005). Since AquaCrop does not simulate biomass partitioning among various organs, variations in partitioning (in the case of alfalfa) between the shoot and the root (in Spring and Fall) are simulated in the alfalfa model by adjusting the WP* (Raes et al., 2023a). Furthermore, AquaCrop adjusts WP* when the mean annual atmospheric CO_2 concentration differs from its reference value (369.41 ppm in the year 2000). The effect of soil fertility stress is simulated by a set of Ks coefficients, which gradually decreases CC and the WP* as discussed below.

2.4 Crop yield (Y)

The partition of above-ground biomass into yield (Y) is simulated by means of a Harvest Index (HI), which increases with time (see insert in Fig. 1) after flowering (fruit/grain producing crops) or tuber formation (root/tuber crops). There is an adjustment of HI to soil water and air temperature stresses, which depends on the timing and the intensity of the stresses.

3 Input requirements

AquaCrop uses a relatively small number of explicit and largely intuitive parameters and input variables, either widely used or requiring simple methods for their determination. Input consists of weather data, crop and soil characteristics, and field and irrigation management practices that characterize the environment in which the crop will develop (Fig. 3).

The weather data can be daily, 10-daily, or monthly. In the absence of daily data AquaCrop invokes built-in procedures to approximate the required daily data (time step of the simulation) from the 10-day or monthly means (Raes et al., 2023b). However, the use of 10-day or monthly total rainfall should be avoided since the dynamic nature of crop responses to water will be lost. A calculator, which computes the reference evapotranspiration (ETo) from imported weather data by means of the FAO Penman-Monteith method (Allen et al., 1998), is incorporated into AquaCrop. For the adjustment of WP* to the average annual CO_2 concentration, AquaCrop uses historically recorded or one of the projected future series of annual atmospheric concentrations available in the database.

The database of AquaCrop contains default values for the required soil profile characteristics for the 12 textural classes. The required input can also be

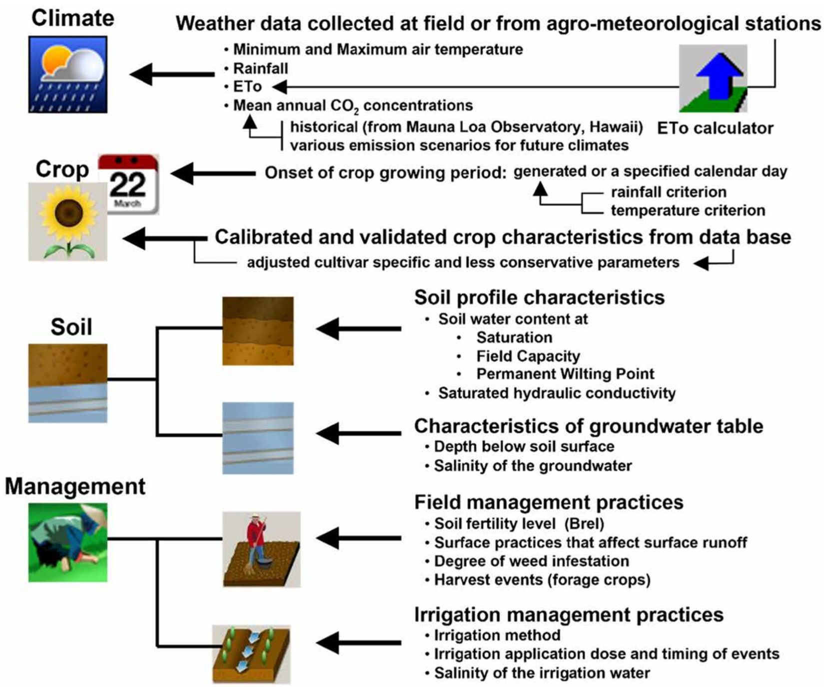

Figure 3 Schematic overview of the required input for AquaCrop.

collected in the field or derived from soil texture with the help of pedotransfer functions (Saxton et al., 1986). Since the groundwater table is not part of the simulated system, its characteristics (depth and water quality) are required as inputs.

4 Parameterization of AquaCrop for crops

4.1 Crop parameters

The database of AquaCrop contains calibrated and validated crop parameters for a number of herbaceous crops. A distinction is made between:Conservative crop parameters. These are parameters which do not change materially with time, management practices, geographic location, or climate, and are mostly genetically dependent. They are also assumed not to change among cultivars unless shown otherwise. In fact, as the model has been used more with time, our experience is that some of these parameters may vary among genotypes of the same species, more so than what was originally anticipated. Table 1 lists specific conservative crop parameters (genotype dependent) for some selected crops that have been already calibrated and validated in AquaCrop.

Table 1 Some specific conservative crop parameters of AquaCrop for selected crops: Crop transpiration coefficient for a full canopy ($Kc_{Tr,x}$); normalized biomass water productivity (WP*); reference Harvest Index (HI_o); upper and lower water stress thresholds for canopy expansion (p_{exp}) and for stomatal closure (p_{sto}), expressed as fractions of total available water (f_{TAW}).

	Cotton	Maize	Potato	Rice	Soybean	Sunflower	Wheat
$Kc_{Tr,x}$ [–]	**1.10**	1.05	1.10	1.10	1.10	1.10	1.10
WP* [$gr.m^{-2}$]	15 (*1)	33.7	18–20	19	15	18 (*2)	15
HI_o [%]	25–40	48–52	70–85	35–50	40	35	45–50
$p_{exp}[f_{TAW}]$	0.2–0.7	0.15–0.7	0.2–0.6	0–0.4	0.15–0.65	0.15–0.65	0.2–0.65
p_{sto} [f_{TAW}]	0.75–1	0.69–1	0.6–1	0.50–1	0.6–1	0.6–1	0.65

WP* of cotton drops to 70% of its value during yield formation.
WP* of sunflower drops to 60% of its value during yield formation.

The parameters chosen in Table 1 are among the most relevant in those that characterize AquaCrop simulations. The variations indicated in some of the parameters (HI, for example) account for the genotypic differences within a specie.

Cultivar-specific and less-conservative parameters. These are parameters which might require an adjustment when selecting a cultivar which is different from the one considered for crop calibration or when the planting method, field management, or conditions in the soil profile differ from the conditions assumed at calibration.

The reader is referred to Annex 1 of the Reference Manual of AquaCrop for the entire list of conservative and less conservative parameters (management and genotype dependent) of each of the 17 crops that have already been calibrated and validated. The Reference Manual can be downloaded from the FAO AquaCrop website (https://www.fao.org/aquacrop/en/).

From the start of reporting about model performance, most AquaCrop publications listed the specific parameters for the different species and cultivars (e.g. Hsiao et al., 2009; Heng et al., 2009; Farahani et al., 2009; Todorovic et al., 2009; Geerts et al., 2009; García-Vila et al., 2009, Wellens et al., 2022b).

4.2 Required adjustment of WP for a correct simulation of above-ground biomass*

As shown in Fig. 1, Aquacrop calculates the above-ground biomass (B) from crop transpiration (Tr) normalized for climate (ETo) by using a normalized biomass water productivity factor (WP*). Since intermediary steps in the accumulation of biomass are not simulated, a single value for WP* can be used for the entire crop cycle (Steduto et al., 2009).

A single value of WP* is, however not justified when the harvestable yield has a high proportion of lipids and protein, since more energy is required per unit of dry weight produced (Penning de Vries et al., 1983; Azam-Ali and Squire, 2002). To consider the formation of energy-rich products, WP* declines during yield formation. This is simulated by adjusting the daily produced mass of the above-ground biomass (b_i):

$$B = \sum f_i b_i = f_i \ WP^* \sum\left(\frac{Tr_i}{ETo_i}\right) \qquad \text{(Eq. 2)}$$

where B is the above-ground biomass produced during the growing cycle, and f_i a correction factor which has the value of one until flowering, and exponentially decreases during yield formation (Fig. 4a). The f_i values were obtained through calibration, giving f_i of 0.70 for cotton, and 0.60 for soybean and sunflower at the end of the reproductive period (Tab. 1). With such f_i values, the attainable yield could be well simulated (Garcia-Vila et al., 2009; Farahani et al., 2009; Todorovic et al., 2009; Mbangiwa et al., 2019).

The AquaCrop model, originally designed for annual crops, was expanded in 2022 to simulate perennial herbaceous forage crops (Raes et al., 2023a). Perennial herbaceous forage crops allocate the carbon assimilated through photosynthesis to above- (leaves and stems) and below-ground organs (crowns and roots). Since AquaCrop does not simulate biomass partitioning among various organs, variations in partitioning along the season are simulated by increasing (remobilisation) or reducing (storage) the daily produced mass of the above-ground biomass (b_i). After mid-season, perennial herbaceous forage crops such as alfalfa transfer a considerable fraction of the assimilates below ground (Teixeira et al., 2008; Moot et al., 2012). This is simulated by an exponential decrease of b_i with the help of the correction factor f_i during the storage stage (Eq. 2). The biomass partitioning below ground in late summer/autumn is cultivar specific. For example, it is greater for higher latitude cultivars (in response to lower temperatures and shorter day length) than for Mediterranean alfalfa cultivars (Moot et al., 2012). For the remobilization of some of the stored assimilates, b_i is increased by f_i at the start of the next season

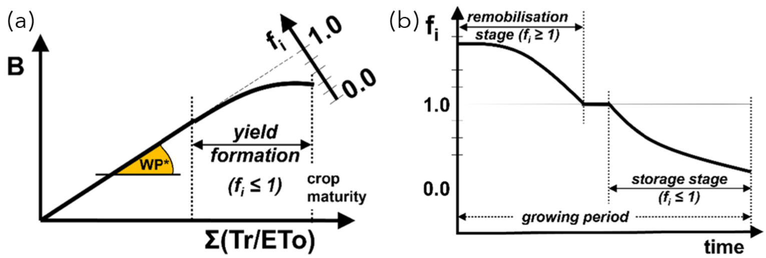

Figure 4 Daily correction (f_i) for WP* (Eq. 2) for (a) crops where the harvestable yield contains energy-rich products, and (b) perennial herbaceous forage which transfer assimilates between above- and below-ground organs.

(remobilisation stage). The rise of f_i gradually decreases to 1, as more and more assimilates are remobilized (Fig. 4b).

To evaluate the simulation of alfalfa, yield data was collected in several different climates, for different alfalfa cultivars, over various years of field and irrigation management strategies (Raes et al., 2023a). There was a good agreement between the observed and simulated cumulative dry above-ground biomass during the growing cycle, and a systematic over- or underestimation by the model of the measured yield was not observed.

4.3 Dealing with genetic differences among species and cultivars

AquaCrop was originally designed to simulate a generic herbaceous crop. All the parameters that are needed for the simulation were then adjusted by calibration to simulate the performance of about a dozen different herbaceous species. However, within any species, different cultivars exist which have vastly different genetic makeup. In AquaCrop, there is no systematic way of including such genetic differences in the form of 'genetic coefficients' that are used in other models. The cultivar differences must be taken into account in the simulations by varying any of the crop parameters to reflect a cultivar-specific feature. Among commercially available cultivars of the major crops, the genotypic variations are relatively small and mostly tied to a few features. Without a doubt, season length (determining biomass accumulation and water use) is the most diverse feature within a single crop that is genetically controlled. In AquaCrop, the duration of the developmental phases is an input to the model and must be known for each specific cultivar. The harvest index also varies within a species (often tied to season length; long season varieties tend to have lower HI). To take into account such differences, the reference HI may be modified in AquaCrop accordingly. Table 1 shows that other parameters, such as WP* vary little outside the obvious difference between C_3 and C_4 crops. There must be sufficient experimental evidence before modifying certain parameters in the simulations of specific genotypes. It is possible, however, to introduce genetic diversity in AquaCrop simulations by varying parameters to reflect features such as a deeper root system, a more drought tolerant genotype, or an early season cultivar.

As an example of the simulation of different cultivars, different conservative crop parameters were considered for three potato cultivars by the Belgian Collaborative Agriculture Monitoring (BELCAM) initiative (Table 2). The data were used in an interactive web-based geo-platform to help farmers monitor their crops and estimate yields. To calibrate and validate the AquaCrop model for potato under Belgian conditions, data were collected in 2015 (a particular dry year) for 80 plots and for 67 fields in 2016 (a rather wet year) in the potato

Table 2 The default values in AquaCrop of conservative crop parameters for potato and the adjusted values for the cultivars Bintje, Fontane and Nicola: normalized biomass water productivity (WP*); reference Harvest Index (HI_o); upper and lower water stress thresholds for canopy expansion (p_{exp}) and for stomatal closure (p_{sto}), expressed as fraction of Total Available Water (f_{TAW}); (adapted from Wellens et al., 2022a).

Conservative crop parameter	Default	Bintje	Fontane	Nicola
WP* [gr.m^{-2}]	18.0	17.5	18.5	18.5
HIo [%]	75	90	80	90
p_{exp}[f_{TAW}]	0.20–0.60	0.30–0.65	0.30–0.65	0.30–0.60
p_{sto} [f_{TAW}]	0.60–1	0.45–1	0.65–1	0.55–1

growing areas in Belgium. Calibration and validation results for the simulation of tuber dry weights are plotted in Fig. 5 (Wellens et al., 2022a).

While all the crop parameters may be adjusted to a specific genotype, it is important to start adjusting those which are known to vary among cultivars,

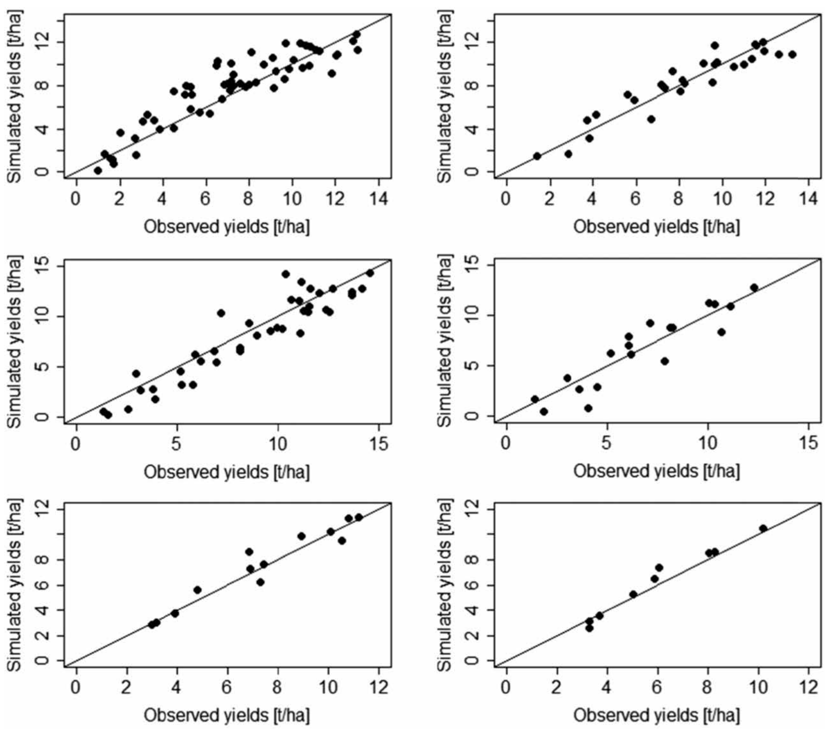

Figure 5 Observed versus simulated dry tuber weight throughout the growing season for Bintje (Row1), Nicola (Row 2), and Fontane (Row 3). Data used for calibration (column 1) and validation (column 2) are presented (from Wellens et al., 2022a).

such as those related to phenological development or harvest index (Fig. 6). These and less conservative crop parameters might require an adjustment when running a simulation for a specific cultivar or in a climate or management different from the environment in which the crop was calibrated and validated.

The plant density, which varies largely with management, determines the initial canopy cover (CCo, the canopy cover at 90% germination) and the maximum canopy cover (CCx) that can be reached at mid-season in the absence of stress. The time to reach 90% germination might require an adjustment since it is affected by field preparation, soil temperature, and soil water content.

As stated above, most differences among commercial crop cultivars are related to the length of development stages, while the maximum effective rooting depth (Z_x) and its deepening rate (or the time to reach Z_x) are also affected by soil physical (temperature, mechanical impedance, aeration) and soil chemical (pH, salinity, high levels of aluminium, or manganese) characteristics. The adjustment of the time to reach a particular stage and/or its duration for the local cultivar can be specified in AquaCrop in calendar days (Fig. 6). After loading the climatic data and specifying the planting date for the year of calibration, AquaCrop converts the specified calendar days into thermal time by considering the corresponding growing degree days. This automatically adjusts the length (number of days) of the various crop development stages and crop cycle to the temperature regime in other years or regions (Fig. 7).

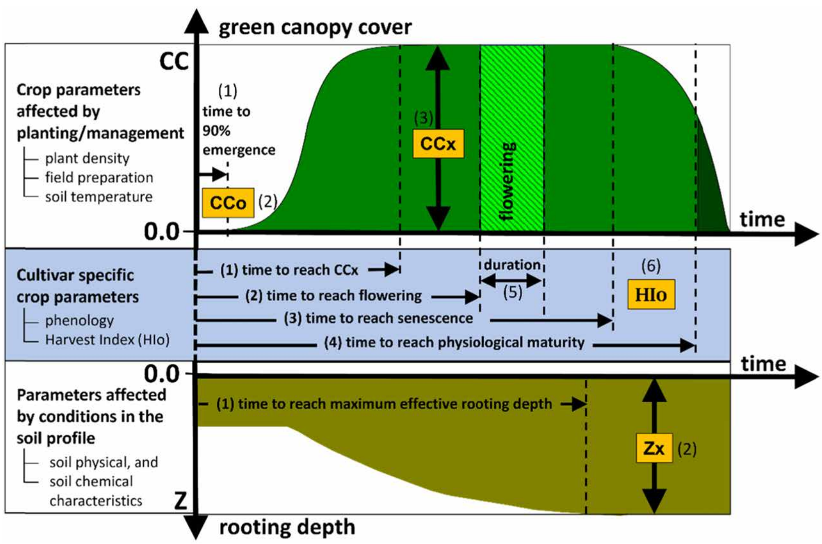

Figure 6 Non-conservative crop parameters affecting the development of the green canopy cover (CC), the extension of the rooting depth (Z), and crop yield (HIo), which might require an adjustment when selecting a cultivar or environment different from the one considered for crop calibration.

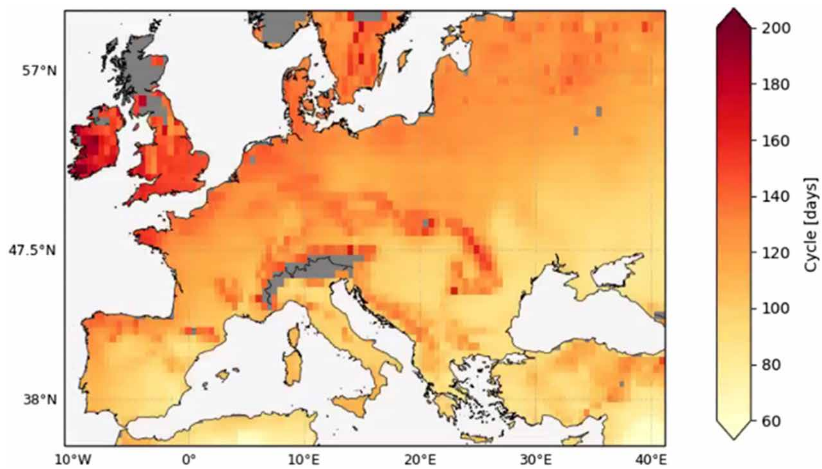

Figure 7 Variation of the average length (days) of the growing cycle of maize (requiring 1,112 growing degree days to reach maturity) across the European continent for the period 1985–2014. Planting dates were generated when the minimum air temperature exceeded 8 °C for four consecutive days from March 1 (from Deketelaere, 2024).

The reference Harvest Index (HI_o) is a representative HI reported in the literature for the crop species under non-stress conditions. Although HI_o is conservative to a large extent, plant breeding has improved HI over the years as a major target, and its improvement has altered the reported values in the database of AquaCrop, which was put together in 2006, using published values which were obtained around 2000. For example, Ruiz et al. (2023) reported an average increase of 0.26% per year for the HIo of maize since 1964, while Hay and Gilbert (2001) provided values for maize landraces that differ widely from the HIo of the high-yielding commercial cultivars in AquaCrop's database. As stated earlier, some of the parameters considered conservative at the launching of the model have shown to vary among genotypes and management conditions. We recommend seeking several sources of knowledge before agreeing on the value of HI_o as an input to the simulations, emphasizing the use of results obtained in local experimentation.

4.4 Calibration and simulation of the crop response to soil fertility stress

In AquaCrop, a soil water and salt balance keep track of the daily incoming and outgoing water and salt fluxes at the boundaries of the root zone. The shape of the various stress response curves determines daily the magnitude of the stresses (Ks) between its upper and lower threshold, and the crop's response to those stresses as described in detail in the AquaCrop Reference Manual (Raes et al., 2023b).

It is common in developing countries that the application of fertilizers is limited, and this adds another constraint on production relative to the limited water supply. Other crop models often use a mass balance for modeling the crop response to soil fertility. However, to counter the vast input requirement for simulating quantitatively the major nutrients and the effects of soil fertility management, AquaCrop adopts a simpler, semi-quantitative approach based on the crop response to nutrient stress. Instead of all the details of nutrient concentrations and the chemical forms, AquaCrop requires as input the relative crop production (with reference to the potential production) that can be achieved with the current soil fertility management in farmers' field in the absence of water or any other stress (Fig. 8).

AquaCrop simulates the effect of soil fertility stress by (a) restricting the canopy growth (CC) and (b) a gradual decrease of the normalized biomass water productivity (WP*) as more and more biomass is produced (Fig. 9). Because AquaCrop does not simulate nutrient cycles and balances but only mimics the effect of soil fertility stress, the crop response to soil fertility management needs to be calibrated.

The crop is calibrated for the relative crop production ($Brel_{cal}$) that can be reached with the soil fertility management in farmers' fields. When specifying $Brel_{cal}$ for calibration, AquaCrop will plot a limited canopy development and reduced WP* for which the integrated effect yields the specified $Brel_{cal}$ (Fig. 9). With observations in the well-watered fertility-stressed field of (1) the

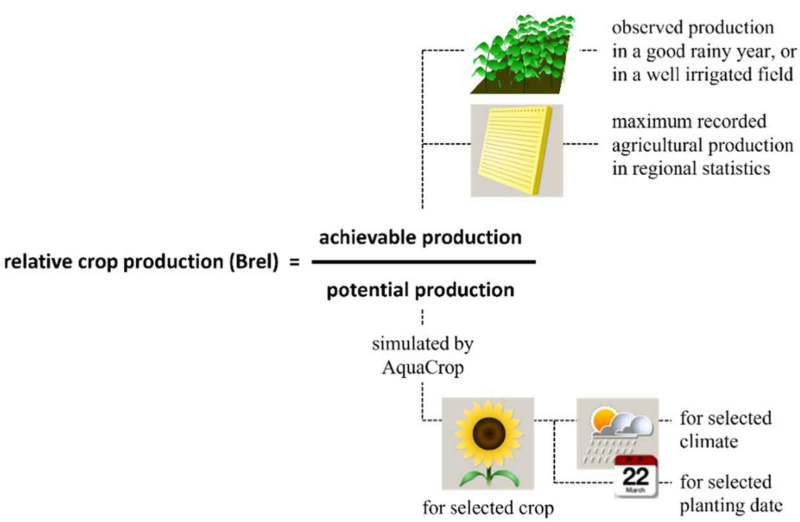

Figure 8 The required input for soil fertility stress, expressed as the relative crop production (Brel) that can be achieved with the actual soil fertility management in famers' field.

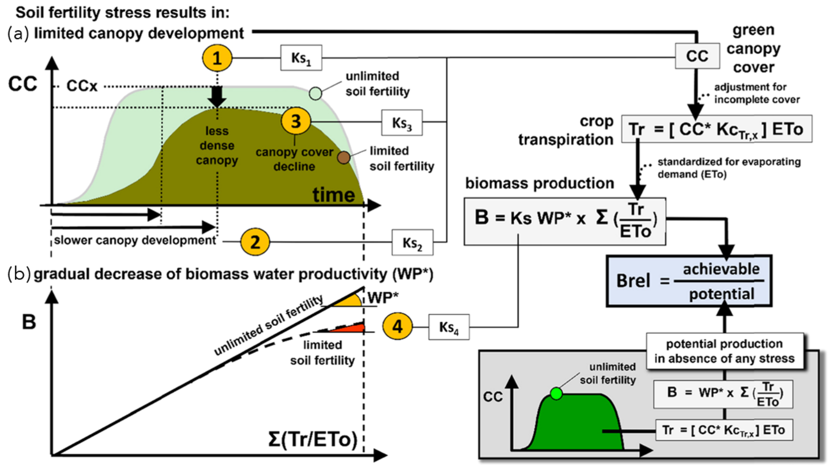

Figure 9 Simulation of the achievable biomass production when limited by soil fertility stress (Brel), resulting from three impacts (Ks 1 to 3) on the green canopy development (CC), and (Ks 4) the gradual decrease of the normalized biomass water productivity (WP*).

maximum canopy cover that can be reached, and/or (2) the time when the canopy closes, and/or (3) the selection of a class (small/medium/high) of the canopy decline in the season, the user can fine-tune the displayed canopy development during the calibration process, while (4) AquaCrop will make the required adjustment to WP* to ensure that the integrated effect still matches with the specified $Brel_{cal}$. The calibration process for soil fertility stress ultimately fixes the shape of four fertility stress coefficients (Ks), which are the modifiers targeting respectively (1) CCx, (2) CGC, (3) in-seasonal canopy-decline, and (4) WP* (Fig. 9).

Once calibrated, AquaCrop simulates the effects on crop production of water and fertility stress, independently or combined. When running a simulation, the level of soil fertility, expressed as a relative crop production ($Brel_{input}$), is available as input in Field Management (Fig. 3). If $Brel_{input}$ differs from $Brel_{cal}$, AquaCrop will jointly increase or decrease the stress indicator of the four Ks coefficients until the integrated effect yields $Brel_{input}$. However, the specified $Brel_{input}$ might not be reached if other stresses also occur during the season. When soil water or soil salinity stress also starts to limit the biomass production, AquaCrop automatically decreases the stress for the four Ks coefficients in the next daily time step(s), since more nutrients would remain in the soil reservoir (the biomass production is less than expected due to water or salinity stress). The higher the other stresses, the greater the Ks adjustments. If the other stresses are relieved by rainfall or irrigation, soil fertility stress increases, and the four Ks coefficients adjust once more to another level. This dynamic adjustment of the Ks coefficients makes the effect

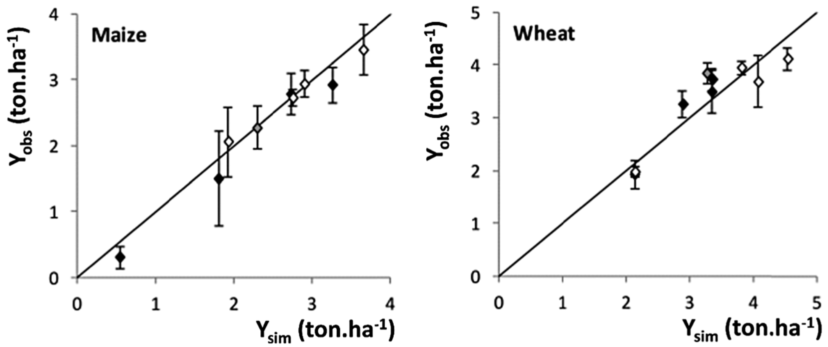

Figure 10 Observed versus simulated yield for maize and wheat in Nepal for various levels of soil fertility and water treatments: white symbols represent irrigation; grey, deficit irrigation, and black symbols represent rainfed agriculture (from Van Gaelen et al. (2015)).

of soil fertility stress automatically adjust to the result of other stresses (Raes et al., 2023b).

Following case-specific calibration for tef in Ethiopia, maize and wheat in Nepal (Fig. 10), and quinoa in Bolivia, it has been shown that AquaCrop was able to accurately simulate the soil water balance, crop development, biomass production and grain yield for several soil fertility levels in different environments (Van Gaelen et al., 2015).

4.5 Parameterization of crops not (yet) available in the database of AquaCrop

In the database of AquaCrop, calibrated and validated values of the conservative crop parameters are provided for 14 major annual herbaceous crops, two less common crops (teff and quinoa), and one perennial herbaceous forage crop (alfalfa). The widespread use of AquaCrop has resulted in its applications for crops not yet available in the database. A literature review in 2019 revealed that the model has already been implemented for 46 different crops (Salman et al., 2021). Although not clearly presented in all publications, detailed data are needed for the validation and parameterization of the model for a particular crop. A guide for the parameterization, calibration, and validation of AquaCrop is available in Steduto et al. (2012). An example for maize is worked out by Hsiao et al. (2009) and Heng et al. (2009).

For varying environmental conditions, guidance on which crop and soil parameters should be given priority during calibration is provided by Vanuytrecht et al. (2014b). Several root and soil parameters have a higher impact on yield simulation under diverse conditions, particularly when water availability is limited. Hence, even though root and soil water characteristics are not the easiest to measure in the field, they require meticulous calibration to ensure good simulation results.

Although applications of AquaCrop for fruit trees are reported in the literature, the model has only been designed for herbaceous crops. The complex behavior of fruit trees makes it difficult to simulate the yield response with AquaCrop's simple calculation procedure. Mixed cropping (intercropping) cannot be simulated either, since uniform large fields are assumed.

5 Simulation of the effects of climate change

When studying the impact of climate change on crop production, both the changing weather conditions and the effects of CO_2 fertilization need to be considered. The structure of AquaCrop allows to assess the combined effect of increased temperature and ETo, altered rainfall patterns, and elevated atmospheric CO_2 concentrations.

In accordance with physiological plant responses, the elevated atmospheric CO_2 concentration induces in AquaCrop (i) a small reduction in transpiration at field level and (ii) a strong increase of the normalized biomass water productivity (WP*) for C3 crops:

- The decrease of the crop transpiration coefficient ($Kc_{Tr,x}$) with increased CO_2 concentration follows the interplay between the decrease in stomatal conductance (due to increased CO_2) and the increased transpiration due to the increased vapor pressure gradient affected by higher temperatures. The simulated decline in transpiration mimics the field-scale effects of elevated CO_2 concentration on agricultural crops in free air CO_2 enrichment (FACE) conditions for C3 and C4 crops (Vanuytrecht et al. 2011, 2012).
- Elevated CO_2 concentration enhances photosynthesis (particularly for C3 crops since C4 crops are considered to be CO_2 saturated at ambient [CO_2] when other resources are adequately present) and therefore crop productivity. This effect of CO_2 fertilization is simulated in AquaCrop by adjusting WP* when the average annual atmospheric CO_2 concentration deviates from its reference value of 369.41 ppm in the year 2000 for which WP* has been normalized (Fig. 11). By means of a sink term, the user can select between a relatively high theoretical adjustment (Hsiao and Xu, 2000; Steduto et al., 2007) corresponding to an assumed strong crop sink capacity, versus a lower adjustment based on the analysis of crop responses in FACE environments (Vanuytrecht et al., 2011) corresponding to an assumed weak crop sink capacity. Lower response levels in FACE

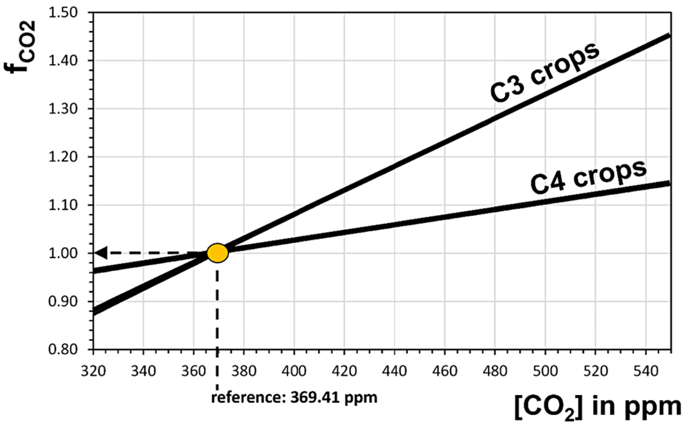

Figure 11 Multiplier for WP* (f_{CO2}) for the theoretical adjustment (assuming strong crop sink capacity) as specified by Steduto et al. (2007) for various atmospheric CO_2 concentrations for C3 crops and for C4 crops (e.g. maize and sorghum).

experiments have been attributed to various causes, including a lack of sink strength to optimally capture the additional atmospheric carbon, partly due to limited crop nitrogen (Vanuytrecht et al., 2012 and 2014a). More recently, it has been further suggested that the experimental setups of the FACE experiments could cause rapid and wide fluctuations in CO_2 concentration and, hence, an unrealistically low crop response to high CO_2 concentration (Allen et al., 2020). This hypothesis suggests that the crop responses observed in FACE experiments may be underestimating the real responses and that any modeling exercises should be performed with a high-value sink term.

To avoid unrealistically high modelled effects of CO_2 fertilization at high atmospheric CO_2 concentrations, the adjustment of WP* starts to decline at concentrations above 550 ppm, and it no longer increases beyond 900 ppm. This is in line with the decreasing trend in crop response with increasing elevated CO_2 levels (e.g. Akita and Moss, 1973; Chapin et al., 2011; Kirschbaum, 2011; Kromdijk and Long, 2016; Yin and Struik, 2009). AquaCrop uses the well-documented and general trend described by Yin and Struik (2009) to model the decreasing trend above 550 ppm. This is, however a purely theoretical adjustment, without any validation by experimental data as FACE experiments generally do not reach these high levels of atmospheric CO_2 concentration.

Compared to the possible positive effects of CO_2 fertilization, the changed weather conditions in a future climate are likely to have a more negative effect on crop production. As a result of the increase in air temperature and therefore

ETo, water stress may become more severe. Also, the plant cycle will be shorter, resulting from its specification in thermal time. The effect of cold stress on crop transpiration and on pollination will be less, but heat stress during flowering can become more severe. Additionally, the changing rainfall patterns and air temperature increase will likely result in different planting dates, which can be generated in AquaCrop by built-in air temperature and rainfall criteria.

The considering of the altered weather conditions and the incorporation of a flexible and realistic crop response to atmospheric CO_2 concentration has allowed the study of future impacts of climate change on crop production in a wide range of studies (e.g. Vanuytrecht et al., 2015; Bouras et al., 2019; Busschaert et al., 2022).

The effect of climate change on crop yield in smallholder farms in West Africa was simulated with AquaCrop (Raes et al., 2021). For the calibration, crop yields, cultivar characteristics, and information on current soil fertility and weed management were collected. For the simulations under future climatic conditions, the three best performing RCM-GCM combinations for 8 sites in the study area were retrieved from the CORDEX-Africa dataset and two emission scenarios were considered. The projected climate change corresponded well with the findings of Sylla et al. (2016), who reported significant warming and a wide range of precipitation uncertainty in the Sahel.

The relative yield change under future climatic conditions, with the current field management, is negative and about –5 to –10% for the irrigated crops and –10 to –20% for the rainfed crops. The simulated negative yield impact corresponds with the median simulated yield loss around 11% found in West Africa based on a review of 16 existing studies (Roudier et al., 2011). The simulations by Raes et al. (2021) revealed that unless soil fertility is addressed, benefits from CO_2 fertilization resulting from elevated CO_2 in the future are insufficient to compensate for the negative impact of the changes in precipitation patterns and the increase in air temperature and the associated increase in evapotranspiration. By increasing soil fertility by 15% to 20% in the simulations, the yield impact of C3 crops became positive (+8 to +10%). Since C4 crops profit much less from the CO_2 fertilization effect (e.g. Leakey, 2009), the response of maize yield remained mostly negative (–2 to 0%).

6 Output

The standard AquaCrop program with a graphical user interface (GUI) has a well-developed user interface. Multiple graphs and schematic displays in the menus help the user to follow the effect of water, salinity, soil fertility, and temperature stresses on crop development and production during the crop cycle. Results are plotted in several graphs, which are updated at the end of each daily time step. Figure 12 presents the result of the simulation of

(a)

(b)

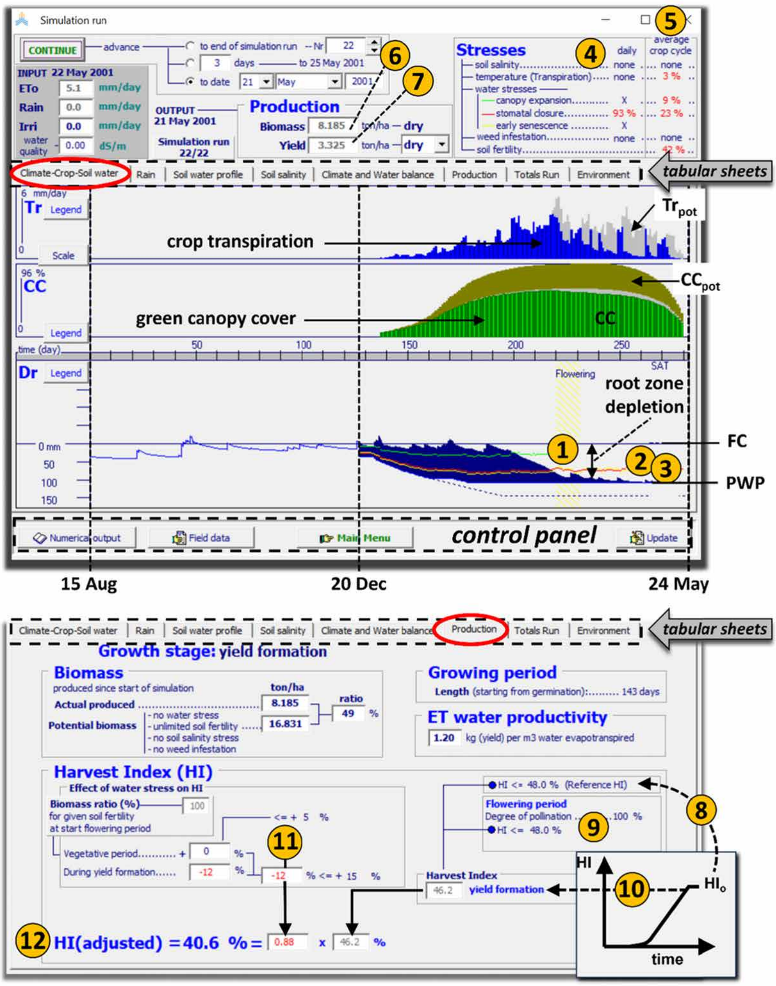

Figure 12 The 'Simulation run' menu of AquaCrop, with (a) the 'Climate-Crop-Soil water' tabular sheet with its three panels showing daily crop transpiration (Tr), green canopy cover (CC), and root zone depletion (Dr) with indication of (1) the upper threshold for canopy expansion (green line), (2) stomatal closure (red line), and (3) early senescence (yellow line). Daily updates are displayed of (4) the degree of several stresses and (5) their averages, (6) the cumulative biomass production, and (7) the crop yield. Information on the Harvest Index adjustment is available in (b) the 'Production' tabular sheet, with indication of (8) the reference Harvest Index (HI_o), (9) the effect of water, cold, and heat stress on pollination, (10) the value of the Harvest Index for that day, (11) the cumulative effect of water stress on HI, and (12) the simulated Harvest Index for that day.

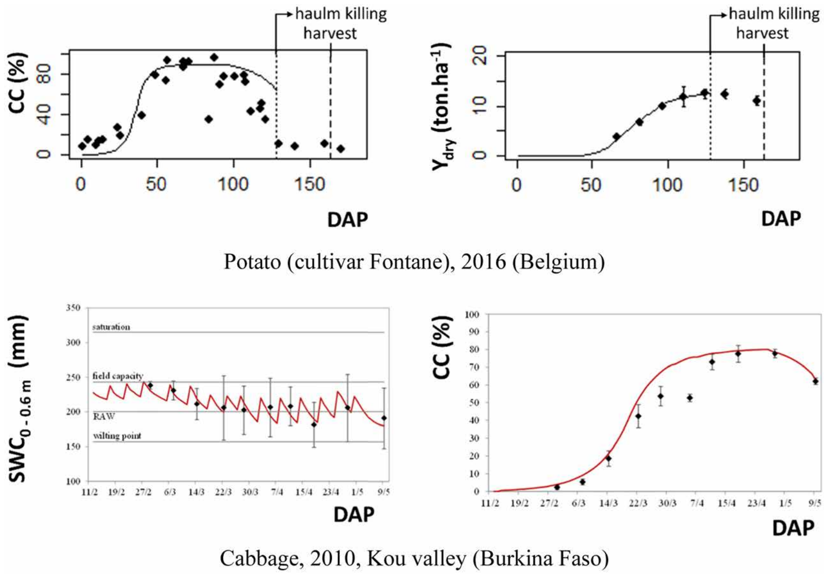

Figure 13 Observed (dots) and simulated (line) green canopy cover (left) and dry tuber yield (right) for potato (cultivar Fontane in Belgium (data from Wellens et al., 2022a); and observed (dots) and simulated (line) soil water content in the top 0.6 m (left) and green canopy cover (right) of Cabbage in Burkina Faso (from Wellens et al., 2013). Potato (cultivar Fontane), 2016 (Belgium)

winter wheat in Tunis (Tunisia), three days before crop maturity (24 May). The simulation started with dry bare soil on 15 August. Germination was generated by AquaCrop on 20 December when the topsoil was sufficiently wet. Using command keys in the control panel at the bottom of the menu (Fig. 12a), the user can overlay the simulations with observed field data and access numerical output.

The simulation results are recorded in output files and can be retrieved in spreadsheet programs for further processing and analysis. Figure 13 provides some examples comparing simulated data with observed data.

7 Recent model improvements

7.1 Release of open-source and stand-alone programs for various operating systems

The AquaCrop model is freely available and fully transparent to the scientific community and society. Furthermore, users can contribute to the model improvement by submitting suggestions. While the original (up to version 6) AquaCrop source code was written in Delphi/Pascal, version 7 was converted line by line to Fortran90, optimized, and released as open source on GitHub to stimulate a wide use and long-term community-based maintenance.

Along with the open-source code distribution, 'stand-alone' (or plugin) AquaCrop programs are provided for the three most used operating systems, i.e. Windows, MacOS, and Linux. The stand-alone program can be readily plugged into any application, including geographical information systems, data assimilation tools, calibration tools, visualization tools, web applications, etc. The stand-alone programs, the open-source code, and the standard program with a graphical user interface (GUI) are the three official AquaCrop assets currently distributed by FAO (https://www.fao.org/aquacrop/en/, Fig. 14).

7.2 Upscaling of AquaCrop for regional applications

For regional spatially distributed simulations at any spatial resolution, the AquaCrop stand-alone program can be run within a Python wrapper (de Roos et al., 2021, Busschaert et al., 2022, https://github.com/KUL-RSDA/RegionalAC_Py). AquaCrop can also be run within NASA's Land Information System (LIS, Kumar et al., 2008, https://github.com/KUL-RSDA/LISF). Both options allow to run AquaCrop in a highly efficient and parallelized way for a large number of pixels and for long-term (e.g. historical or future climate) scenarios.

Large-scale AquaCrop simulations over Europe were performed by de Roos et al. (2021) and Busschaert et al. (2022). In the first study, AquaCrop

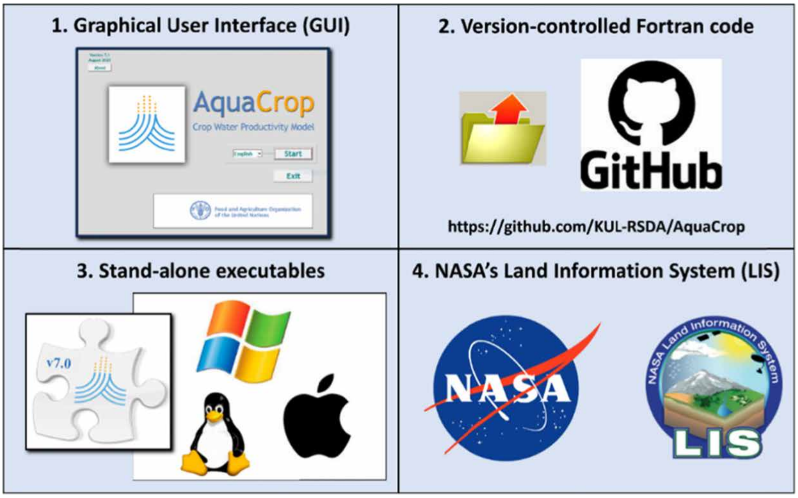

Figure 14 Three official FAO AquaCrop assets available from v7 onwards: (i) the standard GUI, (ii) open-source code on GitHub, and (iii) stand-alone programs for Windows, MacOS, and Linux. A fourth asset is AquaCrop within NASA's LIS.

was run at 1-km resolution using meteorological input from the Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2), a global re-analysis product, and spatially distributed soil parameters linked to soil texture information from the Harmonized World Soil Database. The simulations assumed a generic C3 crop for all agricultural pixels. Despite the latter limitation, the biomass and soil moisture results were similar to satellite-based vegetation and surface soil moisture retrievals in terms of short-term and interannual variability. In follow-up research by de Roos et al. (2023), the soil moisture and biomass simulations from AquaCrop were converted to microwave backscatter estimates, and these were also favorably evaluated against the radar signals from the Sentinel-1 satellite. This confirms that AquaCrop can be reliably upscaled for regional applications and that the output is comparable to a range of satellite observations.

Busschaert et al. (2022) ran AquaCrop at the 50-km resolution over Europe with meteorological data from the Inter-Sectoral Impact Model Intercomparison Project phase 3 (ISIMIP3), both for historical and future climate scenarios. Also for this coarse resolution, the historical AquaCrop simulations compared well against coarse-scale satellite retrievals of soil moisture and vegetation. The climate scenarios included various Shared Socioeconomic Pathways (SSP) and were produced with various global climate models (GCM). In this study, the net irrigation requirement was estimated by AquaCrop to increase by 18% to 35% by the end of the 21st century (relative to 1985–2014), for the mitigated (SSP1-2.6) and unmitigated (SSP5-8.5) scenario respectively, but the results strongly varied with the underlying GCM.

7.3 Upscaling AquaCrop towards satellite-based data assimilation

The NASA LIS framework (Fig. 14) supports AquaCrop simulations with perturbed meteorological or parameter input to estimate the ensemble uncertainty of the simulations. LIS also allows intermittent updates simulated AquaCrop variables when observations become available, i.e. via data assimilation (De Lannoy et al., 2022).

In the last two decades, a wealth of large-scale spatially distributed meteorological, soil, and vegetation data from satellite and re-analysis products has become available. This information allows to force and evaluate large-scale spatial AquaCrop simulations, as illustrated further below. A key to further advance regional crop simulations is the creation of spatially distributed high-resolution crop and management parameter sets that evolve in time with cropping practices. Another pathway to optimize crop estimates is to use frequent satellite observations to adjust the model trajectory of AquaCrop, either via input, state, or parameter updating. Figure 15 shows that

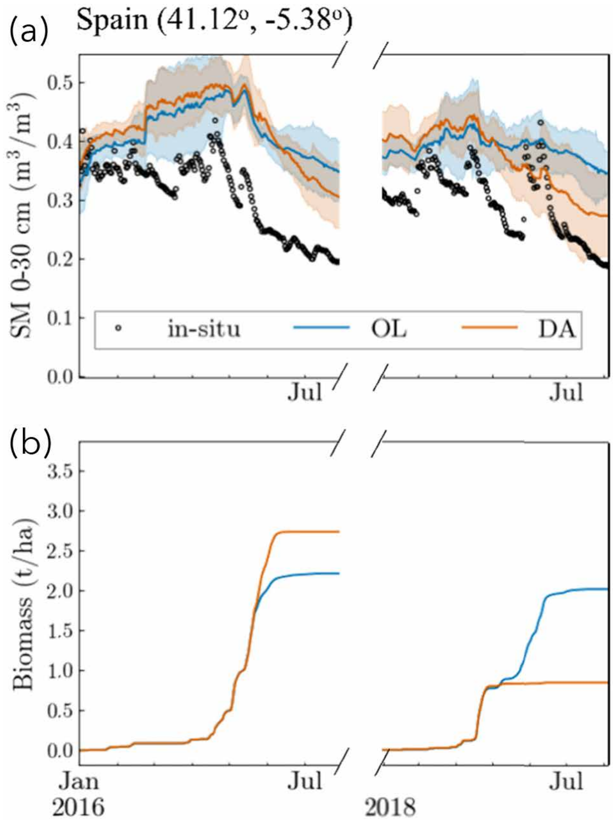

Figure 15 Example time series of (a) surface soil moisture (SM) and (b) biomass. Both figures show open loop AquaCrop simulations (OL, model only, blue) and the results with assimilation of satellite-based soil moisture retrievals (DA, orange). Also shown are *in situ* data for SM (black dots).

satellite-based updates in time series variability of soil moisture can have a significant impact on the simulation of vegetation development and biomass production in water-limited regions.

8 Further model enhancement

Currently, AquaCrop simulates responses to extremely high temperatures through an adjustment of the reference Harvest Index when heat stress affects pollination (Fig. 1). A further adjustment of model routines for crop responses to extreme high temperatures could possibly improve the simulations, as also indicated by Maiorano et al (2017). Particularly, responses to heat under compound impacts, e.g. a combination of drought and heat stress (Webber et al, 2022), which are becoming more common under climate change conditions, could contribute to further model development. These model developments could for example, introduce a heat stress effect on canopy senescence. While heat stress is an obvious and relevant stressor where model development can contribute to more realistic simulations, modeling other responses to climate extremes (Toreti et al, 2020), e.g. late frosts or extreme rainfall, could also be the subject of further research to improve model routines and simulations.

Differences in simulated crop responses across different crop models are common, particularly for responses related to transpiration and water use, and just as other models, AquaCrop would benefit from both further validation and optimization of CO_2 responses in the range of concentrations anticipated in the future, to improve our predictive understanding of these responses (Vanuytrecht and Thorburn, 2017).

9 Conclusion

Aquacrop simulates the yield of annual herbaceous and perennial forage crops by considering the effect of air temperature, soil water, salinity and fertility stress on crop development, biomass production, and harvest index. AquaCrop uses a relatively small number of explicit and largely intuitive parameters and input variables to characterize crop and soil properties and field and irrigation management practices. By varying cultivar-specific crop parameters, differences among varieties can be taken into account in the simulations. AquaCrop is a robust model that has been tested widely worldwide and is very easy to use. The simulation results are recorded in output files and can be retrieved in spreadsheet programs for further processing and analysis. Since its publication in 2009, it has been widely adopted by many stakeholders who have calibrated it for numerous additional crops in different agro-ecological environments, and it has been applied to simulate crop production under current and future climatic conditions.

10 Where to look for further information

AquaCrop is freely available. The software, documentation, training material, and a reference manual containing a user's guide and a detailed description of all calculation procedures can be downloaded from the FAO AquaCrop website (https://www.fao.org/aquacrop). Forty-three training modules (MP4 videos) are posted in an 'AquaCrop Training' channel of YouTube (https://www.youtube.com/playlist?list=PLzp5NgJ2-dK7H85cyEmGc8KSodqm8gCf2). Further information on crop responses, including a guide for the parameterization, calibration, and validation of AquaCrop is available in FAO Irrigation and Drainage Paper No. 66, 501 p. (http://www.fao.org/nr/water/aquacrop.html).

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