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Short communication

AquaCrop-OS: An open source version of FAO's crop water productivity model

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ABSTRACT

Crop simulation models are valuable tools for quantifying crop yield response to water, and for devising strategies to improve agricultural water management. However, applicability of the majority of crop models is limited greatly by a failure to provide open-access to model source code. In this study, we present an open-source version of the FAO AquaCrop model, which simulates efficiently water-limited crop production across diverse environmental and agronomic conditions. Our model, called AquaCrop-OpenSource (AquaCrop-OS), can be run in multiple programming languages and operating systems. Support for parallel execution reduces significantly simulation times when applying the model in large geospatial frameworks, for long-run policy analysis, or for uncertainty assessment. Furthermore, AquaCrop-OS is compliant with the Open Modelling Interface standard facilitating linkage to other disciplinary models, for example to guide integrated water resources planning.

1. Introduction

There is an urgent need to increase the efficiency and productivity of agricultural water use in response to growing pressures on finite water resources worldwide (Schewe et al., 2014; Taylor, 2014; Richey et al., 2015). Critically, tackling this challenge will require a sound understanding of the biophysical response of crop yield to water (Steduto et al., 2012). The relationship between crop yield and water supply traditionally has been based on empirical production functions (Doorenbos and Kassam, 1979), which cannot be extrapolated reliably beyond the location for which they were developed. Calibrated crop simulation models therefore increasingly are being used an alternative means for rapid assessment of water-limited crop yield over a wide range of environmental and management conditions (Grassini et al., 2011; García-Vila and Fereres, 2012; van Ittersum et al., 2013; Foster et al., 2014).

A range of crop simulation models have been reported in the literature (e.g., DSSAT, Jones et al., 2003; CropSyst, Stöckle et al., 2003; APSIM, Keating et al., 2003; Hybrid-Maize, Yang et al., 2004). However, a common feature of the majority of these models is the requirement for highly detailed input data and information about crop growth that are not available in most locations worldwide. To address these limitations, FAO developed AquaCrop in 2009. AquaCrop is a multi-crop model that simulates the water-limited yield of herbaceous crop types under different biophysical and management conditions (Raes et al., 2009; Steduto et al., 2009). It requires a relatively small number of explicit and mostly-intuitive parameters to be defined compared to other crop models, and has been validated and applied successfully for multiple crop types across a wide range of environmental and agronomic settings (for a recent review see Vanuytrecht et al., 2014a).

A limitation of AquaCrop, and indeed most crop and environmental models, is that the model is distributed solely as a compiled software package (Raes et al., 2016b). This constrains applicability, in particular for interdisciplinary policy analysis where a user may want to link AquaCrop directly with other models or adapt the code

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for the specific purposes of their study (e.g., Bulatewicz et al., 2010; Girard et al., 2015). Moreover, despite the extensive documentation of AquaCrop procedures (Steduto et al., 2009; Raes et al., 2009, 2016b), lack of open access to the source code limits transparency by making it difficult for a user to reproduce model calculations and evaluate fully the influence of internal model structure on simulation outputs (Ince et al., 2012; Peng, 2012). Indeed, open access to crop model source codes and data is a key principle of a number of major initiatives to improve assessment and management of global food security, including the Agricultural Model Intercomparison and Improvement (AgMIP) (Rosenzweig et al., 2013) and Modelling European Agriculture with Climate Change for food Security (MACSUR) (FACCE-MACSUR, 2016) programs.

In this paper, we describe the development of an open-source version of AquaCrop, called AquaCrop-OpenSource (AquaCrop-OS). AquaCrop-OS has a number of innovative features, which are described in detail in the following sections. AquaCrop-OS is implemented in Matlab (Mathworks Inc., 2015), and is also fully compatible with the freely available GNU Octave language (Eaton et al., 2015). Unlike the original AquaCrop model that is coded in Delphi and distributed as a Windows executable program, AquaCrop-OS can be run on Windows, Macintosh, and Linux operating systems. Furthermore, the model includes capability for parallelization of simulations to reduce batch run times when conducting simulations over large areas, conditions, and/or time periods. Finally, AquaCrop-OS is also complaint with the Open Modelling Interface (OpenMI) standard, enabling the code to be linked quickly with other disciplinary models to support integrated water resource management. The model source code, along with a user manual, is freely available for non-commercial research and education purposes, and will be distributed via a dedicated website (www.aquacropos.com).

2. Concept of AquaCrop

First, it is important to provide a brief overview of the key concepts in AquaCrop. AquaCrop was designed as an evolution from the original FAO Irrigation Drainage Paper 33 (Doorenbos and Kassam, 1979), which represents yield response to water as a linear, crop-specific function of the ratio of actual to potential evapotranspiration over a growing season. In contrast, AquaCrop simulates soil water balance and crop growth processes as a function of crop, soil, weather, and management input data, on a daily time step. In addition, AquaCrop simulates soil evaporation and crop transpiration explicitly as individual processes. The productive portion of water consumption (i.e. transpiration) is used to estimate biomass accumulated each day, using a crop-specific water productivity parameter that is normalized for reference evapotranspiration (Steduto et al., 2007), making the parameter applicable to a wide range of climates. Subsequently, the proportion of biomass that becomes harvestable yield is calculated using a harvest index parameter that increases over the growing season and responds to water and temperature stresses. It is important to note that AquaCrop is designed to simulate the growth, biomass production, and harvestable yield of herbaceous crop types. The model is not intended currently to simulate perennial tree crops or vines (Steduto et al., 2012), for which yield response to water and biomass partitioning processes are significantly more complex and less well understood.

AquaCrop is distinguished from other crop models by several unique features. First, canopy expansion is simulated in terms of proportional green canopy cover as opposed to leaf area index. This approach has the advantage that simulated model outputs can be related directly to easily accessible data from visual field observations and remote sensing. For example, vegetation indices obtained from earth observation satellites correlate strongly with fractional green canopy cover (Carlson and Ripley, 1997; Calera et al., 2001; Jiang et al., 2006; Johnson and Trout, 2012), enabling use of such indices (e.g. NDVI) to calibrate and validate AquaCrop simulation outputs rapidly over large regional domains (e.g. Kim and Kaluarachchi, 2015). Second, AquaCrop accounts for a broader range of water stress impacts on transpiration than most other water-driven crop models. Specifically, AquaCrop considers water stress impacts on transpiration caused not only by stomatal closure, but also by reductions in leaf expansion and premature canopy senescence. Finally, AquaCrop accounts for the dynamic effects of a range of environmental stressors, especially water and temperature, on crop growth, and captures the impact of elevated atmospheric carbon dioxide concentrations on crop water productivity. The effects of soil fertility and salinity stresses are also considered indirectly by the model based on local calibration to relative biomass under different fertility and salinity conditions. Each environmental stress effect is simulated in AquaCrop by specifying an upper threshold at which crop growth begins to be stressed, a lower threshold at which growth is fully inhibited by stress, and a shape parameter that the determines the magnitude of the stress effect on crop growth processes between these bounds. The physical definition of the upper and lower stress thresholds differs depending between each type of environmental stressor. For example, thresholds are expressed in terms of root zone soil moisture depletion for water stress and in terms of soil electrical conductivity for salinity stress. Importantly, stress thresholds and responses also differ between crop types, reflecting the fact that certain crops will be more or less sensitive to different environmental stress effects. For further information about AquaCrop algorithms and procedures, the reader is referred to the associated publications (Raes et al., 2009; Steduto et al., 2009, 2012; Vanuytrecht et al., 2014a) and model manual (Raes et al., 2016b).

3. AquaCrop-OS

3.1. Structure and key features

The AquaCrop-OS software is structured in to three core functions:

1. 'AOS_Initialize.m' that reads and initializes model parameters and initial conditions from a set of text files, which define crop, soil, weather, management, and time inputs for the simulation.
2. 'AOS_PerformTimeStep.m' that executes a single daily time-step of the model, using a range of functions ('AOS_X.m') that perform AquaCrop calculation procedures (e.g., soil evaporation, root development).
3. 'AOS_Finish.m' that finalizes the model simulation and writes output files describing simulated processes (water contents, water fluxes, crop growth) at both daily and seasonal timescales.

Two scripts are provided to run the model source code: (1) 'AquaCropOS_RUN.m' that can be used to perform a single simulation for one or more growing seasons, holding all other parameters constant, and (2) 'AquaCropOS_BatchRUN.m' that can be used to execute multiple individual simulations as a batch run. An important feature of the model is that the 'AquaCropOS_BatchRUN.m' script can be run in parallel using Matlab's Parallel Computing Toolbox (Mathworks Inc., 2015), or Octave's Parallel Package (Eaton et al., 2015). The user must define separate sets of input files for each simulation run, and then execute the batch simulation in parallel.

The ability to execute simulations in parallel, which is not a feature of the original AquaCrop model, can provide significant computational savings when running large numbers of simulations,

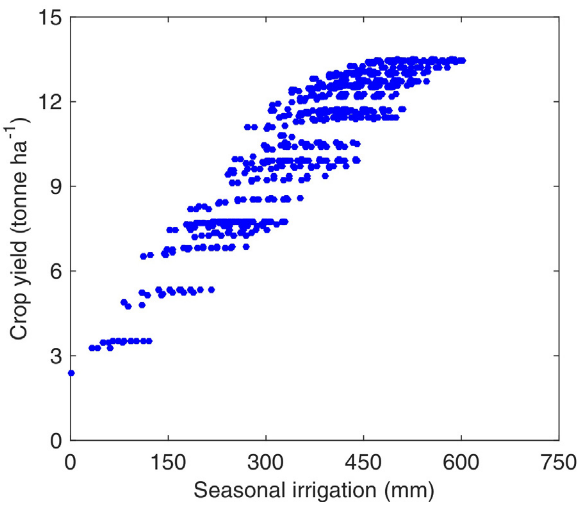

Fig. 1. Simulated relationship between seasonal applied irrigation and crop yield for a maize crop in Nebraska, USA. Each data point represents the output from a simulation using AquaCrop-OS for a specific intraseasonal irrigation strategy averaged over 30 growing seasons (1986–2015).

for example to assess crop production in a geospatial framework (Bulatewicz et al., 2010; Thorp and Bronson, 2013), to analyze impacts of long-term climate change (Ewert et al., 2015), to conduct parameter uncertainty analysis (Vanuytrecht et al., 2014b), or to estimate costs and benefits of alternative irrigation management strategies (Foster et al., 2014; Chukalla et al., 2015). To illustrate the potential time savings offered by parallelization, we perform a set of simulations to develop crop-water production functions that are key inputs to hydro-economic analysis of agricultural water management (García-Vila and Fereres, 2012; Foster et al., 2014).

In order to generate crop-water production functions, data points are required that describe crop yield return to different levels of seasonal applied irrigation. However, crop yield for a given seasonal irrigation depends on irrigation scheduling and the weather conditions within a growing season. Considering a scenario where a farmer triggers irrigation once soil moisture falls below a specified target, and that this target level may be varied from 30% to 80% depletion of total available water (i.e. the water held between permanent wilting point and field capacity) in increments of 10% in each of the four main crop growth stages, yields a total of 1297 potential intraseasonal irrigation strategies. We simulate each irrigation strategy over a 30-year period (1986–2015) for a maize crop in Nebraska, USA, using input parameters described in Foster et al. (2015a). Fig. 1 shows the output from these simulations, which required a total of approximately 1.7 h on an Intel Xeon 3.30 GHz quad-core computer. This equates to a time saving of 86% when compared with a simulation time of approximately 12.6 h using the AquaCrop PlugIn program (Raes et al., 2016a), which is designed to run batch sets of pre-defined simulations outside the main AquaCrop graphical user interface. Time savings could also be further enhanced by running simulations on an external cluster with a larger number of available CPU's. Note that these time savings do not consider pre-processing requirements (i.e. the time to create input files) as we assume that this can be effectively automated using user-defined scripts for AquaCrop-OS, or the AquaData utility that has been developed for the original FAO AquaCrop model by Lorite et al. (2013).

The structure of the AquaCrop-OS model also provides a number of advantages for model integration and interdisciplinary water policy analysis. Direct access to the model source code means that users can readily link the model to external code and databases. For example, in previous work, we have linked preliminary versions of the AquaCrop-OS model with an economic model to predict how climate variability and water scarcity affect farmers' economically optimal field level decisions about groundwater-fed irrigation (Foster et al., 2014, 2015a,b).

Furthermore, the design of the AquaCrop-OS model engine using three core functions ('AOS_Initialize.m', 'AOS_PreformTimeStep.m', and 'AOS_Finish.m') ensures compliance with the requirements of the Open Modelling Interface (OpenMI). The OpenMI defines a standard for the exchange of data between different models, enabling models that operate at different spatial and temporal scales, and which may be coded in different programming languages, to be linked and run simultaneously (Moore and Tindall, 2005; Gregersen et al., 2007). With minimal additional work from the user, AquaCrop-OS could be quickly integrated with other disciplinary codes (e.g. hydrologic, economic, or climate models) through the OpenMI to evaluate feedbacks between natural and human components of irrigated agricultural systems and to devise innovative water management policies. Specifically, implementing AquaCrop-OS in the OpenMI would require the following steps:

1. Addition of 'GetValues' and 'SetValues' functions (Gregersen et al., 2007) to specify the desired data exchanges to/from AquaCrop-OS and other models. For example, AquaCrop-OS could provide daily hydrological fluxes (e.g. irrigation, evapotranspiration, runoff, deep percolation) to a hydrological model, which would in turn return information about water availability for irrigation. AquaCrop-OS could also receive annual information about crop choices and management practices from an external economic component.
2. Development, or modification, of an appropriate model wrapper to facilitate exchange of data and model execution through the OpenMI at run-time. A promising existing tool is the Simple Script Wrapper (Bulatewicz et al., 2013), which was developed explicitly to facilitate linking models developed in scripted languages, such as Matlab, via OpenMI.

3.2. Testing and evaluation

AquaCrop-OS was developed from scratch using the calculation procedures and equations reported in the AquaCrop manual (Raes et al., 2016b), with additional input from FAO model developers where procedures were unclear or discrepancies in model outputs were encountered. We have performed a range of test simulations to ensure that AquaCrop-OS reproduces accurately the calculation procedures and outputs from the most recent release, v5.0, of the FAO AquaCrop model. Our test simulations were drawn from exercises developed by FAO for AquaCrop training workshops (Van Gaelen and Raes, 2016). Test simulations consider three different production systems, which capture the range of environments and crop types that can be modeled using AquaCrop: (1) Wheat production in Tunis, Tunisia; (2) Cereal (rice and wheat) production in Hyderabad, India; (3) Potato production in Brussels, Belgium. For each system, different simulations are conducted to evaluate the ability of AquaCrop-OS to reproduce fully model outputs under different environmental conditions (e.g., soil types, antecedent moisture contents, atmospheric carbon dioxide concentrations) and management practices (e.g., planting dates, irrigation strategies). Comparing the AquaCrop-OS outputs with those simulated by AquaCrop v5.0, the maximum RMSE error and minimum r^2 for simulated crop yields across the full set of simulations were 0.045 tonne ha^{-1} and 0.993, respectively, with the very minor discrepancies in model outputs caused by differences in rounding of outputs by the two models. A detailed description of the test simulations and results is provided in the accompanying supplementary material. Note that test simulations did not consider conditions of limited soil fertility or elevated soil salinity.

These features of AquaCrop are not included in the initial release (v5.0a) of AquaCrop-OS, and will be introduced as part of future model development (see Section 4).

4. Summary and outlook

AquaCrop-OS is an open-source version of FAO's crop water productivity model, AquaCrop. The AquaCrop-OS source code and documentation are freely available for non-commercial purposes, and the model can be run across multiple languages (Matlab and Octave) and operating systems (Windows, Macintosh, and Linux). AquaCrop-OS introduces two important advances to the original FAO AquaCrop model. First, it supports parallel execution of model simulations, greatly reducing run times when large numbers of simulations must be performed. This feature will improve significantly the applicability of AquaCrop, in particular for studies evaluating crop water productivity and water demands over large spatial areas or under future climate change. Second, by providing access to the model source code, AquaCrop-OS increases capacity for users to link the model with other disciplinary tools, for example to perform integrated water policy analysis in agricultural regions experiencing growing pressure on finite water resources.

A dedicated website (http://www.aquacropos.com) has been developed and will be used for long-term distribution of the AquaCrop-OS model and associated documentation. We will work collaboratively with FAO to develop and upload new releases of AquaCrop-OS, which will track in a timely manner modifications and new additions to the procedures in the original AquaCrop model. Future releases will also incorporate two current features of AquaCrop, namely soil salinity and fertility effects on crop growth, that have not been included in the initial release (v5.0a) of AquaCrop-OS. Furthermore, we will also develop additional features to enable users to translate automatically input files developed in the original AquaCrop model (e.g. as part of previous projects) in to formatted input files needed to perform simulations in AquaCrop-OS. Finally, we will also encourage users of the AquaCrop-OS model to share feedback on the code and provide examples of their specific applications and data. It is our hope that these will contribute to an open database of examples and tutorials that will inform learning and research on the use of crop models to tackle global challenges of food and water security.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agwat.2016.11.015.

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