Introduction: Can Water Use Efficiency Be Modeled Well Enough to Impact Crop Management?

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ABSTRACT

Crop water use efficiency (WUE, yield per unit of water use) is key for agricultural production with limited water resources. Policymakers and water resource managers working at all scales need to address the multitudinous scenarios in which cropping systems and amounts, timing and methods of irrigation, and fertilizer applications may be changed to improve WUE while meeting yield and harvest quality goals. Experimentation cannot address all scenarios, but accurate simulation models may fill in the gaps. The nine papers in this special section explore how four simulation models were used to simulate yield, water use, and WUE of cotton (*Gossypium hirsutum* L.), maize (*Zea mays* L.), quinoa (*Chenopodium quinoa* Willd.), and sunflower (*Helianthus annuus* L.) in North and South America, Europe, and the Middle East. All the models simulated WUE adequately under well-watered conditions, but tended to misestimate WUE under conditions of water stress, which limits their use for exploration of deficit irrigation scenarios or rain-fed or dryland situations with expected soil water deficits. None of the experimental conditions reported involved separate measurements of evaporation (*E*) and transpiration (*T*); so there was no opportunity to test the separation of *E* and *T* simulated in the newest of the models, AquaCrop. The lack of separate *E* measurements also limited the authors in exploring reasons why WUE was not simulated well under water stress conditions. Future studies exploring WUE simulation should include *E* or *T* measurements so that effects of management methods that reduce *E* can be studied.

Symposium Papers

In a world of ever-tightening water supplies, where irrigation uses 70% of freshwater supplies while providing 60% of cereal production on ~20% of cultivated land, it is not feasible to simply reduce irrigation to increase water availability for other uses and expect to meet future food and fiber requirements. In fact, irrigated land is increasing worldwide, and for some very good reasons. In arid areas, production depends almost entirely on irrigation; and irrigation is critical to improving WUE in semiarid regions (e.g., Musick et al., 1994). Even in subhumid regions, irrigation is increasingly adopted to prevent declines in yield or harvest quality due to short-term droughts (Evett et al., 2003), with a resulting improvement in both WUE and profitability. Irrigation is essential to feeding a burgeoning world population (FAO, 2002a). In fact, it is underappreciated that a blue revolution—rapid intensification and expansion of irrigated areas and improvements in irrigation methods and management—was a key factor in the success of the green revolution of improved crop varieties and fertilization. Yet, irrigation is not the only key to increasing WUE. Water management on the 80% of cultivated land that is rain fed or dryland is also a key to improving yields and water use efficiencies on those lands. A host of management practices may be used to improve precipitation capture, reduce runoff and evaporation, and improve WUE; and almost all of these practices are applicable to irrigated lands as well.

A long list of scientific efforts aimed at water conservation would include the efforts of FAO and its partners that culminated in FAO Irrigation and Drainage Paper 33, *Yield Response to Water* (Doorenbos and Kassam, 1979). In dryland agriculture, an important milestone was the 1988 International Conference on Dryland Farming that brought together scientists from 53 countries to discuss progress and future challenges for sustainability (Unger et al., 1989). More recently, the severe competition for water in the face of increasing demands for food experienced in much of the world has led to renewed interest in controlled deficit irrigation as a means to improve WUE (e.g., FAO Water Report 22, *Deficit Irrigation Practices*, FAO, 2002b). All of these publications, and thousands more in the scientific literature, improve our knowledge of methods and management schemes that help increase yield per unit of water used. Yet none of these allow easy investigation of management alternatives and the likely outcomes of choosing different management schemes. Crop simulation models may help overcome this deficiency by providing a method for integrating this knowledge and delivering a powerful predictive tool to a wide range of decision makers from policy analysts to individual farm managers.

Since 2002, FAO has reassessed the information in its prior publications and has consulted with experts from scientific, academic, and governmental institutions worldwide, leading to development of a simulation model of yield response to water for herbaceous plants—the AquaCrop model. AquaCrop was

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Abbreviations: *E*, evaporation measurement; ET, evapotranspiration; *T*, transpiration measurement; WUE, water use efficiency.

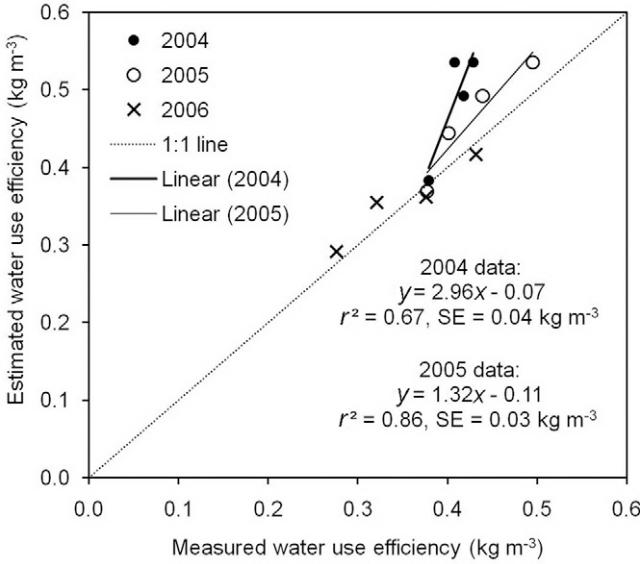

Fig. 1. Cotton water use efficiency as estimated using AquaCrop and as measured for 3 yr in Syria. Data from Farahani et al. (2009, this issue).

conceived as a functional, engineering type of model, aimed at simulating biomass and yield in response to water, and using, at base, the relative yield versus relative water use paradigm (Eq. [1] in Steduto et al., 2009). Another distinctive model feature is the expression of canopy development as canopy cover rather than leaf area index. Although this feature conflicts with the approach of most mechanistic models constructed for scientific investigations, it simplifies the model and naturally accounts for plant density variations, including the partial canopy cover situations common in many water short regions. It also allows a user to directly input observed canopy cover percentage, a key for use of the model for crop management. A third and key model feature is the separation of ET (evapotranspiration) into *E* and *T*, which opens the way toward simulating the improvements in WUE due to reductions in *E* caused by residue management practices or irrigation application methods (e.g., subsurface drip irrigation) if and when the appropriate residue and irrigation application modules are included in the model. Model development was aided by collaboration with institutions whose long-term research has included accurate measurements of crop water use, yield, and WUE under a variety of management practices and for many crops. Among these, important contributions came from the Agronomic Research Service, Zaragosa, Spain; the Conservation & Production Research Laboratory of the USDA-ARS at Bushland, Texas, USA; the International Center for Agricultural Research in Dry Areas, Aleppo, Syria; the Mediterranean Agronomic Institute of Bari, Italy; the University of California, Davis, USA; and the University of Florida, Gainesville, USA; but researchers in several other institutions and countries were involved.

This multinational cooperation led to a symposium, "Yield Response to Water: Examination of the Role of Crop Models in Predicting Water Use Efficiency" at the 2007 International Annual ASA–CSSA–SSSA meeting. Models examined included AquaCrop, CERES-Maize v. 4.0, CSM/DSSAT, CropSyst, DSSAT 4.0, ecosys, EPIC, RZWQM2, and WOFOST. Crops studied included chickpea (*Cicer arietinum* L.), cotton, dry bean (*Phaseolus vulgaris* L.), faba bean (*Vicia faba* L.), maize, peanut (*Arachis hypogaea* L.), quinoa, soybean [*Glycine max* (L.) Merr.], sunflower, and wheat (*Triticum aestivum* L.). All authors were invited to contribute to this special section of Agronomy Journal on modeling of water use efficiency. Of the nine papers published here, three focus on the concepts and underlying principles of the AquaCrop model (Steduto et al., 2009), the main algorithms and software description (Raes et al., 2009), and an example of model parameterization and testing (Hsiao et al., 2009). The other papers describe the application of the AquaCrop, CropSyst, GOSSYM, and WOFOST models to crops such as cotton, maize, quinoa, and sunflower to simulate yield and water use under a variety of dryland, fully irrigated, and deficit irrigated regimes.

Using a previously validated GOSSYM model, Baumhardt et al. (2009) simulated cotton lint yield and water use in a semi-arid climate for a range of initial soil profile water contents and irrigation capacities. They found that overall WUE could be improved under conditions of water shortage by not irrigating some land (growing dryland cotton) so that water could be concentrated on the remaining land. This result agrees with the commonly observed convex upward curvilinear increase of WUE with increasing water application depth, which tapers off to a zero rate of increase as application depth increases to a certain threshold and then declines as application depth passes that threshold. Farahani et al. (2009) modeled cotton seed lint yield and water use with the AquaCrop model and found good agreement between measured and simulated values of both for the second year of a 3-yr study. Data from the third year (2006) were used to calibrate the model. Data supplied by the authors showed that WUE was estimated reasonably well for 2005, though not for 2004 due to overestimation of yield and underestimation of water use, which led to simulated values of WUE that were larger than measured ones (Fig. 1). Cotton yield and water use were also simulated using AquaCrop by Garcia-Vila et al. (2009) using data from 4 yr of production near Cordoba, Spain. Data from 1 yr (1986) were used to calibrate the model. During testing, the model tended to overestimate WUE for conditions of severe water stress due to the fact that the model uses "a constant value for normalized WUE."

Maize water use and grain yield were simulated using AquaCrop by Heng et al. (2009) for a semiarid location with very large ET and wind speeds and a deep, clay loam soil (Bushland, TX, USA); for a rainy, humid location with sandy soil (Gainesville, FL, USA); and for a semiarid location with loamy soil having a layer of gravel at depths varying from 0.8 to 1.7 m (Zaragosa, Spain). Model parameters were those developed by Hsiao et al. (2009) using data from Davis, CA, USA. AquaCrop simulated crop ET accurately, even for the Bushland site, but did less well simulating grain yields, particularly for water-stressed conditions. There were no ET measurements for the locations in Spain and Florida, but at Bushland the WUE was reasonably well simulated [standard error (SE) of the slope, SE = 0.17 kg m^{-3}, about 9% of maximum WUE] except for a short-season maize crop, for which WUE was underestimated because yield was underestimated.

In the Bolivian Altiplano at 4000 m above sea level, quinoa was studied in several fields for 3 yr by Geerts et al. (2009). Parameterizing the AquaCrop model with data from some years and fields, they tested the model for other fields, years, and varieties, and found acceptable results. Observed biomass was

modeled well, but there was somewhat less good agreement for grain yield. Water use was not reported, but the model simulated soil water contents well compared with measured values. In Italy, sunflower was grown for 2 yr by Todorovic et al. (2009) who used data from 1 yr to calibrate the AquaCrop, CropSyst (Stöckle et al., 2003), and WOFOST (Boogaard et al., 1998) models and data from another year for model testing. AquaCrop results showed less variation between observed and simulated grain yields than did the other two models, even though AquaCrop was not recalibrated for the second year and CropSyst and WOFOST were. However, AquaCrop and CropSyst overestimated ET by 8.9 and 5.5%, respectively, in comparison with WOFOST, which underestimated ET by 3%. CropSyst did the best job of estimating sunflower WUE, although the error rate of estimation was about 14% of the greatest measured WUE (SE = 0.19 kg m^{-3}). AquaCrop was somewhat better than WOFOST (SE = 0.28 and 0.36 kg m^{-3}, respectively), but both produced WUE estimates that were biased in relation to the 1-to-1 line and which underestimated WUE in most cases, particularly under water deficit conditions.

One can pick apart the results of any simulation study and expose weaknesses. The saying that *all models are wrong but some are useful* still applies. Despite many years of crop model development, it appears that simulated WUE is still not entirely useful, particularly under conditions of water stress. Thus, a gap exists between what can be done using crop simulation models and what policymakers and managers need to develop useful management alternatives for crop selection and timing, tillage systems, and irrigation and fertilization practices. When water is inexpensive, managers tend to focus on yield responses to management and not on WUE responses; and water is still inexpensive to farmers in most of the world. However, not only is water becoming more expensive but other factors come increasingly into play. For example, irrigation practices that conserve water will also conserve applied fertilizers due to avoidance of deep percolation losses. This may translate into the happy circumstance of yield increases associated with declines in water applied. As crop models are increasingly folded into more complex decision support systems, a stated goal of the AquaCrop effort, it will become necessary to simulate accurately not only yield and water use, but also the ratio of these—the WUE. Moreover, many of the cropping systems and irrigation application tools that can improve WUE do so by reducing the evaporative loss from the soil surface. Examples include subsurface drip irrigation and no-tillage or limited tillage systems that keep residues on the soil surface. To accurately simulate the effects of these practices on WUE will require that the E and T components of ET be simulated as individual processes, something that is done, but in different ways, by all the models examined in this special section. However, the effects on E of canopy cover, residue management, tillage, and irrigation application methods, amounts, and timing must also be simulated accurately; and this is where most models fall somewhat short. As water costs increase, economic analysis must include not only yield response to water but WUE response to management practices. Thus, some future challenges to crop modelers are made clear. Correspondingly, future challenges to experimentalists are clarified. Without separate measures of E and T, under management conditions that cause a reduction in E/T, simulation results pertinent to E reduction effects on WUE cannot be verified. The papers in this special section demonstrate some problems that crop models face and point the way to solutions that should improve the utility of crop models for guiding management decisions.

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