CROP YIELD SIMULATION USING AQUACROP MODEL UNDER RAINFED AND IRRIGATED CONDITIONS

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Introduction

Globally, it is well debated fact that the water productivity in agriculture needs to be raised in order to meet the increasing demand for food, which will double by 2050. Thus, on one hand, failure to develop and implement the technologies to enhance water productivity will result in use of more water in future to sustain the present level of agricultural production and on the other hand, use of water in excess of that required for crop growth will have a significant negative impact on ecosystem and livelihood of the region (FAO, 2006). Keeping view of the above, it is imperative to enhance the water productivity in agriculture. To accomplish this, there are broadly two options such as a) to improve productivity at the farm level through better management and use of improved varieties having drought resistance and higher yield potential and b) to optimize the use of land resources, irrigation and rainfed farming technologies and judicious management of surface and ground water resources. All this can be achieved by using appropriate tools to predict water productivity under different irrigation regimes or deficit irrigation approaches for different crops. The complexity of crop responses to water deficits led to the use of empirical production functions as the most practical option to assess crop yield response to water. However, the production functions developed using regression equations or empirical methods are purely location specific and these black box models have limited applicability to different crops, locations and management practices. Therefore use of physics based crop simulation models were preferred over the regression equations. Crop models developed so far rely on the physics based concept of soil, plant water and climatic interactions and these models have been used by different researchers.

The Crop Systems model (CropSyst) (Stockle et al., 2003) is a process based simulation model designed to predict the performance of multiple cropping systems across genotype, soil, weather and management combinations. Decision Support System of AgroTechnology Transfer (DSSAT) (Jones et al., 2003) comprises nine different crop modules including cereal crops viz. rice, wheat and maize which simulated different processes pertaining to the effect of soil, crop phenotype, weather and nutrient management options. By simulating probable outcomes of crop management strategies, DSSAT offers options for new crops, products, and practices for adoption. The World Food Studies crop growth model (WOFOST) is a mechanistic model in which the crop growth is simulated using the underlying processes of photosynthesis and respiration. The model describes crop growth as biomass accumulation in combination with phenological development (van Ittersum et al., 2003). However, most of these models require an extended number of variables and input parameters, which are not easily available for the diverse range of crops and sites around the world. Some models use generic data base with an assigned parameter values corroborating experimental data generated from the study region for calibration.
and validation purposes. Moreover, accurate modeling of crop response to water plays an important role in optimizing crop water productivity in agriculture (Geerts et al. 2009). There are a plethora of models that simulate the growth and development of maize and other cereal crops. The CERES-Maize (Crop Environment Resource Synthesis) model is a deterministic model designed to simulate maize growth, soil, water and temperature and nitrogen dynamics at a field scale (Jones et al., 1986). The input data required by most of these models are difficult to obtain or require detailed empirical measurements to establish hybrid-specific genetic coefficients as inputs to run the model and these can be suitably applied to the locations for which these are calibrated. Besides this, the models require more number of input parameters which is difficult to generate from field experiments and the crop growth engines are not water driven, i.e. separate module to account for crop growth responses under variable water supply situations is not available. Keeping in view of these limitations, a crop water productivity model AquaCrop was developed by the Land and Water Division of FAO and released for use during 2009 (Steduto et al., 2009; Raes et al., 2009). AquaCrop is a water-driven crop model to simulate yield response to water of several herbaceous crops. It is designed to balance simplicity, accuracy and robustness, and is particularly suited to address conditions where water is a key limiting factor in crop production. The AquaCrop model has been parameterised and validated for simulating maize yield response to water (Hsiao et al. 2009; Heng et al. 2009). Although AquaCrop is based on complex crop physiological processes, it uses a relatively small number of explicit and mostly intuitive parameters with simplicity and accuracy (Steduto et al., 2009; Raes et al., 2009). Some of the advantages of AquaCrop are: a) it is widely applicable with acceptable accuracy; b) it requires only commonly available input (i.e. climate, soil, crop and field data); c) it allows easy verification of simulation results with simple field observations. In an attempt to compare performance of AquaCrop, CropSyst, and WOFOST Models, Todorovic et al. (2009) simulated sunflower (Helianthus annuus L.) growth under different water regimes in a Mediterranean environment. These three models differ in the level of complexity describing the crop development in the main growth modules driving the simulation of biomass growth, and in the number of input parameters. AquaCrop is exclusively based on the water-driven growth module, in which the transpiration is converted into biomass through water productivity (WP) parameter. The CropSyst model is based on both water and radiation driven modules, while WOFOST simulates crop growth using a carbon driven approach and fraction of intercepted radiation. The models were calibrated on data from a full irrigation treatment in 2007, and were validated on a full irrigation treatment in 2005 and several deficit irrigation (DI) treatments, including regulated deficit irrigation (RDI) and rain-fed (RF) conditions. Although AquaCrop required less input information than CropSyst and WOFOST, it performed at par with them in simulating both biomass and yield. Use of minimal data input and water-driven crop growth module of AquaCrop resulted in simulated yield in line with the data intensive and radiation driven CropSyst and WOFOST models. Therefore, it can be recommended that under conditions of limited input information and yield predictions under variable water supply situations, the AquaCrop model should be preferred over other models and the use of simpler models should be encouraged.
Governing equations and concepts of FAO AquaCrop model

AquaCrop model is based on the crop growth engine which is basically water driven, in which, the crop growth and production are driven by the amount of water used through consumptive use of the plant. Among the empirical function approaches, FAO Irrigation & Drainage Paper n. 33 (Doorenbos and Kassam, 1979) represented an important source to determine the yield response to water of field, vegetable and tree crops, through the following equation

\[
\frac{Y_s - Y}{Y_s} = K_y \left( \frac{ET_s - ET}{ET_s} \right)
\]

Eq.1

where, Yx and Y are the maximum and actual yield, ETx and ET are the maximum and actual evapotranspiration, and Ky is the proportionality factor between relative yield loss and relative reduction in evapotranspiration. There was a constant scientific and experimental progress in crop-water relations from 1979 till date, which led to a revision framework that treats separately field crops from tree crops. For the field crops, it was suggested to develop a model of proper structure and conceptualization that would evolve from Eq.1 and be designed for planning, management and scenario simulations. The result is the AquaCrop model which differs from the main existing models for its balance between accuracy, simplicity and robustness. AquaCrop is a FAO’s crop water productivity simulation model. AquaCrop evolves from the previous Doorenbos and Kassam (1979) approach (Eq. 1) by separating (i) the ET into soil evaporation (E) and crop transpiration (Tr) and (ii) the final yield (Y) into biomass (B) and harvest index (HI). The separation of ET into E and Tr avoids the confusing effect of the non-productive consumptive use of water (E), especially during incomplete ground cover. The separation of Y into B and HI allows the distinction of the basic functional relations between environment and B from those between environment and HI and also avoids the confusing effects of water stress on B and on HI. The changes led to the following equation for the AquaCrop model

\[
B = WP \times \sum T_r
\]

Eq.2

Where, Tr is the crop transpiration (in mm) and WP is the water productivity parameter (kg of biomass per m2 and per mm of cumulated water transpired over the time period in which the biomass is produced). The main change from Eq. 1 to AquaCrop is in the time scale used for each one. In the case of Eq. 1, the relationship is used seasonally or for long periods (of the order of months), while in the case of Eq. 2 the relationship is used for daily time steps, a period that is closer to the time scale of crop responses to water deficits. A schematic representation of the evolution of AquaCrop is shown in Fig. 1
Equation 1 is based on two intermediary steps *i.e.* separation of soil evaporation (E) from crop transpiration (Tr) and the attainment of yield (Y) from biomass (B) and harvest index (HI). AquaCrop has a structure that is based on the soil-plant-atmosphere continuum. It includes the soil, with its water balance; the plant, with its development, growth and yield processes; and the atmosphere, with its thermal regime, rainfall, evaporative demand and carbon dioxide concentration. Additionally, some management aspects are explicitly considered (*e.g.*, irrigation, fertilization, etc.), as they will affect the soil water balance, crop development and final yield. The functional relationships between the different model components are shown in the following flow chart. The model details as mentioned in this document is excerpted from [www.fao.org/nr/water/aquacrop.html](http://www.fao.org/nr/water/aquacrop.html) and further details can be referred from this source.
Fig. 2. Flowchart of AquaCrop indicating the main components of soil-plant-atmosphere continuum

**Input data requirement of AquaCrop Model**

**A. Environment and Crop Data**

1. Climate
   - i. Daily /10 days/monthly Rainfall
   - ii. Daily /10 days/monthly $E_T$
   - iii. Daily /10 days/monthly Temperature
   - iv. $CO_2$ concentration

2. Crop
   - i. limited set (crop development and production parameter which include phonology and life cycle Length)
   - ii. Full or all crop parameters
     - a. Crop development at no water, fertility and Salinity stress
     - b. Evapotranspiration
c. Crop water productivity  
d. Water stresses  
e. Air temperature stresses  
f. Soil salinity stress  
g. Effect of soil fertility stress  
h. Calendar of growing cycle  

3. Management  
i. Irrigation type  

ii. Field  
a. Soil fertility  
b. Mulches  
c. Field surface practices  

Surface run off  
Soil bund  
Occurrence  

4. Soil  
i. Soil profile  
b. Soil surface  
   (runoff, evaporation)  
c. Restrictive soil layer  
d. Capillary rise  

ii. Ground water (constant or varying depth and water quality)  

a. Characteristics of soil horizon  
   (no. of soil horizon, thickness, PWP, FC, SAT, $K_{sat}$)
B. Simulation data

1. Simulation period (linked to growing season)
2. Initial condition

![Diagram showing the flow of data input: Simulation period, Initial condition, Initial soil water content, soil layer thickness, soil salinity.]

All these input data were used in the model to predict the yield, water productivity, biomass and harvest index of a given crop. However, the model should be calibrated and validated using the data acquired from field experiments for its further use.

Case Study: (Calibration and validation of FAO AquaCrop for kharif Maize under rainfed and irrigated situations)

AquaCrop model, developed by FAO was calibrated and validated for kharif maize crop (BIO-9681) under varying irrigation and nitrogen regimes. The experiment was conducted at the research farm of the Water Technology Centre, IARI, New Delhi during kharif 2009 and 2010. Calibration was done using the data of 2009 and validation with the data of 2010. Irrigation applications comprised rainfed i.e., no irrigation (W₁) irrigation at 50% of field capacity (FC) (W₂) at 75% FC (W₃) and full irrigation (W₄). Nitrogen application levels were no nitrogen (N₁), 75 kg ha⁻¹ (N₂) and 150 kg ha⁻¹ (N₃). Model efficiency (E), coefficient of determination (R²), Root Mean Square error (RMSE) and Mean Absolute Error (MAE) were used to test the model performance. The model was calibrated for simulating maize grain and biomass yield for all treatment levels with the prediction error statistics 0.95<E<0.99, 0.29<RMSE<0.42, 0.9<R²<0.91 and 0.17<MAE<0.51 t ha⁻¹. Upon validation, E between 0.95 and 0.98; MAE between 0.11 and 1.08 and RMSE between 0.1 and 0.75 for grain and biomass yield, respectively. The prediction error in simulation of grain yield and biomass under all irrigation and nitrogen levels ranged from a minimum of 0.47% to 5.91% and maximum of 4.36% to 11.05%, respectively. The highest and the lowest accuracy to predict yield and biomass was obtained at W₄N₃ and W₁N₁ treatments, respectively. The model prediction error in simulating the water productivity (WP) varied from 2.35% to 27.5% for different irrigation and nitrogen levels (Fig 3
to Fig.5). Over all, the FAO AquaCrop model predicted maize yield with acceptable accuracy under variable irrigation and nitrogen levels (Abedinpour et al., 2012).

**Fig. 3** Model calibration results for biomass yield under all irrigation and nitrogen levels

Biomass = 0.674x + 4.122

R² = 0.91
RMSE=0.42
E=0.95
MAE=0.98

**Fig. 4** Model calibration results for grain yield under all irrigation and nitrogen levels

Yield = 1.027x
R² = 0.90
RMSE=0.29
E=0.99
MAE=0.17
Advantage of AquaCrop over other crop growth simulation models

- Canopy development expressed as canopy cover (CC) of the ground and not through leaf area index (LAI). This offers a significant simplification in the simulation by reducing canopy development with time to a sigmoid function using a canopy growth coefficient. Senescence of the canopy is simulated with a decline function.
- Root development is expressed in terms of effective rooting depth as a function of time. A functional relationship is also established between roots and shoots development.
- Biomass (B) is calculated using WP and Tr. WP is normalized for climate (atmospheric evaporative demand and carbon dioxide) so that it can be used in different climatic zones in space and time. WP is also partially affected by fertility levels.
- Yield (Y) is calculated as the product of B and HI. HI increases mostly linearly with time, starting after pollination and until near physiological maturity.
- Water stress is expressed through stress coefficients (Ks) specific of each basic growth expression. These are canopy expansion, stomatal control of transpiration (gs), canopy senescence and harvest index.
- AquaCrop uses a relatively small number of explicit and mostly-intuitive parameters and input variables.

Applications of AquaCrop model:

- Assessing water-limited, attainable crop yields at a given geographical location
- As a benchmarking tool, comparing the attainable yields against actual yields of a field, farm, or region, to identify the yield gap and the constraints limiting crop production
- Assessing rainfed crop production on the long term
- Developing irrigation schedules for maximum production (seasonal strategies and operational decision-making), and for different climate scenarios
- Scheduling deficit and supplemental irrigation
• Evaluating the impact of fixed delivery irrigation schedules on attainable yields
• Simulating crop sequences
• Carrying out future climate scenario analyses
• Optimizing a limited amount of water available (economic, equitability, and sustainability criteria)
• Evaluating the impact of low fertility and of water-fertility interactions on yields
• Assessing actual water productivity (biological and/or economic) at the field and higher scales, up to regions
• Supporting decision making on water allocation and other water policy actions
• Appraising the role of various water-related crop responses in yield determination for ideotype design

Conclusions
The AquaCrop model predicts yield of a crop through crop physiological responses based on different irrigation regimes and rainfed situations. The model have been successfully calibrated and validated for different crops and vegetables. The salinity module of AquaCrop is under development and can provide the crop response under irrigated saline environment. The AquaCrop model is useful for developing irrigation strategies under water deficit situations; preparation of the most suitable crop calendar under rainfed agriculture; obtaining yield estimates for field crops under a variety of environmental conditions besides salinity; impact of climate change on future yield and water productivity of different crops and climate change and irrigation management, project planning, and scenario simulations at different scales.

References
FAO, 2009. How to feed the world in 2050. Issue brief from the High-Level Expert Forum held in Rome, 12-13 October. FAO, Rome, Italy


