Chapter 1

The AquaCrop procedure to simulate crop response to agricultural management

1.1 Introduction

AquaCrop simulates daily crop canopy cover and root development, transpiration, dry above-ground biomass production, yield and the soil water balance in a cropped field, based on user-specified inputs of environmental and agronomic conditions.

This chapter presents AquaCrop's input requirements and calculation procedures to simulate soil water balance and crop productivity as influenced by the environmental and agronomic conditions in the cropped field. Furthermore, this chapter intents to give a complete overview of all field management practices that can be simulated with AquaCrop as well as their effect on the standard calculation procedure. Also, evaluation and application of these field management simulation procedures is discussed. Finally, evaluation of AquaCrop simulation results is touched upon.

It should be noted that this chapter only discusses the most relevant AquaCrop calculation procedures as implemented in AquaCrop version 4.0 and 5.0. More detailed information on the algorithms and calculation procedures can be found in the AquaCrop reference manuals (Raes et al., 2012, 2015).

1.2 Input requirements

AquaCrop requires user-specified input describing the environmental and agronomic conditions of the cropped field.

Required weather data include precipitation, minimum and maximum temperature (T_{min} and T_{max}), reference evapotranspiration (ET_0) calculated with the FAO penman monteith method (Allen et al., 1998), and atmospheric

CO_2 concentration ([CO_2]). Ideally, weather data are supplied on a daily basis, but the model can interpolate between 10-daily or monthly values of T_{min}, T_{max} and ET_0 as well. [CO_2] is specified on a yearly basis. By default, AquaCrop uses historical [CO_2] measurements of the Mauna Loa Observatory in Hawaii. However, [CO_2] can also be specified by the user for the past or future according to a certain CO_2 emission scenario.

Furthermore, the cultivated crop and its (trans)planting date need to be specified. Crop characteristics are described by a set of crop parameters, which include both conservative and non-conservative parameters. While the former do not change with time and are valid for various environmental conditions, management practices and cultivars, the later need calibration to match the local cultivar and cropping system. Non-conservative parameters include amongst others growing cycle length, length of different growing stages, plant density, maximum canopy cover, maximum rooting depth and crop response to soil fertility. Conservative parameters, on the other hand, include for example the water stress and temperature stress thresholds for crop development. A complete list of crop parameters is presented in Annex X. The AquaCrop database includes default sets of crop parameters for 14 crops including widely cultivated crops such as barley, maize, wheat and cotton (Garcia-Vila et al., 2009; Heng et al., 2009; Andarzian et al., 2011; Abrha et al., 2012) as well as under-utilized crops such as quinoa and tef(Geerts et al., 2009; Tsegay et al., 2012). When using these default sets, only the non-conservative parameters need to be fine-tuned to local conditions. In addition, parameter sets for more than 30 crops, calibrated for local conditions, have been presented in literature. These can be used as starting values when calibrating conservative and non-conservative crop parameters for crops that are not included in the AquaCrop database.

Next to weather and crop data, soil profile characteristics need to be defined. A soil profile can consist of up to 5 soil layers, each with its own set of parameters. These parameters include the layer thickness, saturated hydraulic conductivity (K_{sat}) and the volumetric water content at saturation (θ_{SAT}), field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}). The latter two define the total available soil water content (TAW). In addition, also soil surface characteristics (curve number (CN) and readily evaporable water (REW)), the depth of a soil layer blocking root growth (if present) and parameters defining capillary rise from the groundwater table need to be specified. Soil parameters can be specified based on field measurements, or default values suggested by AquaCrop based on soil texture can be used.

Furthermore, the groundwater, being the lower boundary condition to the soil profile, needs to be characterized with respect to its depth below the soil surface (either constant or time variable) and quality of the water. Also, information on the applied irrigation and field management practices need to be specified (see Section 1.6). Finally, the model requires specification of the simulation period as well as initial conditions of soil water and salinity content.

1.3 Crop canopy development and production

Being a water-driven model, AquaCrop calculates crop production based on the amount of water transpired by the crop (Tr). Crop transpiration (Equation 1.1) depends on the weather conditions (ET_0) and the crops' green canopy cover (CC), through the crop transpiration coefficient (Kc_{Tr}). The expansion of the canopy cover from its initial value (CC_0) to reach the maximum canopy cover (CC_x) is described by a logistic function determined by the canopy growth coefficient (cgc). At the end of the growing season, the decline of the canopy cover due to senescence is described by means of the canopy decline coefficient (cdc). Transpiration is converted into dry above-ground biomass production (B) by means of the normalized crop water productivity (WP^*) (Equation 1.2). Next, crop yield is calculated from biomass by means of the harvest index (HI) (Equation 1.3). The amount of crop yield produced per unit of water evapotranspired in the cropped field is defined as the ET crop water productivity (WP_{ET}) (Equation 1.4).

$$Tr_i = Ks_i \cdot Kc_{Tr_i} \cdot ET_{0_i} \tag{1.1}$$

$$B = Ks_{b_i} \cdot WP^* \cdot \sum_{i=1}^{n} \frac{Tr_i}{ET_{0_i}} \tag{1.2}$$

$$Y = HI \cdot B \tag{1.3}$$

$$WP_{ET} = Y \sum_{i=1}^{n} ET_i \tag{1.4}$$

where Tr_i is the crop transpiration (mm/day) on day i, ET_{0_i} is the reference evapotranspiration (mm/day), Kc_{Tr_i} is the crop transpiration coefficient (-) proportional to the crop's canopy cover (CC, $\mathrm{m}^2/\mathrm{m}^2$), Ks_i is the soil water stress coefficient (-), Ks_{b_i} is the cold stress coefficient for biomass production (-), B is the cumulative dry above-ground biomass production (g/m^2), WP^* is the normalized crop water productivity (g/m^2), Y is the dry mass of yield (g/m^2), HI is the harvest index (g/g), ET is the crop evapotranspiration, WP_{ET} is the ET crop water productivity (kg/m^3), and n is the number of sequential days spanning the growing period.

1.4 Soil water balance

AquaCrop calculates the daily soil water content (SWC) in the soil profile by means of a soil water balance that keeps track of incoming (rainfall, irrigation, capillary rise) and outgoing (surface runoff, deep percolation, evaporation, crop transpiration) water fluxes (Figure 1.1). While rainfall and irrigation are user-specified inputs, other components of the soil water balance are simulated on the basis of the simulated crop canopy development as well as input of daily weather data, the depth of the groundwater table and soil characteristics.

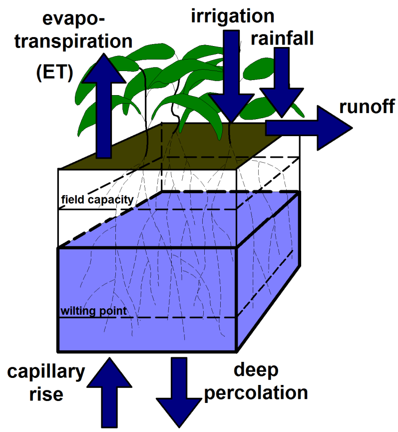

Figure 1.1: AquaCrop determines the soil water content in the root zone by calculating the soil water balance of incomming and outgoing water fluxes

1.4.1 Crop transpiration and soil evaporation

Crop transpiration (Tr, Equation 1.1) and soil evaporation (E, Equation 1.5) are simulated as separate components of the soil water balance.

$$E_i = Kr_i \cdot Ke_i \cdot ET_{0_i} \tag{1.5}$$

where E_i is soil evaporation (mm/day) on day i, Kr is the evaporation reduction coefficient (-), Ke the evaporation coefficient (-) proportional to the non-covered soil fraction (1-CC), and ET_{0_i} is the reference evapotranspiration (mm/day).

Nevertheless, both components are proportional to the evaporative power of the atmosphere (ET_0) and simulated crop canopy cover via the crop transpiration (Kc_{Tr}) and evaporation (Ke) coefficients, respectively (Equation 1.1 and 1.5). In addition, transpiration and evaporation are adjusted to the soil water content and corresponding water stress which is expressed by the soil water stress (Ks) or evaporation reduction (Kr) coefficient.

1.4.2 Surface runoff

Surface runoff (RO) is calculated using the USDA (1969) curve number (CN) equation:

$$RO_i = \begin{cases} 0 & \text{if } P_i \leq I_a \\ \dfrac{(P_i - I_a)^2}{P_i - I_a + S)} & \text{if } P_i > I_a \end{cases} \tag{1.6}$$

where RO_i is surface runoff (mm/day) on day i, P_i is rainfall (mm/day), I_a initial abstraction (mm) and S is storage capacity (mm). Surface storage is derived from the runoff curve number (CN) with equation:

$$S = 254 \cdot \frac{CN}{100} - 1 \tag{1.7}$$

where CN is the runoff curve number (-) equal to the CN value selected by the user on the basis of soil and field management characteristics (CN_{input}), but automatically adjusted to soil moisture conditions during simulation.

$$CN = CN_{input} \cdot f_{CN,SWC} \tag{1.8}$$

where CN_{input} is the user-specified curve number (-) and $f_{CN,SWC}$ the correction factor for the soil water content in the top soil (0-0.3 m).

For the recent release of AquaCrop version 5.0, the surface runoff calculation procedures have been revised according to latest advances on the curve number approach (Hawkins et al., 2009). First, the standard value of initial abstraction has been altered. Originally, AquaCrop applied the common assumption that I_a equals 20% of the storage capacity. However, it was found that 5% of S is a more appropriate value for general application (Hawkins et al., 2009). Consequently, this value was adopted as the new standard in AquaCrop version 5.0. It should be noted that also the CN input values should correspond to this assumption. Hence, CN values for $I_a = 20\%S$, such as found in the SCS curve number tables (USDA, 2007), should be converted before they are used as AquaCrop input. This can be done by means of the conversion equation proposed by Jiang (2001).

A second update was inspired by the fact that surface runoff depends as much on soil properties as on field surface management. Therefore, CN_{input} is no longer uniquely defined based on soil properties (K_{sat}). In AquaCrop version 5.0 the CN specified as soil parameter (by default linked to the topsoil K_{sat}) is adjusted for field surface management (see Subsection 1.6.3).

$$CN_{input} = CN_{soil} \cdot f_{CN,mgmt} \tag{1.9}$$

where CN_{soil} is the input curve number as defined by soil properties (-) and $f_{CN,mgmt}$ is the adjustment factor for field surface management.

1.4.3 Deep percolation and capillary rise

To simulate vertical movement of water, the soil profile is divided into soil compartments of 10 cm by default. When the soil water content in one compartment exceeds field capacity, it drains to the next one at a rate controlled by a drainage coefficient which is proportional to K_{sat}. Drainage from the bottom compartment is considered to be deep percolation to the groundwater.

The amount of water reaching the root zone via capillary rise depends on the soil properties and the depth of the groundwater table:

$$CR_i = exp\left(\frac{ln(z_i) - b}{a}\right) \tag{1.10}$$

where CR_i is the potential capillary rise (mm/day) on day i, z the user-specified depth of the ground water table below the soil surface, and a and b soil parameters. The soil parameters are automatically defined by AquaCrop based on soil texture and soil hydraulic properties (K_{sat}) but can be further calibrated by the user.

The potential capillary rise as determined by Equation 1.10 is divided over the soil compartments by filling up the bottom compartment of the soil profile to field capacity and proceeding upwards.

1.5 Crop response to abiotic factors

Next to environmental factors, AquaCrop considers various abiotic stresses including water stress, temperature stress, soil salinity stress and soil fertility stress. The degree of stress is expressed using stress coefficients (Ks) which vary between 1 (no stress) and 0 (full stress). Ks modifies a certain target variable (e.g. B is the target of Ks_{b_i}). Stress curves or stress response functions determine how Ks changes in function of a certain stress indicator (e.g. temperature for Ks_{b_i}). Stress curves have a linear, convex or logistic shape between the upper and lower threshold for which Ks equals 1 and 0 respectively.

1.5.1 Crop response to water stress

Crop response to water stress, either excess or shortage of water, is determined by several crop-specific water stress coefficients. Each Ks is linked to a crop-and process-specific threshold of soil water content in the root zone. Water shortage reduces speed of crop canopy development and root expansion, causes early crop senescence, reduces crop transpiration because of stomatal closure, and increases or decreases the harvest index depending on the timing of the water shortage. Water excess, on the other hand, limits root expansion and reduces crop transpiration because of aeration problems.

1.5.2 Crop response to air temperature stress

Crop response to air temperature stress, i.e. both heat and cold stress, is determined by three stress coefficients. Biomass production is affected by cold stress (Ks_{b_i} in Equation 1.2), while pollination is affected by both cold and heat stress. Additionally, air temperature also affects simulation of crop development when crop parameters are specified in growing degree days (GDD). These GDD are calculated from the average air temperature taking into account crop-specific base and upper temperatures which are the limits for crop canopy development. This means for example that if the average air temperature is low, crop development is slower than when average air temperature is higher.

1.5.3 Crop response to CO_2

Crop biomass increases with increasing atmospheric CO_2 concentration. The crop response to CO_2 is simulated by means of a sink term (f_{CO_2}) which alters the normalized biomass water productivity (WP^*)(Vanuytrecht et al., 2011) according to $[CO_2]$. This adjustment is especially crucial for simulation of future time horizons, as climate change affects crop production not only because of altered weather conditions but also through the CO_2 fertilization effect.

1.6 Agricultural management

AquaCrop considers the effect of agricultural management for simulation of the soil water balance and crop productivity. Various agricultural management practices can be simulated, either through adjustment of crop and soil characteristics or directly by input of the field management practices' characteristics.

It should be noted that this manuscript focusses on rainfed agriculture. As such, the extensive options to simulate crop production in irrigated fields will not be discussed. For more information on irrigation management the reader is referred to the multitude of studies that demonstrate application of AquaCrop to study irrigation water requirements (e.g. Shrestha et al., 2014; Palumbo et al., 2012), optimize irrigation management (e.g. Xiangxiang et al., 2013; Garcia-Vila and Fereres, 2012) and develop deficit irrigation strategies (e.g. Geerts et al., 2010; Garcia-Vila et al., 2009; Akhtar et al., 2013).

1.6.1 Crop management

Crop cultivar choice is considered through the non-conservative crop parameters. Cultivars might differ with respect to, for example, crop phenology (length of different phenological stages and growing cycle length), harvest index (landraces versus high-yielding cultivars) and rooting depth. Also, crop establishment practices are considered through the crop parameters. Canopy development depends on both the initial canopy cover which is linked to plant density and the crop establishment technique: sowing (e.g maize), transplanting (e.g. rice) or regrowth (e.g. grass). Also, the (trans)planting date is an input, either directly specified by the user or automatically generated based on user-specified rainfall or temperature criteria.

Jin et al. (2014) evaluated AquaCrop simulation of wheat production for various sowing dates. In addition, AquaCrop has been applied to optimize the timing of planting for barley in Ethiopa (Abrha et al., 2012; Araya et al., 2012), tef in Ethiopia (Tsegay et al., 2015), maize in Zimbabwe (Mhizha et al., 2014; Nyakudya and Stroosnijder, 2014) and sunflower and soybean in Lebanon (Saab et al., 2014). Changing the planting date has also been investigated as a climate change adaptation strategy for wheat in Italy (Bird et al., 2016), tomatoes in Tunisia(Bird et al., 2016), and rice in Vietnam and the lower Mekong delta (Mainuddin et al., 2012, 2013; Shrestha and Trang, 2014). Moreover,the effect of plant density was studied for rice in Tanzania (Katambara et al., 2013) and maize in Zimbabwe (Nyakudya and Stroosnijder, 2014). Production differences between maize cultivars with varying rooting depth were simulated by Nyakudya and Stroosnijder (2014), whereas Mainuddin et al. (2012, 2013) simulated rice production differences in the lower Mekong delta where several varieties with varying HI are cultivated.

1.6.2 Soil management

Soil management practices such as soil tillage, subsoiling and application of organic matter or soil conditioners (e.g. hydroabsorbents) focus on soil and water conservation aside from increasing crop production. As these practices affect soil texture and physical properties, they are considered through the user-specified soil input parameters. Adjustment of soil depth, TAW and K_{sat} input in correspondence to soil management affects simulation of the soil water content and consequently water stress affecting crop production. Also the presence of a hard soil layer (or breaking up this layer) can be simulated by specifying the depth of the restrictive soil layer. This impedes impedes root expansion beyond that depth.

AquaCrop's performance to simulate soil water content and wheat production on stony soils in Italy was evaluated by Mekuria et al. (2015). Furthermore, Campi et al. (2015) studied the effect of organic- and clay-based soil amendments on maize production in Laos.

1.6.3 Field surface management

AquaCrop considers field surface practices that reduce or impede surface runoff, including crop and planting arrangement, land preparation, and soil and water conservation practices (e.g. soil ridges). The effect of field surface management on surface runoff is considered by the adaptation of the soil dependent runoff curve number to management(Equation 1.9). Build-in SCS curve number tables support users to select a suitable adjustment factor. For practices that impede surface runoff, for example tied ridges, the fraction of rainfall that is automatically considered as surface runoff (determined by Equation 1.6) is considered to be zero. Surface runoff will only be simulated if a rainfall or irrigation event exceeds the infiltration rate of the topsoil. By addition of soil bunds, also the later runoff will be inhibited and water is stored on the soil surface. Only water exceeding the user-specified bund height will give rise to surface runoff.

Next to tied ridges also other forms of rainwater harvesting can be simulated.Van Gaelen (2012) developed a procedure to simulate runoff agriculture, i.e. the practice where surface runoff is deprived from one part of an uncropped or unproductive part of land ('catchment area') to concentrate it on another cropped part of land. Runoff agriculture can be simulated with a two-step procedure. First, the amount of surface runoff generated on the catchment area is simulated. In a second step, the simulated runoff, scaled according to the catchment-to-cropping area ratio, is specified as additional rainfall or irrigation input for simulation of the cropped field.

The Aquacrop calculation procedure for field surface management relies on the curve number method which has been toroughly tested for many agricultural areas around the world. AquaCrop has been applied by Biazin and Stroosnijder (2012) to study the effect of tied ridges as water conservation strategy in the semi-arid Ethiopian highlands, and by Kikoyo and Nobert (2015) to study the effect of field surface practices as climate change adaptation strategies for maize cultivation in Uganda.

1.6.4 Mulches

Mulches such as straw, peat, sawdust, plastic and gravel influence crop growth and production due to their effect on soil temperature, soil organic matter content, soil physical properties, water availability, weed infestation, etc. Although mulches affect crop production in many ways, AquaCrop only considers the reduction of soil evaporation due to mulches. The reduction depends on the fraction of soil covered by mulch and the type of mulch. Plastic mulches reduce soil evaporation by default by 100%, while organic mulches reduce soil evaporation by only 50%. Those default values can be adapted by the user if more detailed information is available.

The calculation procedure for evaporation reduction due to mulches was developed based on work by X. AquaCrop has been applied to study effect of mulches as climate change adaptation strategy for maize production in Uganda (Kikoyo and Nobert, 2015) as well as tomato production in Tunisia and wheat production in Italy (Bird et al., 2016). Also Mekuria et al. (2015) applied AquaCrop to study the effect of mulches on maize crop water productivity in Laos.

1.6.5 Soil fertility management

The procedure to simulate crop response to soil fertility management is discussed and evaluated in Chapter 3.

1.6.6 Weed management

A preliminary procedure to simulate crop response to weed management, proposed by Abrha (2013), was implemented in a testversion of AquaCrop 4.0. This procedure was revised and evaluated by Van Gaelen et al. (2016) as presented in Chapter 4. The new improved procedure was implemented in a testversion of AquaCrop 5.0, and will eventually be released in AquaCrop version 5.1.

1.6.7 Overview AquaCrop versions

Through time the field management calculation procedures implemented in AquaCrop were updated and procedures for new field management practices were added. Table 1.1 presents an overview of the field management procedures implemented in AquaCrop version 4.0 and 5.0, the AquaCrop versions that were used in the following chapters.

Table 1.1: Overview of field management procedures in AquaCrop version 4.0 and version 5.0. Test versions (marked with *) include a weed management module that was not released by FAO

AquaCrop version	**4**	**4.0***	**5**	**5.0***
Applied in	Chapter 3	Chapter 5	Chapter 6 & 7	Chapter 4
Field surface management				
Runoff calculation with Ia=20%S	x	x		
Runoff calculation with Ia=5%S			x	x
Soil fertility management				
Procedure Chapter 3	x	x	x	x
Weed management				
Procedure Abrha (2013)		x		
Procedure Chapter 4				x
Other management				
Original procedure	x	x	x	x

1.7 Evaluation of simulation results

AquaCrop simulation results of soil water content, green canopy cover, dry above-ground biomass production and crop yield can be evaluated against field observations by means of graphical displays as well as statistical performance indicators:

(i) the coefficient of determination or squared Pearson's correlation coefficient (R^2, -):

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2} \cdot \sqrt{\sum_{i=1}^{n}(P_i - \overline{P})^2}} \right) \tag{1.11}$$

(ii) the relative root-mean-square error (RRMSE,%)(Loague and Green, 1991)

$$\begin{aligned} RRMSE &= RMSE \cdot \frac{100}{\overline{O}} \\ &= \frac{\sqrt{\sum_{i=1}^{n}(O_i - P_i)^2}}{n} \cdot \frac{100}{\overline{O}} \end{aligned} \tag{1.12}$$

(iii) the Nash-Sutcliffe model efficiency (EF, -) (Nash and Sutcliffe, 1970):

$$\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \tag{1.13}$$

(iv) the relative model error (RME, %) (Bennett et al., 2013):

$$\frac{\sum_{i=1}^{n}(O_i - P_i)}{\sum_{i=1}^{n}(O_i)} \cdot 100 \tag{1.14}$$

where O_i are the observed values, P_i are the predicted values, $\bar{\mathrm{O}}$ is the mean of the observed values, $\bar{\mathrm{P}}$ is the mean of the predicted values and n is the number of observations.

Model performance is considered better when R^2 and EF approach one, and when RRMSE and RME approach zero. Following Jamieson et al. (1991), model performance can be classified based on RRMSE values as excellent (RRMSE $<$ 10 %), good (10 % $<$ RRMSE $<$ 20 %), fair (20 % $<$ RRMSE $<$ 30 %) and poor (RRMSE $>$ 30 %).

Appendix A

AquaCrop input parameters

Table A.1: Aquacrop crop parameters

Parameter	Description	Units
anaer	Anaerobiotic point at which deficient aeration occurs	vol% below θ_{SAT}
ccs	Soil surface covered by an individual seedling at 90% emergence	cm^2
CCx	Maximum canopy cover	m^2 · m-2
cdc	Decrease in canopy cover	fraction · GDD-1 or fraction · day-1
cgc	Increase in canopy cover	fraction · GDD-1 or fraction · day-1
den	Number of plants per hectare	plants · ha-1
det	Crop determinancy linked (1) or unlinked (0) with flowering	
eme	Period from sowing to emergence	GDD or day
etos	ETo-sum to be exceeded during stress period before senescence is triggered	mm
evardc	Effect of canopy cover in reducing soil evaporation in late season stage	
exc	Excess of potential fruits	%
flo	Period from sowing to flowering/tuber formation	GDD or day
flolen	Length of flowering	GDD or day
fsink	Crop performance under elevated atmospheric CO2 concentration	%
fwpy	Ratio of water productivity normalized for ETo and CO2 during yield formation	%
hilen	Period of harvest index building-up during yield formation	GDD or day
hinc	Allowable maximum increase of specified HI	%
hingsto	Coefficient describing negative impact on HI of stomatal closure during yield formation	
hio	Reference harvest index	%
hipsflo	Possible increase of HI due to water stress before flowering	%
hipsveg	Coefficient describing positive impact on HI of restricted vegetative growth during yield formation	
kc	Crop coefficient when canopy is complete but prior to senescence	
kcdcl	Decline of crop coefficient as a result of ageing, nitrogen deficiency, etc.	% · day-1
m	Determination of crop cycle by calendar days (1) or by growing degree-days (0)	
mat	Total length of crop cycle from sowing to maturity	GDD or day
pexlw	Soil water depletion factor for canopy expansion - lower threshold	
pexshp	Shape factor for water stress coefficient for canopy expansion (0.0 = straight line)	
pexup	Soil water depletion factor for canopy expansion - upper threshold	
polmn	Minimum air temperature below which pollination starts to fail (cold stress)	°C
polmx	Maximum air temperature above which pollination starts to fail (heat stress)	°C
ppol	Soil water depletion factor for pollination - upper threshold	
psen	Soil water depletion factor for canopy senescence - upper threshold	
psenshp	Shape factor for water stress coefficient for canopy senescence (0.0 = straight line)	
psto	Soil water depletion fraction for stomatal control - upper threshold	
pstoshp	Shape factor for water stress coefficient for stomatal control (0.0 = straight line)	
root	Period from sowing to maximum rooting depth	GDD or day
rtexlw	Maximum root water extraction in bottom quarter of root zone	m3 · m-3 soil · day-1
rtexup	Maximum root water extraction in top quarter of root zone	m3 · m-3 soil · day-1
rtn	Minimum effective rooting depth	m
rtshp	Shape factor describing root zone expansion	
rtx	Maximum effective rooting depth	m
sen	Period from sowing to start senescence	GDD or day
sow	Crop is sown (1) or transplanted (2)	
stbio	Minimum growing degrees required for full biomass production	°C · day-1
tb	Base temperature below which crop development does not progress	°C
tup	Upper temperature above which crop development no longer increases with an increase in temperature	°C
typ	Crop type (1= leafy vegetable crop, 2 = fruit/grain producing, 3 = root/tuber)	
WP*	Water productivity normalized for ETo and CO2	g · m-2

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