PERFORMANCE REVIEW OF AQUACROP - THE FAO CROP-WATER PRODUCTIVITY MODEL

EXAMEN CRITIQUE DE L'AQUACROP – MODELE DE LA FAO SUR LA PRODUCTIVITE EN EAU DES CULTURES

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ABSTRACT

This article introduces the FAO crop model AquaCrop and its performance as reported from most of the users around the world from its launch in January 2009.

The model simulates yields of herbaceous crops as a function of water consumption. Growth is calculated by translating transpiration into biomass using a conservative, crop-specific parameter: the biomass water productivity, normalized for atmospheric evaporative demand and air CO_2 concentration. The normalization allows AquaCrop to be applicable to diverse locations and seasons. Simulations are carried out in daily time-steps, using canopy ground cover instead of leaf area index (LAI) as the basis to calculate transpiration and to separate out soil evaporation from transpiration. Yield is calculated as the product of biomass and harvest index (HI). Other than for the yield, there is no biomass partitioning into the various organs. Crop responses to water deficits are simulated with four modifiers that are functions of fractional available soil water, modulated by evaporative demand, based on the sensitivity to water stress of four key plant processes: canopy expansion, stomatal control of transpiration, canopy senescence, and harvest index.

AquaCrop distinguishes itself from the other models existing in the literature because of its reduced complexity in simulating crop growth and yield.

AquaCrop has been used to simulate different crops and farming conditions in several Regions

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around the world, from West and South Africa, to Near East, to Asia. Overall, the users find AquaCrop explicit and mostly intuitive, appreciate the use of a relatively small number of parameters and the good balance between simplicity, accuracy and robustness, and value very positively its performance. The model has been used successfully also for the evaluation of climate change impact on crop yield in the lower Mekong basin.

Key words: *AquaCrop, Crop-water productivity model, Harvest index.*

RESUME ET CONCLUSIONS

Le nouveau modèle de la FAO sur la productivité en eau des cultures - AquaCrop - simule la réponse en terme de rendements des cultures herbacées à l'apport en eau (Steduto et al., 2009 ; Raes et al., 2009). Ce modèle est particulièrement adapté pour améliorer les conditions où l'eau est un facteur limitant de la production agricole. Il a été conçu pour atteindre un équilibre optimal entre simplicité, précision et robustesse, tout en minimisant le nombre de variables et de paramètres d'entrée, explicites et intuitifs. Il est destiné aux praticiens, ceux qui travaillent pour les services de vulgarisation, les agences gouvernementales, les ONG, et les divers types d'associations d'agriculteurs. Il est également intéressant pour les scientifiques et à des fins pédagogiques.

L'AquaCrop a été conçu pour un large éventail d'applications, y compris la prévision de rendement dans les scénarios de changement climatique. Il se distingue des autres modèles existants dans la littérature, car son architecture réduit la complexité de la croissance des cultures et du rendement en ciblant les processus de base. Il adopte un critère de simplification qui permet un équilibre malgré les incertitudes des différents algorithmes et qui évite les sophistications inutiles. En fait, le moteur de croissance de l'AquaCrop est mû par l'eau, puisque c'est la transpiration qui est calculée d'abord puis traduite en utilisant un paramètre de conservation spécifique aux plantes : la productivité de l'eau utilisée de la biomasse, normalisée pour la demande d'évaporation de l'atmosphère et la concentration de l'air en CO2. La normalisation vise à rendre applicable AquaCrop à différents endroits et saisons. Le modèle, fonctionnant en étapes - temps journalières, utilise la couverture du sol au lieu de l'indice foliaire (LAI) comme base de calcul de la transpiration et pour séparer l'évaporation du sol de la transpiration. Le rendement des cultures est calculé comme un produit de l'indice de biomasse et de l'indice de récolte (HI). Hormis part pour le rendement, il n'y a pas de partage de la biomasse entre les différents organes.

La réponse des cultures au déficit en eau est simulée avec quatre modificateurs qui sont des fonctions de la fraction d'eau du sol disponible modulé par la demande en évaporation; celle-ci est basée sur la sensibilité différentielle au stress hydrique de quatre processus clés des plantes: l'expansion de la canopée, le contrôle de la transpiration stomatique, la sénescence du couvert, et HI.

Après son lancement dans le domaine public en Janvier 2009, AquaCrop a été utilisé pour simuler les différentes cultures et les conditions de gestion de l'agriculture dans plusieurs régions du monde permettant des tests indépendants de la performance du modèle.

En particulier, AquaCrop a été utilisé pour simuler: le mais irrigué et le maïs avec déficit en eau (Heng et al, 2009.); le coton irriguée en continu et celui irrigué en supplémentaire (Farahani *et el 2009; García-Vila et al, 2009..); le degré de réponse du rendement de la quinoa à l'eau (Gaerts et al, 2009, 2010.), la croissance du tournesol selon différent régimes d'apport en eau et comparé à d'autres modèles (Todorovic et al, 2009.);. la biomasse et le rendement de l'orge irriguée ou en régime déficitaire (Araya et al, 2010); le degré de réponse du rendement d'Eragrostis tef à l'eau (Araya et al, 2010);. l'évaluation de l'impact du changement climatique sur le riz et le maïs dans le bassin du Mékong (Mainuddin et al, 2010);. plusieurs études de cas au Bangladesh, Inde, Iran, Ghana, Kenya, Syrie, Ethiopie et Afrique du Sud (UNW-DPC, 2011).*

Les conclusions générales sur les performances AquaCrop différents confirment l'idée d'équilibre optimal entre simplicité, de précision et de robustesse, et l'applicabilité du modèle pour une large gamme d'expérimentations sur le design (sur la densité des plantes, le calendrier cultural, les régimes d'apport en eau variables, l'analyse des impacts du changement climatique, à la stratégie et tactique des enquêtes de gestion, etc.) Les utilisateurs ont apprécié la transparence et la clarté des algorithmes, l'utilisation d'un nombre relativement restreint de variables et de paramètres d'entrée, et la convivialité du logiciel pour l'utilisateur. Dans tous les cas, la performance de l'AquaCrop a été jugée très positive et même dans certains cas mieux que d'autres modèles sur les cultures plus complexes. Récemment, l'AquaCrop a été choisie pour être testée dans un grand projet nommé "Le projet sur la comparaison de modèles d'amélioration de l'Agriculture» (AgMIP, 2011).

Mots clés : *AquaCrop, modèle de la productivité en eau des cultures, indice de récolte.*

(Traduction française telle que fournie par les auteurs)

1. INTRODUCTION

The complexity of crop responses to water deficits has led to the use of empirical production functions as the most practical option to assess yield response to water of various agricultural crops. Among the empirical function approaches, FAO *Irrigation & Drainage* Paper n. 33 (Doorenbos and Kassam, 1979) represented an important foundation to determine the yield response to water of field, vegetable and tree crops, through the following equation:

$$\left(\frac{Y_x - Y_a}{Y_x}\right) = Ky\left(\frac{ET_x - ET_a}{ET_x}\right) \tag{1}$$

where Y_x and Y_a are the maximum and actual yield, ET_x and ET_a are the maximum and actual evapotranspiration, and *Ky* is the proportionality factor between relative yield loss and relative reduction in evapotranspiration. The relationship has proved valid for several conditions and crops and has been extensively used since its introduction for planning, management and analysis of yield response to water. The approach suffers however drawbacks for more accurate predictions on yields due to the confounding effects introduced by a generalized harvest index and evapotranspiration component. As a result, the yield response factor (*Ky*) was highly variable for different cultivars, agro-climatic conditions and crop management options.

Scientific and experimental progresses in crop-water relations from 1979 to date, along with the strong demand for improving water productivity as one of the major features to cope with water scarcity, induced FAO to develop an improved approach, departing from the original concept of a direct link between crop water use and crop yield and that materialized in a crop model called *AquaCrop*.

The FAO crop-water productivity model *AquaCrop* (Steduto et al., 2009; Raes et al., 2009) simulates yield response to water of herbaceous crops, and is particularly suited to address conditions where water is a key limiting factor in crop production. It has been designed to achieve an optimal balance between simplicity, accuracy and robustness, while minimizing the number of variables and input parameters, intended to be explicit and mostly-intuitive and was targeted for practitioners such as those working for extension services, governmental agencies, NGOs, and various kinds of farmers associations. It is also of interest to scientists and for teaching purposes.

AquaCrop has been conceived for a wide range of applications including yield prediction under climate change scenarios. It distinguishes itself from the other models existing in the literature because its architecture reduces the complexity of crop growth and yield to the most basic processes, adopting a criteria of simplification providing a balance in the uncertainties of the different algorithms and that avoids unnecessary sophistications.

This article introduces the FAO crop model *AquaCrop* and its performance and user-friendliness as reported from most of the users around the world from its launch in January 2009.

2. MODEL DESCRIPTION

AquaCrop evolves from the previous Doorenbos and Kassam (1979) approach (Eq. 1) by separating (i) the ETa into soil evaporation (Es) and crop transpiration (Ta) and (ii) the final yield (Y) into biomass (B) and harvest index (HI). The separation of ETa into Es and Ta avoids the confounding effect of the non-productive consumptive use of water (Es). This is important 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. These relations are in fact fundamentally different and their use avoids the confounding effects of water stress on B and on HI. The changes described led to the following equation at the core of the *AquaCrop* growth engine:

$$B = WP \cdot \Sigma Ta \tag{2}$$

where Ta 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). This evolution from Eq. (1) to Eq. (2) has a fundamental implication for the robustness of the model due to the conservative behavior of WP (Steduto et al., 2007). It is worth noticing, though, that both equations are expressions of a *water-driven growth-engine* in terms of crop modeling design (Steduto, 2003). The other main change from Eq. (1) to *AquaCrop* is in the time scale. 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.

For most herbaceous crops, only part of the biomass produced is partitioned to the harvested organs to give yield (Y), and this is calculated through the following equation:

$$Y = HI \times \sum B \tag{3}$$

where HI is the harvest index and ΣB is the accumulation of biomass (B) over the developmental growth and maturity stages. A schematic representation of the evolution of *AquaCrop* from Eq. (1) is shown in Figure 1.

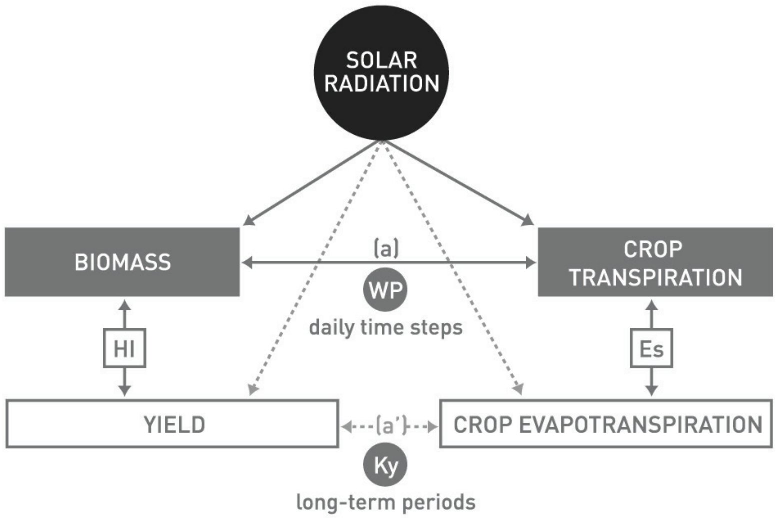

Figure 1. Evolution of *AquaCrop* from Eq. (1), based on the introduction of two intermediary steps: the separation of soil evaporation (Es) from crop transpiration (T_a) and the attainment of yield (Y) from Biomass (B) and harvest index (HI). The relationship **a'**, linking Yield to crop evapo-transpiration, is expressed through Eq. (1) via the k_y parameter and normally applies to long-term periods. The relationship **a** linking biomass to crop transpiration is expressed through Eq. (2) via the WP parameter and has a daily time step [Evolution de AquaCrop à partir de l'éq. (1), basée sur l'introduction de deux étapes intermédiaires: la séparation de l'évaporation du sol (Es) de la transpiration des cultures (Ta) et la réalisation de rendement (Y) à partir de la biomasse (B) et l'indice de récolte (HI). La relation **a'**, entre le rendement et l'évapo-transpiration des cultures, est exprimée par l'équation (1) via le paramètre ky et s'applique normalement à de longues périodes. La relation a liant la biomasse à la transpiration des cultures est exprimé par l'équation (2) via le paramètre WP et a un pas de temps journalier]

Equations (2) and (3), at the core of the model, were inserted in a complete set of additional model components, including: *the soil*, with its water balance; *the crop*, with its development, growth and yield processes; and *the atmosphere*, with its thermal regime, rainfall, evaporative demand and carbon dioxide concentration. Additionally, a range of *management* aspects are explicitly considered (e.g., irrigation, fertilization, etc.). *AquaCrop* allows simulating yield response to water under various management and growth conditions, including crop production under climate change scenarios (global warming and elevated carbon dioxide concentration) and salinity and fertility conditions. Aspects related to pests, diseases, and weeds are however not considered in the model.

The functional relationships between the different model components are depicted in the chart of Figure 2.

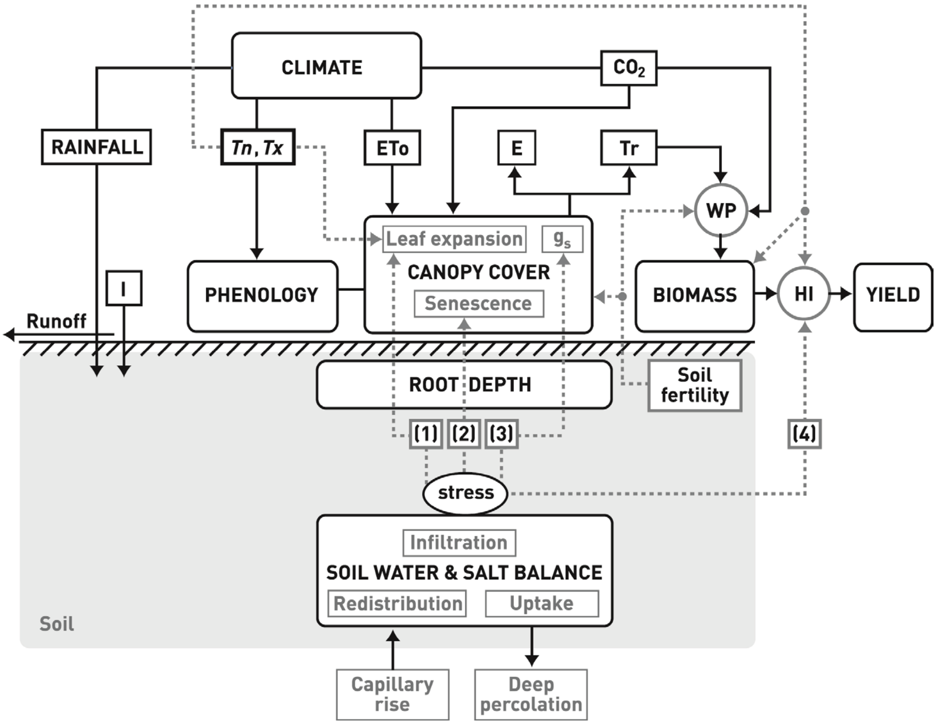

Figure 2. Chart of *AquaCrop* indicating the main components of the soil–plant–atmosphere continuum and the parameters driving phenology, canopy cover, transpiration, biomass production, and final yield. [I, irrigation; Tn, minimum air temperature; Tx, Max air temperature; ETo, reference evapotranspiration; E, soil evaporation; Tr, canopy transpiration; gs, stomatal conductance; WP, water productivity; HI, harvest index; CO2, atmospheric carbon dioxide concentration; (1), (2), (3), (4), water stress response functions for leaf expansion, senescence, stomatal conductance and harvest index, respectively]. Continuous lines indicate direct links between variables and processes. Dashed lines indicate feedbacks. See text for further explanation [Tableau de AquaCrop indiquant les principales composantes du continuum sol-plante-atmosphère et les paramètres qui conduisent la phénologie, le couvert végétal, la transpiration, la production de biomasse et le rendement final. [I, de l'irrigation; Tn, minimum air température; Tx, Max température de l'air; ETO, l'évapotranspiration de référence; E, l'évaporation du sol; Tr, la transpiration canopée; GS, la conductance stomatique; WP, la productivité de l'eau; HI, l'indice de récolte: le CO2, la concentration de dioxyde de carbone atmosphérique; (1), (2), (3), (4), les fonctions de réponses au stress hydrique, respectivement, de la croissance des feuilles, la sénescence, la conductance stomatique et l'indice de récolte]. Les lignes continues indiquent des liens directs entre les variables et les processus. Les lignes pointillées indiquent les effets rétroactifs. Voir le texte pour plus d'explications]

The reader is referred to Steduto at al. (2009), to Raes et al. (2009) and to the "*AquaCrop* Reference Manual" (FAO, 2011) for further insights on *AquaCrop*.

3. PERFORMANCE REVIEW OF AQUACROP

Before and after its official launching for public use, *AquaCrop* has been tested in several environments around the world to simulate different crops and farming management conditions, allowing independent assessment of the model performance. Furthermore, a series of training workshops were organized that allowed to collect feedbacks on the user friendliness of the software. Here after, brief summaries of the various published works that used *AquaCrop* are reported.

3.1 Maize

Heng et al. (2009) have validated *AquaCrop* performance when simulating maize crops grown under a wide range of environmental conditions, irrigated and rainfed, with water stress occurring at different growth stages. The original calibration of the model occurred under the environmental conditions of Davis, California, while the validation was carried out (with no adjustment of any of the crop parameters) using data from field experiment in Bushland (Texas), Gainesville (Florida) and Zaragoza (Spain). All simulations (over a time span of five years) focused on canopy cover (CC), biomass accumulation, grain yield, evapotranspiration (ET) and Water Use Efficiency (WUE), and were limited to the non-limiting nitrogen treatments, as the effect of nutrient stress were not yet operational in the version of *AquaCrop* used for this study (v. 2.4).

The Bushland site is characterized by a clay-loam deep soil and high wind velocity with daily mean, often exceeding 7 m s^{-1}, and high daily ET rates, often exceeding 10 mm d^{-1}. The Gainesville site is characterized by a fine sand deep soil and low wind velocity, high relative humidity and relatively lower ET rates as compared to Bushland. The Zaragoza site was characterized by a sandy-loam soil with variable depth (from 0.8 to 1.7 m) and a high wind speed (mean daily about 2-3 m s^{-1}) although less than Bushland and a daily ET rates not exceeding the 8 mm d^{-1}.

The treatments involved five maize cultivars (including hybrids), sowed at different planting dates, and had full irrigation, reduced irrigation and rainfed, with water stresses of various intensities occurring at different phonological stages (during the vegetative growth and during reproductive phase). Irrigation was provided by sprinkler systems in the experiments of Bushland and Gainesville, and by flooding in the Zaragoza experiment.

The model performance was evaluated using the root mean square error (RMSE) and the coefficient of efficiency (E) according to Nash and Sutcliffe (1970).

The authors found that good agreement was obtained by *AquaCrop* in simulating the CC, growth of aboveground biomass, and grain yield in the non-water-stress treatments and mild stress conditions in the three study locations. The model was less satisfactory in simulating severe water-stress treatments especially when stress occurred during senescence. The model was also able to simulate the crop water use (ET) under the very high evaporative demand and windy conditions of Bushland.

Considering that all the conservative parameters were taken from Hsiao et al. (2009), developed for maize in Davis, and used without any adjustment, these results can be considered remarkable. The experiment utilized for the test, in fact, covered environments very different from that in Davis, such as the extremely windy conditions of Bushland and consequently the very high ETo, and the humid and rainy weather in Gainesville. While the effect of severe water stress needs further assessment and probably development, the ability of *AquaCrop* to simulate mild water stress occurring at various stages in the growing period makes it very useful for the design and evaluation of deficit irrigation strategies, water management options, and to study the effect of location, soil type, irrigation management, and sowing date on plant production under rainfed and irrigated agriculture. The simplicity of *AquaCrop* in its required minimum input data, which are readily available or can easily be collected, makes it user-friendly and easily used by the practitioner-type of end users.

3.2 Cotton

Farahani et al. (2009) have calibrated and validate *AquaCrop* for cotton under full- and deficit-irrigation in the semiarid environment of northern Syria, using data from a three-year experiment (2004-06) conducted at the International Center for Agricultural Research in the Dry Areas (ICARDA).

The experimental site is characterized by a Mediterranean climate with a single rainy season from the fall to early spring, averaging 350 mm, with a well drained clay and deep soil. The cotton growing season in northern Syria usually starts in early May and ends in late September, typically a hot and windy season with high evaporative demand ~10 mm d−1 of ETo.

The treatments, drip irrigated, involved four levels of irrigation regimes, corresponding to 40, 60, 80, and 100% of full crop water needs.

AquaCrop was parameterized using data from the cropping season of 2006, as it provided the most extensive in-season plant measurements. The performance of the parameterized model was tested by simulating cotton yield, water use, and soil water in the 2004 and 2005 seasons.

The authors found that the parameterization of *AquaCrop* was less demanding than other system-wide and mechanistic cropping models. Model predictions (tested using RMSE) of ETa, total biomass, yield, and soil water across four levels of irrigation regimes were particularly promising considering the simplicity of the model and the limited parameterization. Nevertheless, the parameterized variables needed to be further tested under differing climate, soil, variety, irrigation methods, and field management in order to ensure a higher level of confidence in the simulation. Therefore, results from this study provided a set of first estimates for these difficult-to-determine parameters for further testing and use of the model at other locations.

A second test for cotton was conducted by García-Vila et al. (2009) that calibrated and validated *AquaCrop* to illustrate the use of the model to optimize irrigation management under different scenarios.

The data of four experiments carried out in two locations of the Cordoba Province, in southern Spain, were used to calibrate and validate the model. Two of the four irrigation experiments were conducted at the Agricultural Research Center of Cordoba, in 1985 and 1986. The other two experiments were conducted at Santaella, Spain in 2006 and 2007. The soil of the Cordoba experiments was a sandy loam with no restriction for root penetration. The soil of the Santaella experiments was clay–loam with a depth of 1.5 m. Drip irrigation was used to impose three differential irrigation treatments supplying 60, 80, and 100% of the crop ET. The experimental data set of 1986 was used for model calibration, while the data sets of 1985, 2006 and 2007 experiments were used for model validation. Calibration was performed by first matching the performance of the fully irrigated treatment in terms of biomass and canopy ground cover (CC) evolution, and then checking the ETc and yield. The different model parameters were varied until satisfactory results for all treatments in 1986 were achieved.

To evaluate *AquaCrop* performance, a linear regression was determined between the observed and simulated values of yield, biomass, HI, and seasonal ETc, and the slope, intercept, and correlation coefficients were determined. The statistics specifically designed for model goodness of fit were: maximum error (ME), root mean square error (RMSE), Willmott's Index of Agreement (Willmott,1982), and modeling efficiency (EF), according to Loague and Green (1991). Yield and biomass were very well predicted in three of the four treatments. The yield and biomass of the treatment that received the least irrigation was over-predicted by the model. The trend in HI as a function of water deficits was reasonably well simulated relative to the observed values. The model underestimated the ETa of the treatment that received the highest level of irrigation, while the ETa of the other three treatments was well simulated. The agreement between measured and simulated CC, instead, was very good in all cases. The yield differences observed in response to deficit irrigation were very well reproduced by the model.

Overall, the model performance may be considered satisfactory, particularly when compared with the performance of more complex models such as those of the Decision Support System for Agrotechnology Transfer (DSSAT; Jones et al., 2003). It is therefore encouraging that this model was capable of predicting cotton yield responses to water.

3.3 Quinoa

Geerts et al. (2009) have reported the calibration and validation of the *AquaCrop* model for the simulation of actual crop transpiration, biomass and seed yield of quinoa (*Chenopodium quinoa*, Willd.) in Central and Southern Bolivian Altiplano, using datasets from 22 field experiments over the time period from 2005 to 2007. Additionally, a sensitivity analysis was performed for key input variables of the calibrated model.

In each experimental site, various irrigation treatments were considered: rainfed, different strategies of deficit irrigation (DI), and full irrigation. In the DI strategies, irrigation was limited to the sensitive growth stages, such as plant establishment, flowering and post-anthesis and early grain-filling stages.

The authors found that *AquaCrop* simulated soil water balance with acceptable precision. Simulation of the aboveground biomass production and seed yield gave good results, but the latter with somewhat higher variability. Sensitivity analysis of different input parameters revealed the robustness of *AquaCrop* for quinoa. This is supported by the fact that calibrations and validations were performed for different varieties in different agro-climatic regions and under different management conditions. The sensitivity analysis indicated that adequate attention should be paid to the correct calibration of the threshold soil moisture depletions for triggering canopy expansion and early senescence stresses. Overall, the calibration and validation of the *AquaCrop* model for quinoa gave good results, although the simulated versus observed values for harvest index showed "moderate" agreement. The *AquaCrop* peculiarity is its balance between limited parameterization and good accuracy, and it is therefore a powerful tool to study different scenarios and management conditions of quinoa cultivation in the Bolivian Altiplano.

3.4 Bambara Groundnut

Karunaratne et al. (2011) reported on the calibration and validation of *AquaCrop* for the simulation of canopy cover, biomass accumulation and final yield of bambara groundnut (*Vigna subterranea*). Bambara groundnut is a relatively adaptable plant and tolerates harsh conditions being suited to hot, dry regions compared to other pulses in sub-Saharan Africa, and has the peculiarity of being cultivated from local landraces and there are no true varieties of the species bred for specific traits. This makes its modeling a real challenge.

A full set of experiments were carried out in order to explore the potential growth and development of bambara groundnut in various agro-ecological regions with variable rainfall patterns, with the support of suitable modeling approaches (Karunaratne *et al.*, 2010). However, the limited nature of information from experimental sites across sub-Saharan Africa, where bambara groundnut is traditionally grown, makes several mechanistic models unsuitable for meaningful simulations. Therefore, the model AquaCrop was chosen for this study.

The calibration and validation of *AquaCrop* were carried out using four bambara groundnut landraces originating in three zones in semi-arid Africa (Swaziland, Namibia, and Botswana) grown under different temperature and moisture regimes both in glasshouse experiments (in Nottingham, UK) and in field experiments (in Swaziland and in Botswana). The details of experimental design, plant sampling procedures, irrigation treatments and standard measurements are described in Karunaratne et al. (2010).

To test the performance of *AquaCrop*, the root mean square error (RMSE) between simulated and measured values was used. Canopy cover simulations for both field grown and glasshouse crop reported an excellent fit to the observed data. The linear regression of simulated v. measured biomass shows very small overestimation at the early stage, while simulation of end-of-season yield can be considered satisfactory.

On average, bambara groundnut canopy cover, biomass and yield can be successfully predicted by the *AquaCrop* model, although there is a tendency to underestimate these variables. It should be noted, though, that whilst most crop simulation models deal with genetically uniform varieties of major species, *AquaCrop* can be used for a series of genetically variable landraces of underutilized and under-researched species. The deviation of model predictions from measured values, in fact, can be explained at least in part by the intra-landrace variability.

The authors concluded that canopy development and biomass production of the four tested landraces of bambara groundnut are successfully simulated by AquaCrop, although simulations of final yield are less satisfactory. The possible reasons for the discrepancies of simulated values from measured data are identified in the variability of growth and developmental processes within landraces and in the significant differences in radiation levels in Africa and in Nottingham, UK. They also suggest that the example for bambara groundnut can be used within the AquaCrop network as a basis for other underutilized crops that have genetically variable landraces rather than genetically improved varieties or cultivars.

3.5 Barley

Araya et al. (2010a) have calibrated and validated *AquaCrop* for barley in Ethiopia, one of the major staple food crops in the country, to evaluate proper planting dates to improve the crop productivity under rainfed conditions. This is particularly important in Ethiopia as the crop cycle is longer of the rainy season, leading to a terminal drought with consequent low grain yield.

The calibration and validation of *AquaCrop* (version 3.0) had the objective to simulate barley biomass and yield with different planting dates and water availability conditions so that the performance of the model in the optimization of planting date, and in the evaluating water use efficiency, under irrigated and rainfed conditions in northern Ethiopia (Mekelle study site) could be assessed.

The data sets for the study were derived from field experiments conducted at Mekelle in 2006, 2008 and 2009. The mean annual rainfall and reference evapotranspiration for Mekelle during the period 1960–2009 was approximately 600 and 1700 mm respectively. The maximum and minimum temperatures at the site during the growing periods were 28 and12 °C, respectively. The soil was silt loam, 0.6m deep overlaid on fragmented white calcareous soil.

A locally adapted major barley cultivar (Birguda) was grown. The treatments were variables planting dates (from July 4 to July 22) and different water regimes (rainfed and/or rainfed with supplementary irrigation). All crop management techniques were carried out following regional recommendations, i.e., sowing was by broadcasting, seeding rate was 120 kg ha^{-1}, corresponding to approximately 155 plants per m^2, and the fertilization rate was 64 kg ha^{-1} of N and 46 kg ha^{-1} of P.

AquaCrop was calibrated using the data of 2008 whereas it was validated using the dat of 2006 and 2009. For the performance evaluation of the model, best fits between simulated and measured data were evaluated both graphically and statistically using root mean square error (RMSE) and model efficiency (ME), based on Loague and Green (1991).

The model underestimated and over estimated the biomass of the under irrigated and rainfed treatments by −4.3% and +14.6% respectively. Despite this deviation, the RMSE values for biomass (0.36–0.90 tha^{-1}) were considerably low implying that the simulation by the model was satisfactory. Similarly the predicted grain yield deviated from the observed data within the maximum range of −13% to +15%. Also in this case, the RMSE values for grain yield were very low (0.07–0.27 tha^{-1}), confirming the satisfactory performance of AquaCrop.

The authors concluded that AquaCrop version 3.0 has adequately simulated the soil water content in the root zone, as well as the biomass and grain yield of barley under various planting dates and water availability conditions. They also suggested that improvement in the model simulation could be obtained by a better calibration of the harvest index and the crop water stress coefficients, as well as accounting for the sensitivity of the crop to aeration stress. Overall, AquaCrop can be used to optimize planting time under water constraint environment and supplementary irrigation strategies.

3.6 Teff

Araya et al. (2010b) have calibrated and validated *AquaCrop* for teff (Eragrostis tef, Zucc.) in Ethiopia, as one of the major staple crop food for the Ethiopian population (more than half of the area under cereals in Ethiopia is for teff production).

As most teff is currently produced by smallholders under natural rainfall, the overall objective for using *AquaCrop* was to investigate strategies to increase the efficiency of rainwater use. Most of the soil, crop and climate data needed for calibration and validation of the model (version 3.0) were obtained from field measurements of two seasons (2008 and 2009) and two sites in northern Ethiopia (Ilala and Mekelle), simulating canopy cover, soil water data, biomass, and final yield.

Mekelle and Ilala are typical teff-growing areas of northern Ethiopia having cool semi-arid climate. There are two rainy seasons in this region: the main one from June to September and a short one from March to May. The dry period is from October to February. Mean annual rainfall is 600 mm in Mekelle and 650 mm in Ilala, and the values for reference evapotranspiration are 1700 mm and 1750 mm, respectively. Mean monthly minimum and maximum temperatures during the crop cycle are 11.5 °C and 23.2 °C for Mekelle and 14.8 °C and 25.8 °C for Ilala. The soil at Ilala is reach of clay (Vertisol) while at Mekelle is mainly silt loam (Cambisol).

Two common teff varieties were grown at Mekelle in 2008: 'DZ-974' (improved) and a local variety, named 'Keyh'. In 2009, only the local variety 'keyh' was sown at Mekelle. The varieties received supplementary irrigation after start of flowering (0, 2, 4, 6, 8 irrigations). With an plant density of approximately 1900 plants per m^2, the crops received 60 kg N and 46 kg P per hectare. Other cultural practices were based on regional recommendations.

Some of the treatments of the 2008 field experiment, at both locations, were used to calibrated the model, while the remaining treatments of 2008 and those of 2009 were used for validation of final aboveground biomass and grain yield.

The goodness of fit of these comparisons was evaluated using graphic and statistical tests. Comparisons of the simulated against the observed canopy cover development, aboveground biomass accumulation were appraised through the coefficient of determination (R2), root mean square of error (RMSE), and model efficiency (ME, Loague and Green, 1991).

The results showed that simulated aboveground biomass and grain yield agreed accurately with their corresponding observed data for all treatments: R2>0.95, RMSE range = 0.20–0.9 ton ha^{-1}, and ME values of 0.82–1. In particular, *AquaCrop* simulated the aboveground biomass accurately at different growth stages of the crop. The final aboveground biomass in the different irrigation treatments differed significantly from each other but almost all of them on the 1:1 line. However, it was observed that the grain yield was well simulated under optimal and mild water stress conditions, while it was slightly under estimated under severe water stress conditions.

Overall, the authors concluded that the *AquaCrop* model can be considered valid to assess yield from scenarios for alternative water management strategies in teff.

3.7 Comparison between AquaCrop and other models

Todorovic et al. (2009) have compared the performance of *AquaCrop* with that of two other, more complex and well-established models: CropSyst (Stockle et al., 2003), and WOFOST (Boogaard et al., 1998). The calibration, validation, and performance evaluation of the three models was carried out using experimental data of sunflower crops grown in a Mediterranean environment over 2 years and under different water regimes.

The experiments were conducted in 2005 and 2007 in Southern Italy. The soil, around 0.6–0.7 m deep over a bedrock, is a sandy clay-loam. The area is characterized by a typical Mediterranean climate, with average annual rainfall of about 530 mm, distributed mostly during autumn and winter, and with a hot and dry summer season.

Sunflower hybrid Sanbro-MR, characterized by early flowering and maturity and high yield potential, was cultivated under different water regimes. The plant density was 5.56 plants m^{-2} in both years. Pests were controlled by integrated pest management strategies that were standard for the region. The water treatments in 2005 were: full irrigation (FI), deficit irrigation (DI) at 70% of full irrigation supply, and rainfed (RF); while in 2007 they were: FI, DI at 70% of full irrigation during the whole season, regulated deficit irrigation (RDI) at 50% of full irrigation until flowering and at 70% of full irrigation thereafter, and RF.

The models were calibrated for the full irrigation treatment of 2007 and validated for the DI and RF treatments of 2007 and for all the treatments of 2005. However, WOFOST and CropSyst needed a second run of calibration with some of the data of 2005 while *AquaCrop* remained untouched.

The models performance comparison focused on: biomass growth over the whole growing cycle; final biomass and harvestable yield; and water use efficiency (WUE) representing the ratio between the dry grain yield at harvest and the cumulative crop evapotranspiration. The average difference between simulation outputs and experimental data was described by the RMSE. In addition, the index of agreement (IoA) was calculated according to Wilmot (1982). IoA is a descriptive parameter that varies between 0 and 1, with the value of 1 indicating excellent agreement.

The evaluation of the model performances was done for each treatment separately and also for all treatments together evaluating average prediction error of final biomass and yield. The overall results of biomass simulations are almost satisfactory for all models and for all treatments, with the exception of the RF treatment in 2005 where only WOFOST performed well, while both *AquaCrop* and CropSyst underestimated significantly the observed biomass. In 2005, the second part of June (the period after flowering) was characterized by dry and very hot weather that was interrupted by a heavy storm at the beginning of July, causing partial lodging of plants.

When evaluating the models considering the final biomass and yield of all treatments as one single data set, both final biomass and yield were simulated satisfactorily by all models, although slightly better results were obtained by *AquaCrop* than by the other two models. CropSyst, instead, performed better than the other two models in simulating WUE, while *AquaCrop* results showed less variation between observed and simulated grain yields than did the other two models. Though, it should be emphasized that *AquaCrop* was not recalibrated for the second year and CropSyst and WOFOST were.

The authors concluded that all three models simulated fairly well most of the situations encountered in the experimental works on sunflower growth in Southern Italy. However, they also highlighted that for subsequent calibration/validation studies of the model(s), a parameter estimation algorithm with a well-defined goodness of fit criterion should be implemented. Moreover, for a more robust model calibrations, it is necessary to have much more than two years of experimental work under different weather and soil conditions. Overall, the *AquaCrop* model introduces notable simplifications and requires fewer input parameters than the other two models, without affecting negatively its performance. Therefore, the authors indicated that for management purposes and in the conditions of limiting input information, the use of simpler models, such as *AquaCrop*, should be encouraged.

3.8 Use of AquaCrop in climate change studies

Mainuddine et al. (2010) have used *AquaCrop* in the project "Adaptation options to reduce the vulnerability of Mekong water resources, food security and the environment to impacts of development and climate change", funded by the Australian Agency for International Development (AusAID) and carried out by the Commonwealth Scientific and Industrial Research Organization (CSIRO), in collaboration with the Mekong River Commission (MRC) and the International Water Management Institute (IWMI).

Specifically for the assessment of climate change impact on agricultural productivity, they have used *AquaCrop* to simulate rice and maize in 14 agro-climatic zones, distributed between Laos, Thailand, Cambodia and Vietnam, under the climate-change scenarios A2 and B2 (IPPC, 2007) and for the period 2010-2050.

The model has been calibrated and validated using data from the above-mentioned 14 locations for the years 1996-2000.

In the preparatory phase of the project, the authors have investigated the different alternatives in crop models available in order to make an optimal choice. They have looked at APSIM (Keatinge et al., 2003), DSSAT (Jones et al., 2003), ORYZA2000 (Bouman et al., 2001), WOFOST (Boogaard et al., 1998), INFOCROP (Aggarwal et al., 2004), CropSyst (Stockle et al., 2003), and CERES (Jones and Kiniry, 1986). However, they have found these models quite complex for the objective of their study. Furthermore, detailed data such as crop physiological parameters, genotypes, water and nutrient management, with corresponding yield and biomass etc. were not available. Hence, *AquaCrop* was found to be very suitable for their study.

The mode performance was considered highly satisfactory and the authors recommended for further studies in the Mekong to recalibrate and validate the model for more recent years and then simulate the yield for future condition using the generated data of different GCM models.

3.9 User-friendliness of *AquaCrop* and benefits from its use

Between July 2009 and March 2010, five training workshop were organized jointly by FAO and the UN-Water Decade Program on Capacity Development (UNW-DPC) addressing "Capacity development for farm management strategies to improve crop-water productivity, using *AquaCrop*" (Ardakanian and Walter, 2011). The main objective was to have the participant mastering the use of the model in order to improve their skills to investigates different strategies for increasing the water productivity of crops farmed under both rainfed and irrigated conditions.

A total of 146 participants, from over 45 countries all-over the world, attended the regional workshops held in Burkina Faso, Iran, China, Egypt and South Africa. The background of the participants was variable and having different affiliation (Governmental Agencies, International Development Organizations, universities, national research institutes, NGOs and private companies).

At the end of every workshop, an evaluation of the training classes and material was performed through questionnaires, including the friendliness in the use of *AquaCrop* and more specifically on its user-interface. Of all the participants, 53% of them judged the friendliness of the software and its user interface as "excellent", 67% as "very good" and 14% as "satisfactory". None of the participants judged *AquaCrop* friendliness/interface as "weak" or "poor".

An additional question of the evaluation addressed the benefits that the participants had gained from the use of the model, i.e., if the training workshop was considered relevant for the participant's job. In this case, 52% of all participants responded by rating the relevance as "excellent", 42% as "very good" and 6% as satisfactory. None rated the relevance as "weak" or "poor".

4. CONCLUSIONS

The *AquaCrop* model has been conceived to bring crop modelling out from the academic environment to the practitioners working for extension services, governmental agencies, NGOs, and various kinds of farmers associations. It narrows down crop growth and yield processes to the back boon of physiology so that an optimal compromise is achieved between simplicity, accuracy and robustness.

Most of the simulation carried out so far with *AquaCrop* seems to confirm that the planned objectives have been reached successfully. When compared with other models of higher sophistication and complexity, in fact, several users have indicated that the reduced demand in input variables and calibration parameters of *AquaCrop* does not diminish its performance. Furthermore, its versatility, user friendliness and applicability to a broad ranges of environmental conditions, including future climate change scenarios, makes *AquaCrop* of significant comparative advantage for a range of users not comfortable in using modelling tools in their job.

Nevertheless, several tests have indicated that calibration represents a critical step in the model reliability. The calibrations already provided by the FAO for the different crops may requires additional local refinements, especially in the cases of severe water stresses.

The *AcquCrop* networks of developers, data-providers and end-users is continuing to improve the model to get better user graphic interface and to also include salinity and other features. Furthermore, features to plug the model in GIS and remote sensing platforms are being also developed and provided for public domain.

Recently, *AquaCrop* is being tested within a large project named "*The Agriculture Model Intercomparison and Improvement Project*" (AgMIP, 2011) with the overall purpose of providing the users with a tool that would help in improving the efficient and productive use of water in field cropping systems.

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