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Introduction to AquaCrop

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Introduction to AquaCrop

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Main references:

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Slide 1

Title page

Slide 2

Structure of the presentation

1. The AquaCrop model

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Simulation has been used by engineers for more than 50 years. Simulation is done by means of mathematical models which are simplified representations of a particular system. A system is a part of the reality that the engineer wants to study. When designing a model to simulate crop development and yield, the soil-plant-atmosphere continuum (SPAC) should be considered as the system.

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In the model the engineer describes the interactions between the plant, the soil from which the plant extracts water and nutrients, and the atmosphere which determines the evaporative demand (ET_o) and supplies CO₂ and energy to grow. With such type of explanatory model, realistic estimations of crop yield can be simulated for various environmental conditions.

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Simulation combined with a limited number of field experiments to validate the results, is a good way to quickly obtain promising field management strategies. Further-on successful strategies applied in other regions or which are valid for other crops can be tested with the

help of the simulation model for the local climatic conditions and crop types. Simulation models are valuable for outscaling the experimental findings to new environments.

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Existing models require often an extended number of variables and input parameters not easily available for the diverse range of crops and sites around the world. Usually these variables are much more familiar to scientists than to end users. Furthermore, the insufficient transparency and simplicity of the model structure for the end use are considered a strong constraint. To address these constraints FAO has developed AquaCrop. When designing the model an optimum balance between simplicity, accuracy and robustness was pursued. To be widely applicable the model should use a relatively small number of explicit parameters and mostly-intuitive input-variables requiring simple methods for their determination. On the other hand the calculation procedures should be grounded on basic and the often complex biophysical processes to guarantee an accurate simulation of the response of the crop in the SPAC system. This resulted in 2007 in the release of the first version of the AquaCrop model.

2. Practical applications

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Practical applications

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AquaCrop estimates the crop yield that can be expected in a given environment. The environment is specified by the user as input. It consists of weather conditions (rainfall, air temperature and the evaporative demand of the atmosphere), soil (soil type and depth of the groundwater table) and plant characteristics, and field management practices (fertilizer management, irrigation, etc.). By altering the input, the expected crop production and yield can be simulated for different environmental conditions and the crop responses to environmental changes can be understood.

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AquaCrop can be used as a planning tool or to assist in management decisions for both irrigated and rainfed agriculture. AquaCrop is particularly useful:

- to understand the crop response to environmental conditions (educational tool).
- to design optimum management practices for the given environment such as planting date, cultivar selection, fertilization, irrigation, ...;
- to develop irrigation strategies under water deficit conditions by maximising the water productivity;
- to compare attainable against actual yields in a field, farm, or a region, to identify the constraints limiting crop production and water productivity (benchmarking tool);
- to study the effect of climate change on food production;
- to analyze scenarios for planning purposes for use by economists, water administrators and managers,
- to formulate guidelines for farmers to improve water productivity, etc

3. The calculation scheme

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In AquaCrop crop yield is simulated in four steps.

- Crop development, which consists of the development of a green canopy and the deepening of its root system;
- Crop transpiration, which is basically proportional to the simulated canopy cover;
- Plant biomass production, which is obtained by linking the biomass production to the simulated amount of water transpired by the crop;
- Crop yield, which is derived from the simulated biomass with the help of a harvest index.

▪ **Crop development**

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AquaCrop simulates (i) the development of the green canopy cover (above ground) and (ii) the deepening of the root system (below ground surface). In the simulation canopy expansion is separated from the expansion of the effective rooting depth. The interdependence between shoot and root is indirect via water stress.

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In AquaCrop foliage development is expressed through green canopy cover (CC) and not via Leaf Area Index (LAI). It introduces significant simplification in the simulation by consolidating leaf expansion growth, angle, and distribution to an overall grow function. The green canopy cover (CC) is the fraction of the soil surface covered by the canopy. It ranges from zero at sowing (0 % of the soil surface covered by the canopy) to a maximum value at mid season which can be 1 when a full canopy cover is reached (100 % of the soil surface covered by the canopy). The shadow of the canopy cover on the soil surface when the sun is right overhead is the canopy cover.

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One of the advantages of using CC is that it can be easily estimated (by eye) or measured in the field to check the simulated CC. Software is available to derive CC from pictures of the canopy taken overhead with a digital camera.

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The slide shows the development of the green canopy cover (CC) of winter wheat in Northwest Europe (Walshoutem, Belgium) starting from just after crop emerging in the late fall (20 October), 5 months later after winter at the start of spring (16 March), and at 14 April and 12 May at the start of summer when the canopy develops rapidly. The CC was determined by software from pictures of the canopy taken overhead with a digital camera.

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The canopy development for non-limiting conditions is described in AquaCrop with only a few parameters. A logistic equation describes canopy expansion till maximum canopy cover is reached. The equation requires information on (i) the canopy cover at germination (as determined by plant density), (ii) the maximum canopy cover that can be reached for the given plant density (might be smaller than 100 %) and (iii) the canopy growth coefficient. Once senescence starts, CC declines requiring (i) a canopy decline coefficient and (ii) the starting time. The growth and decline coefficients, the CC at germination and at full canopy cover and the length of growth stages are the only crop parameters required to simulate CC

for non limiting conditions. The parameters are retrieved from file at the start of the simulation when the crop is selected.

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In a schematic way the root zone can be considered as a reservoir in which the water content fluctuates as a result of incoming (rainfall, irrigation and capillary rise) and outgoing (runoff, evapotranspiration and deep percolation) water fluxes at its boundaries. When as a result of excessive rainfall or irrigation the soil water content exceeds field capacity (FC), the soil profile starts to drain returning its water content to FC. In the absence of any rainfall or irrigation, the water content in the root zone will drop as a result of evapotranspiration and might reach its minimum value which is permanent wilting point (PWP) at which the crop dies off.

By adjusting daily the soil water content in the soil profile, AquaCrop keeps track of the soil water balance in the root zone. The model considers various thresholds of soil water content (SWC). When SWC drops below one of the thresholds, soil water stress will affect a specific process. There is (1) a threshold for leaf and hence canopy expansion and (2) one for canopy senescence. Once SWC drops below the threshold for leaf expansion, the increase of CC is reduced and the canopy development becomes less than the expansion given for non limiting conditions. The stronger the water stress, the stronger the reduction in canopy expansion. When water stress becomes very severe the expansion will stop even completely. Similarly when the SWC drops below the threshold for senescence, early canopy senescence will be triggered.

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Given the canopy and root zone development for a specific crop for the non-limiting conditions (input retrieved from file once the crop is selected), AquaCrop will simulate at run time the actual canopy development by checking at each daily time step the soil water content (SWC) in the root zone. The canopy expansion will be hampered when SWC drops below the threshold for leaf expansion. Early canopy senescence will be triggered when SWC drops below the threshold for senescence.

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In AquaCrop simulation results are plotted in a number of graphs which are updated at the end of each daily time step, as illustrated by the print screen of the canopy cover (CC) in the slide. From the CC plot the user can follow throughout the simulation run the effect of water stress on canopy development. For reference the canopy development for non limiting conditions (CC_{pot}) is plotted in light gray in the back of the figure. The simulated green canopy cover might differ from CC_{pot} when water stress affects canopy development. It is plotted in green in the front of the picture.

Due to the absence of rain, canopy expansion started to be reduced quickly after germination (period 1) and subsequently it halted completely when the water stress became more severe (period 2). After rainfall (period 3) the soil water content (SWC) in the root zone ascended above the threshold for expansion and the canopy expansion was restored to its potential value. However water stress decreased once again the canopy development and after a while halted it completely (period 4). As a result the maximum canopy cover for non limiting conditions could not be reached. In period 5, water stress became so severe that the SWC dropped below the threshold for senescence, and canopy senescence was triggered and the

crop died off early. Due to the induced early canopy senescence, the crop life was much shorter than for the non-stressed conditions.

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Given (i) the canopy development for non-limiting conditions and (ii) the thresholds for the water content in the root zone affecting canopy expansion and early canopy senescence, AquaCrop simulates the actual canopy cover (CC) with the help of a soil water balance model. Each time the soil water content drops below a specific threshold, the corresponding growth process will be affected. This is also true for the deepening of the root zone. It will be affected when the soil water content in the root zone drops below its specific threshold.

▪ **Crop transpiration**

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Crop transpiration consists of the vaporization of liquid water in the intercellular spaces, and the vapour removal to the atmosphere through the stomata. It is basically proportional to the simulated canopy cover.

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In AquaCrop, crop transpiration for well watered conditions is calculated by multiplying the reference evapotranspiration (E_{To}) with a crop coefficient ($K_{c_{Tr}}$). The reference evapotranspiration is the evapotranspiration from a well watered reference grass surface. It expresses the evaporating power of the atmosphere and can be derived from the weather conditions. The crop coefficient is proportional to CC and hence varies throughout the life cycle of the crop in correspondence with the simulated canopy cover. The proportional factor ($K_{c_{Tr,x}}$) integrates the effects that distinguish the crop from the reference grass.

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Given the simulated canopy cover (CC) and the actual weather conditions, crop transpiration is calculated at each daily time step by multiplying E_{To} (which is derived from the given weather conditions) with $K_{c_{Tr}}$ (which is proportional to CC).

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Water stress does not only affect canopy development but also crop transpiration. Next to the thresholds for canopy expansion and for early canopy senescence there is also a specific threshold inducing stomata closure and hence affecting crop transpiration. Also this threshold is crop specific and given as an input.

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The effect of water stress on transpiration is simulated in AquaCrop by means of a water stress coefficient (K_s) which becomes smaller than 1 when the soil water content in the root zone drops below the threshold for stomata closure. The stronger the water stress, the smaller the value for K_s . At permanent wilting point (PWP) water stress will be so severe that K_s becomes zero and crop transpiration is completely halted.

▪ **Biomass production**

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In AquaCrop the development of the plant biomass is obtained by deriving crop production from the simulated amount of water transpired by the crop. When the stomata are open to remove water vapour (H_2O) to the atmosphere, green plants at the same time will absorb

carbon dioxide (CO₂) from the atmosphere and transport it through the stomata to the intercellular spaces. By photosynthesis the absorbed CO₂ and water is converted to carbohydrates in the presence of sunlight. The carbohydrates are the building stones for the plant biomass. There exists hence a direct link between crop transpiration and biomass production. If the crop is well watered, the stomata are wide open and the gas exchange between the intercellular spaces and the atmosphere will be important. If due to water stress the stomata are partly closed, both crop transpiration and the photosynthetic CO₂ assimilation (i.e. biomass production) are hampered.

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The stable and conservative nature between crop transpiration (Tr) and biomass production (B) is expressed by the biomass water productivity (WP) which is another crop parameter. It expresses the relation between the cumulative amount of crop transpiration (ΣTr) and the above ground biomass (B) produced. The more the crop transpires, the more biomass is produced. Since the relationship between ΣTr and B is linear, WP is given by the slope of the relationship. The crop water productivity (WP) expresses the aboveground dry matter (g or kg) produced per unit land area (m² or ha) per unit of water transpired (mm).

AquaCrop does not simulate lower hierarchical processes, those intermediary steps involved in the accumulation of biomass. The underlying processes are summarized and integrated into a single coefficient WP.

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Many experiments have shown that the relationship between biomass produced and water consumed by a given species is highly linear for a given climatic condition. As an example the biomass water productivity (WP) is plotted for sorghum, sunflower, chickpea and wheat as derived from field data. Since the relationship is specific for the climatic conditions (i.e. geographical location and time of planting) AquaCrop does not use WP for the simulation of aboveground biomass but a WP corrected for the effect of the climatic conditions, which is the normalized water productivity (WP^{*}). The goal of the normalization is to make WP applicable to diverse location and seasons. The normalization for climate is obtained by dividing the daily amount of water transpired (Tr) with the reference evapotranspiration (ET_o) for that day. After normalization, recent findings indicate that crops can be grouped in classes having a similar WP^{*}, which are depicted in the graph. Distinction can be made between C4 crops (such as sorghum) with a WP^{*} of about 30 to 35 g/m² (or 0.30 to 0.35 ton per ha) and C3 crops (such as sunflower, wheat, and chickpea) with a WP^{*} of about 15 to 20 g/m² (or 0.15 to 0.20 ton per ha).

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The slide shows the normalized biomass water productivity (WP^{*}) for maize. Field data from China, Ghana, Spain, USA, Hungary proofs that WP^{*} for maize does not change with the geographic location. WP^{*} is a conservative crop parameter which requires no adjustment to the local conditions.

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Using the normalized biomass water productivity (WP^{*}), AquaCrop calculates daily aboveground biomass production (B) from daily transpiration (Tr) and the corresponding daily evaporative demand of the atmosphere (ET_o).

- **Yield formation**

Slide 30

The last step in the calculation scheme of AquaCrop is the simulation of crop yield.

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The simulated above ground biomass (B) integrates all photosynthetic products assimilated by the crop during the season. By using a Harvest Index (HI), which is the fraction of B that is the harvestable product, crop yield (Y) is obtained from B.

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Using the Harvest Index (HI), AquaCrop calculates crop yield (Y) from the simulated above ground biomass (B). The reference Harvest Index is another crop parameter loaded from file once the crop is selected at the start of the simulation. During simulation, AquaCrop will however alter the Harvest Index from its reference value when water stress develops. The adjustment of HI to water deficits depends on the timing and extent of water stress during the crop cycle.

4. Input data

Slide 33

AquaCrop uses a relative small number of explicit parameters and largely intuitive input variables, either widely used or requiring simple methods for their determination. Input consists of weather data, crop and soil characteristics, and management practices that define the environment in which the crop will develop. Soil characteristics are divided into soil profile and groundwater characteristics and Management practices into two categories: field management and irrigation management practices

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The inputs are stored in climate, crop, soil and management files which can be retrieved in the Main Menu. The data can be easily adjusted through the user interface. By selecting files the environment is specified.

- **Climate (weather data)**

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For each day of the simulation period, AquaCrop requires reference evapotranspiration (ET_o) as a measure of evaporative demand of the atmosphere. ET_o is derived from weather station data by means of the FAO Penman-Monteith equation (as defined in the Irrigation and Drainage Paper N° 56). An ET_o calculator is available for that purpose. The calculator, which is public domain software, can be downloaded from the FAO website. The climatic data can be given in a wide variety of units, and procedures are available in the calculator to estimate missing climatic data.

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Other climatic data required for the simulations are the minimum (T_n) and maximum (T_x) air temperature, and rainfall. This is standard data collected in agro climatic station. The daily, 10-daily or monthly air temperature, ET_o and rainfall data for the specific environment are stored in climate files from where the program retrieves data at run time. In the absence of daily weather data, the program invokes built-in approximation procedures to derive daily temperature, ET_o and rainfall from the 10-daily or monthly means. For rainfall, with its

extremely heterogeneous distribution over time, the use of long-term mean data might reduce the accuracy of the simulations.

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Additional the mean annual CO₂ concentration has to be known. CO₂ concentration affects crop transpiration and most of all biomass water productivity (WP*). AquaCrop provides for that purpose an historical time series of mean annual atmospheric CO₂ concentrations measured at Mauna Loa Observatory in Hawaii, as well as the expected concentrations for the near future. The data is used to adjust the WP* to the CO₂ concentration of the year for which the simulation is running. The user can enter other future year's CO₂ for prospective analysis of climate change.

▪ **Crop characteristics**

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Crop characteristics are described by a set of parameters required for the simulation of the different processes of crop growth and production such as (i) the canopy development for non-limiting conditions, (ii) the biomass production (by means of WP*, the biomass water productivity normalized for climate), (iii) the yield formation (by means of H₁₀, the reference Harvest Index), (iv) the crop response to water, fertility and temperature stress (by means of thresholds for soil water depletion, air temperature, etc.), etc. Although grounded on basic and complex biophysical processes, AquaCrop uses a relative small number of crop parameters

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FAO has calibrated crop parameters for major agriculture crops, and provides them as default values in the model. When downloading crop data, distinction is made between conservative, cultivar specific and less conservative parameters:

- The conservative crop parameters do not change materially with time, management practices, or geographical location. They were calibrated with data of the crop grown under favorable and non-limiting conditions and remain applicable for stress conditions via their modulation by stress response functions. As such the conservative parameters require no adjustment to the local conditions and can be used as such in the simulations;
- The cultivar specific crop parameters might require an adjustment when selecting a cultivar different from the one considered for crop calibration. Less-conservative crop parameters are affected by field management, conditions in the soil profile, or the weather (especially when simulating in calendar day mode). These crop parameters might require an adjustment after downloading to account for the local variety and or local environmental conditions.

▪ **Soil profile characteristics**

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The soil profile can be composed of up to five different horizons of variable depth, each with their own physical characteristics. The hydraulic characteristics considered are the soil water content at saturation, field capacity (the upper limit of volumetric water holding capacity), and at permanent wilting point (the lower limit of water holding capacity), and the hydraulic conductivity at saturation. Infiltration and soil water movement are described by a dimensionless drainage coefficient (τ) which is derived from the saturated hydraulic conductivity of the soil horizon.

The user can make use of the indicative values provided by AquaCrop for various soil texture classes, or import locally determined or derived data from soil texture with the help of pedo-transfer functions.

- **Groundwater characteristics**

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The considered characteristics of the groundwater table are its depth below the soil surface and its salinity, which can vary throughout the year. If the groundwater is shallow, water and salts might move upward from the water table to the root zone by capillary rise. The amount of water transported upward is determined by the depth of the groundwater table, and characteristics and soil water content of the soil profile

- **Irrigation management practices**

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Under irrigation management the user chooses whether the crop is rainfed or irrigated. If irrigated, the user can select the application method (sprinkler, drip, or surface), and specify for each irrigation event, the irrigation water quality, the timing and the applied irrigation amount. There are also options to generate irrigation schedules based on specified time and depth criteria. Since the criteria might change during the season, the program provides the means to test deficit irrigation strategies by applying chosen amounts of water at various stages of crop development.

- **Field management practices**

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Under field management practices are choices of practices that affect the soil water balance such as soil bunds to store water on the field, and tillage practices such as soil ridging or contours reducing run-off of rain water.

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Other field management practices that affect the soil water balance are mulching which will reduce soil evaporation.

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AquaCrop also allow to select a soil fertility level. The fertility levels range from non-limiting to poor, and affect the biomass water productivity and canopy development. When selecting a fertility level, the affected crop parameters are automatic adjusted to the selected level. AquaCrop does not compute nutrient balances, but offers the semi quantitative options to assess the effects of the fertility regime on the canopy development and yield response.

5. Limitations

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Limitations

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The field is the spatial scale for which the simulations are valid. In the simulations of the soil water balance only vertical soil water fluxes are considered. Soil, management and environmental conditions are considered as uniform over the entire field.

The use of AquaCrop is restricted to annual crops with a single growth cycle.

6. Under development

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Regular new versions of AquaCrop are released. Check FAO web site for latest updates.
<http://www.fao.org/nr/water/aquacrop.html>

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Under the development are

- the introduction of new crop files;
- forage crops;
- extra field management strategies.