Validating the FAO AquaCrop Model for Irrigated and Water Deficient Field Maize

Lee Kheng Heng,* Theodore Hsiao, Steve Evett, Terry Howell, and Pasquale Steduto

ABSTRACT

Accurate crop development models are important tools in evaluating the effects of water deficits on crop yield or productivity. The FAO AquaCrop model predicts crop productivity, water requirement, and water use efficiency (WUE) under water-limiting conditions. A set of conservative parameters [calibrated and validated for maize (*Zea mays* L.) in a prior study and considered applicable to a wide range of conditions and not specific to a given maize cultivar] were used to further evaluate the performance of AquaCrop model for maize using data from three studies performed under diverse environmental conditions: Bushland, TX; Gainesville, FL; and Zaragoza, Spain. The three locations were characterized by the extraordinarily high evapotranspiration (ET) and wind speed in the Bushland study; rainy weather and sandy soil in the Gainesville study; and the semiarid conditions in the Zaragoza study. The model was able to simulate the crop water use (ET) under very high ET and wind conditions. Furthermore, the model performed satisfactorily for the growth of aboveground biomass, grain yield, and canopy cover (CC) in the non-water-stress treatments and mild stress conditions, but it was less satisfactory in simulating severe water-stress treatments, especially when stress occurred during senescence. The ease of use of the AquaCrop model, the low requirement of input parameters, and its sufficient degree of simulation accuracy make it a valuable tool for estimating crop productivity under rainfed conditions, supplementary and deficit irrigation, and on-farm water management strategies for improving the efficiency of water use in agriculture.

Maize is one of the most important crops known to humankind, accounting for nearly 30% of the total global grain production. The crop is cultivated on more than 142 million ha of land worldwide, producing over 637 million Mg of grain (FAO, 2003). Recently, demand for maize is increasing as it is used to produce ethanol as biofuel, besides being a staple food in many countries and a feed for livestock in the form of forage, silage, or grain. The strong demand is putting tremendous pressure on production, hence, competition for available water. At the same time, it increases the price of maize, which in turn has raised food prices in general. Improving the WUE for maize production is therefore of paramount importance to obtain "more crop per drop" with declining worldwide irrigation resources and the uncertainty in precipitation from global climate change.

Simulation models that quantify the effects of water on yield at the farm level can be valuable tools in water and irrigation management. In the case of maize, many such models have been tested: for example, the CERES-Maize model (Jones and Kiniry, 1986), the Muchow–Sinclair–Bennett (MSB) model (Muchow et al., 1990), the EPICphase model (Cavero et al., 2000), CropSyst (Stöckle et al., 2003), and the Hybrid-Maize model (Yang et al., 2004). Most of these models, however, are quite sophisticated, demanding advanced skills for their calibration and operation, and require large number of parameters; some are so cultivar-specific they are not easily measured or accessible to end-users.

The newly developed AquaCrop model (Raes et al., 2009; Steduto et al., 2009) is a user-friendly and practitioner-oriented type of model, as it maintains an optimal balance between accuracy, robustness, and simplicity, and requires a relatively small number of parameters. AquaCrop has been parameterized and tested on maize using six seasons' data collected at the University of California Davis, (Hsiao et al., 2009). That study showed that AquaCrop was able to properly simulate the CC, biomass development, and grain yield of four maize cultivars over six different crop seasons differing in plant density, planting date, and atmospheric evaporative demand, with irrigation treatments that withheld the water up to tasseling, from tasseling onward, intermittently, or completely, under conditions of little rainfall but with the soil at or near field capacity at planting time.

AquaCrop simulates the crop green foliage CC (not leaf area index, LAI) from crop emergence through the development and senescence of the canopy. The CC and the reference evapotranspiration (ET_o) are then used with the crop coefficient for

L.K. Heng, IAEA–Soil and Water Management and Crop Nutrition Section, Wagrammer Strasse 5, P.O. Box 100, 1400 Vienna, Austria Vienna 1010; T. Hsiao, Univ. of California, Dep. of Land, Air and Water Resources, Davis, CA 95616; S. Evett and T. Howell, USDA-ARS, Soil and Water Management Research Unit, P.O. Drawer 10, Bushland, TX 79012; P. Steduto, FAO, Viale delle Terme di Caracalla, Rome, Italy 00153. Received 24 July 2008. *Corresponding author (L.Heng@iaea.org).

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Abbreviations: CC, canopy cover; CC_x, maximum canopy cover; ET, evapotranspiration; ET_o, reference evapotranspiration; GDD, growing degree day; HI, harvest index; LAI, leaf area index; SWO, initial soil water content; WP, water productivity; WP*, the water productivity of the crop species normalized for both evaporative demand and atmospheric CO2; WUE, water use efficiency.

transpiration to calculate transpiration for nonstress conditions, and with the soil evaporation coefficient to calculate Stage 1 or Stage 2 (Ritchie, 1972) soil evaporation each day. The daily transpiration (Tr_i) is converted to daily aboveground biomass production (B_i) using the daily ET_o and the water productivity of the crop species normalized for both evaporative demand and atmospheric CO_2 (WP*), as follows:

$$B_i = WP^* \left(\frac{Tr_i}{ET_{o,i}} \right) \quad [1]$$

AquaCrop performs a daily water balance that includes all the incoming and outgoing water fluxes (infiltration, runoff, deep percolation, evaporation and transpiration) and changes in soil water content. The effects of water deficit on the crop is expressed through four stress response coefficients, which are functions of the fractional depletion of the total available water (the volume the soil holds between field capacity and permanent wilting point) in the root zone. The four coefficients are for leaf growth, stomatal conductance, canopy senescence, and pollination failure, each with its own sensitivity to water stress. Harvestable yield is calculated from the cumulative biomass with harvest index (HI), which increases with time after the onset of anthesis. For more detailed description of the principles and operation of the model and the water stress response functions, see Steduto et al. (2009) and Raes et al. (2009) of this issue.

In this study, the conservative (i.e., constant) crop parameters derived in Hsiao et al. (2009) were used to further validate the performance and robustness of AquaCrop by comparing the simulated canopy development, biomass accumulation, grain yield, ET, and WUE of maize against field measurements made under a wide range of environmental conditions, both irrigated and rainfed crops with water stress occurring at different stages of growth, and in locations other than Davis. All the simulations are limited to the nonlimiting N treatments of the studies, as the effects of nutrient stress are not yet operational in the version of AquaCrop (v. 2.4) used for this study.

MATERIALS AND METHODS

Experimental Data

Data from maize studies performed in Bushland, TX (Howell et al., 1996, 1998), Gainesville, FL (Bennett et al., 1986; Ma et al., 2006), and in Zaragoza, Spain (Cavero et al., 2000) were used to validate AquaCrop. While the full experimental descriptions are reported in the corresponding cited papers, the following are the key elements and characteristics of the various locations relevant to the simulation tests.

Full-season hybrid maize was planted at the USDA-ARS Conservation and Production Research Laboratory in Bushland, TX (35°119′ N, 102°69′ W; elevation 1170 m above mean sea level) during the 1989, 1990, and 1994 growing seasons, under irrigation and in both weighing lysimeters and the surrounding large experimental fields (4.4 ha) (Howell et al., 1996). In the 1994 season, besides the full-season hybrid, a short-season hybrid under irrigated and nonirrigated conditions was grown as well. The short-season hybrid reached physiological maturity 12 d earlier than the full-season hybrid, and was harvested 11 d sooner. The sowing dates were 26 Apr. 1989, 9 May 1990, and 15 Apr. 1994, and the planting densities were 6, 6, and 8 plants m^{-2} for the 1989, 1990, and 1994 seasons, respectively (Table 1). Sprinkler irrigations by a lateral-move machine were scheduled to replenish the water lost through ET. The soil is a Pullman clay loam (fine, mixed, thermic, superactive Torrertic Paleustoll) (Table 2). Soil water at various depths to 2.3 m in the field surrounding the lysimeter was measured with a neutron probe, and ET was monitored in the lysimeters over the season (Howell et al., 1996, 1998). The Bushland site is characterized by high wind velocities with daily mean velocity often exceeding 7 m s^{-1} at 2 m on windy days (the mean wind velocity for April–June for the 3 yr was 5 m s^{-1}) and high daily ET rates often exceeding 10 mm d^{-1} (Howell et al., 1996). The LAI, biomass, final grain yield, and other crop parameters were measured (Howell et al., 1996).

The data for the Gainesville and Zaragoza studies were obtained from ICASA Data Exchange (IDE) at www.icasa.net (verified 25 Feb. 2009). The Gainesville study was performed at the University of Florida (29°38′ N, 82°22′ W, elevation 10 m) in 1982 on effects of low and high N and different irrigation regimes (full irrigation, partial irrigation with water stress occurring during the vegetative stage, and rainfed) on grain yield. Only the data for the high N (275 kg N ha^{-1}) treatments were used in this study. The crop was sown on 26 Feb. 1982 at a density of 7.2 plants m^{-2} and harvested in July that year (Table 1). Irrigation was by overhead sprinklers; the vegetative stress treatment had a 10-d water stress period before 50% silking on 2 May (at 65 d after planting). The soil is a Millhopper fine sand (loamy, siliceous, hyperthemic Grossarenic Paleudults) (Table 2). The LAI, seasonal biomass and grain yield, and other crop parameters were measured (Bennett et al., 1986).

The Spanish study was performed in 1995 and 1996 at the experimental farm of the Agronomic Research Service (SIA) in Zaragoza (41°43′ N, 0°48′ W, elevation 225 m). The objective was to study the effect of water stress at different stages of maize development. The soil is a loam, classified as Typic Xerofluvent. Although the soil depth was reported to be variable within the field due to a gravel layer between 0.8 and 1.7 m (Cavero et al., 2000), in the simulation a depth of 1.5 m was assumed (Table 2). Maize was planted on 17 May 1995 and 16 May 1996, at a density of 8.0 plants m^{-2} for both years (Table 1). The growing season was divided into three phases: (i) from emergence to tassel emergence, (ii) from tassel emergence to milk stage of grains, and (iii) from milk stage to physiological maturity. In each of the phases, flood irrigation was applied either in the full amount necessary to meet the crop ET, or about one-third or one-half of the full amounts, by skipping some of the irrigation events. A total of eight irrigation treatments with water stress imposed at different development stages of maize were performed each year (Cavero et al., 2000). The 1995 aboveground biomass and LAI measured in the Zaragoza study were presented graphically, and had to be digitized from Fig. 4 of Cavero et al. (2000). Only final biomass and grain yield were available for the 1996 season.

Table 1. Experimental and agronomic information for Bushland, Gainesville, and Zaragoza used in AquaCrop validation.

	Bushland				Gainesville 1982			Zaragoza			
Growing season†	1989 Full Irrigation	1990 Full Irrigation	1994 Full Season Full Irrigation	1994 Short Season Full Irrigation	1994 Short Season Nonirrigated	Full Irrigation	Veg. Stress	Rainfed	1995 Full Irrigation	1995 50% Irrigation	1995 33% Irrigation	1996 Full to 33% Irrigation
Cultivar	PIO 3124	PIO 3124	PIO 3245	PIO 3737	PIO 3737	McCurdy 84aa	McCurdy 84aa	McCurdy 84aa	Prisma	Prisma	Prisma	Prisma
Planting density, plants m^{-2}	6.0	6.0	8.0	8.0	8.0	7.1	7.1	7.1	8.0	8.0	8.0	8.0
Sowing date	26 Apr.	9 May	15 Apr.	15 Apr.	15 Apr.	26 Feb.	26 Feb.	26 Feb.	17 May	17 May	17 May	16 May
Emergence	7 May	18 May	4 May	4 May	4 May	4 Mar.	4 Mar	4 Mar	25 May	25 May	25 May	24 May
Physiological maturity	10 Oct.	21 Sept.	6 Sept.	25 Aug.	25 Aug.	4 July	4 July	4 July	5 Oct	5 Oct.	5 Oct.	6 Oct.
Harvest	24 Oct.	16 Oct.	27 Sept.	16 Sep	16 Sept.	8 July	8 July	8 July	NA	NA	NA	10 Oct.
CC_x, %	96	96	96	89	89	90	90	90	96	96	96	96
WP*, g m^{-2}	32.3	32.4	32.9	32.9	32.9	31.3	31.3	31.3	33.0	33.0	33.0	33.2
Seasonal rainfall, mm	484	224	320	320	320	670	670	670	38	38	38	103
Irrigation, mm	282	578	577	465	0	264	201	0	568	321	174	505-105
Seasonal ET_o, mm	966	1017	995	927	927	587	587	587	572	572	572	708
Max rooting depth, m	1.6	1.6	1.6	1.5	1.5	1.8	1.8	1.8	1.5	1.5	1.5	1.5

† CC_x, maximum canopy cover; ET_o, reference evapotranspiration; WP*, the water productivity of the crop species normalized for both evaporative demand and atmospheric CO_2.

Table 2. Soil properties at Bushland, Gainesville, and Zaragoza for validation of the AquaCrop model.

Thickness	Water content at saturation	Field capacity	Permanent wilting point	K_{sat}†
m	$m^3\ m^{-3}$			mm d^{-1}
	Bushland Pullman clay loam			
0.18	0.42	0.33	0.18	66.0
0.56	0.44	0.33	0.18	18.0
0.61	0.43	0.35	0.20	6.6
0.95	0.46	0.30	0.16	200.0
	Florida Millhopper fine sand‡			
0.60	0.23	0.086	0.023	3792
0.60	0.23	0.076	0.021	5412
0.30	0.23	0.130	0.027	72.0
0.30	0.36	0.258	0.070	24.0
	Zaragoza shallow sandy loam§			
0.30	0.368	0.267	0.103	228.0
0.30	0.333	0.275	0.091	117.6
0.30	0.342	0.271	0.080	103.2
0.60	0.350	0.283	0.078	100.0

† K_{sat}, saturated hydraulic conductivity.

‡ Bulk density was 1.3, 1.4 and 1.45 g cm^{-3} for the top three layers, respectively.

§ Cavero et al. (2000) reported a gravel layer in the soil varied between 0.8 to 1.7 m in depth, but the soil water properties given in ICASA Data Exchange does not indicate gravel down to 1.5 m.

Model Parameters and Input Data

Weather and Soil Data

The weather data required by AquaCrop are the daily values of minimum and maximum air temperature, ET_o, and rainfall (Raes et al., 2009, Steduto et al., 2009). The standard procedure is to calculate ET_o following the FAO Penman–Monteith equation (Allen et al., 1998), which was done for the Bushland data from daily maximum and minimum temperature, dew point, wind velocity at 2 m, and solar radiation. For the Gainesville and Zarogosa locations, only daily solar radiation and temperatures data are available in the ICASA Data Exchange, necessitating the use of Hargreaves method (Hargreaves and Samani, 1985) to estimate ET_o. The calculated seasonal ET_o for the above three locations are given in Table 1.

Rainfall and irrigation during the growing seasons at the three locations are depicted in Fig. 1. At Bushland (Fig. 1a, b, c) rainfall totaled 484 mm in 1989, 224 mm in 1990, and 320 mm in 1994 for the April through September maize season (Howell et al., 1996). The amounts of irrigation applied for the three seasons were 282, 578, and 577 mm for 1989, 1990, and 1994, respectively (465 mm for the short season hybrid in 1994).

The Gainesville rainfall was reasonably well distributed during the growing season; intense rainfall was recorded in the middle of April with nearly 100 mm d^{-1} (Fig. 1d). A total of 670 mm of rainfall over the growing season was recorded. Irrigations applied for the full and vegetative stress treatments were 264 and 201 mm, respectively.

In contrast, rainfall totaled only 45 mm in 1995 and 103 mm in 1996 for Zaragoza (Fig. 1e, f). Rainfall was distributed over both seasons but the amount per event was much lighter for 1995. Irrigation applied for the full, 50%, and 33% of total irrigation were 505, 259, and 150 mm, respectively.

The required input soil parameters for AquaCrop are the saturated hydraulic conductivity (K_{sat}), volumetric water content at saturation (θ_{sat}), field capacity (θ_{FC}), and permanent wilting point (θ_{PWP}) (Table 2). These parameters were derived from field measurements for Bushland. For Gainesville and Zaragoza, the lower limit (LL) of plant available water and drained upper limit (DUL) given by ICASA Data Exchange were assumed to coincide with θ_{PWP} and θ_{FC}, respectively. The hydraulic properties of Florida Millhopper fine sand was obtained from Table 1 in Ma et al. (2006),

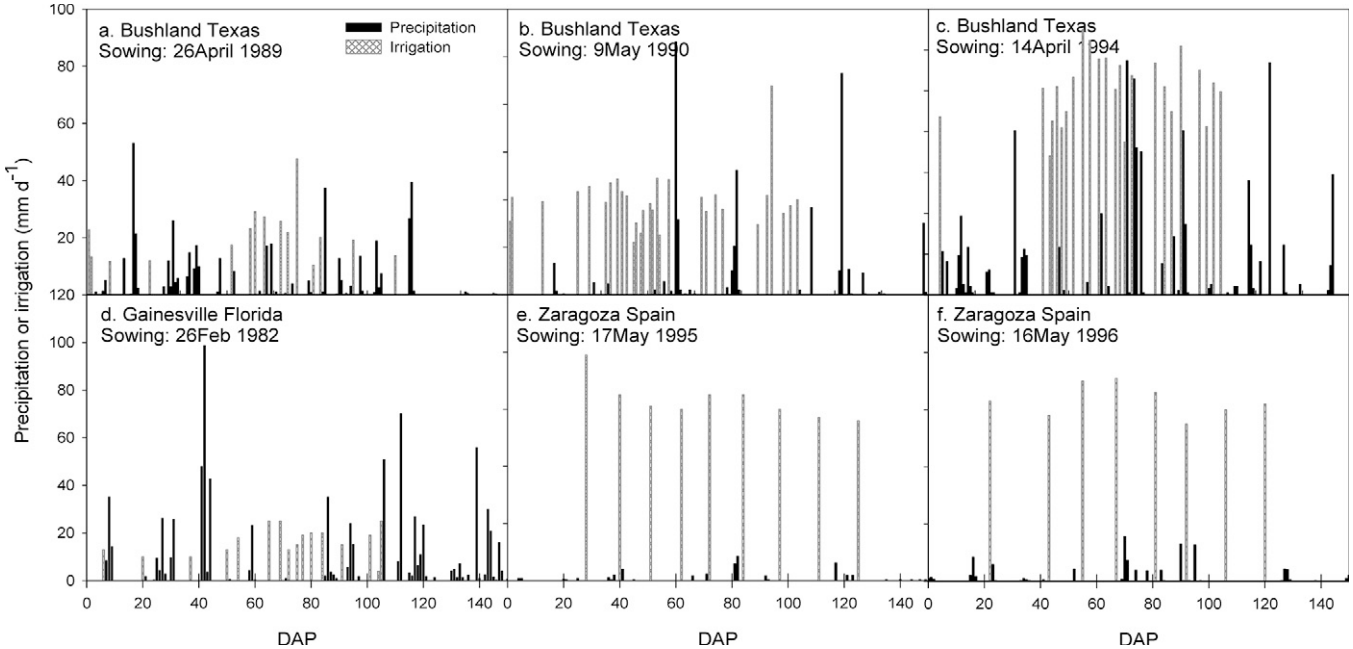

Fig. 1. Daily rainfall (solid bars) and applied irrigation (gray bars) during the cropping seasons in (a–c) Bushland, TX, USA; (d) Gainesville, FL, USA; and (e–f) Zaragoza, Spain. The irrigation for Gainesville and Zaragoza shown are that for full irrigation, for the other treatments please refer to text.

with bulk density was 1.3, 1.4 and 1.45 g cm^{-3} for the top three layers, respectively (Table 2).

Crop Parameters, Phenology, and Development

Conservative Parameters

Out of all the crop parameters in AquaCrop, 21 of them were demonstrated or assumed to be conservative (constant) in the study of Hsiao et al. (2009). The same values of this set of 21 parameters were used in the validation reported here to further evaluate the performance and robustness of AquaCrop. These parameters, reported in Table 3, include canopy growth and canopy decline coefficient; crop coefficient for transpiration at full canopy; WP* for biomass; soil water depletion thresholds for the inhibition of leaf growth and of stomatal conductance, and for the acceleration of canopy senescence; reference harvest index; and coefficients for adjusting the HI in relation to inhibition of leaf growth and of stomatal conductance. These parameters are presumed to be applicable to a wide range of conditions and not specific for a given crop cultivar; the same parameters are used to simulate stress conditions, with stress effects manifested through the stress coefficients. More information on how these parameters were derived is given in Hsiao et al. (2009), while hereafter some of their specific characteristics are briefly described.

Table 3. Conservative parameters of AquaCrop taken from Hsiao et al. (2009) and used to simulate the studies at the three locations.†

Description	Value	Units or meaning
Base temperature	8	°C
Cut-off temperature	30	°C
Canopy cover per seedling at 90% emergence (CC_o)	6.5	cm^2
Canopy growth coefficient (CGC)	1.3%	increase in CC relative to existing CC per GDD
Maximum canopy cover (CC_x)		function of plant density
Crop coefficient for transpiration at CC = 100%	1.03	full canopy transpiration relative to ET_o
Decline in crop coef. after reaching CC_x	0.3%	decline per day due to leaf aging
Canopy decline coefficient (CDC) at senescence	1.06%	decrease in CC relative to CC_x per GDD
Water productivity, normalized to year 2000	33.7	g (biomass) m^{-2}, function of atmospheric CO_2
Leaf growth threshold p—upper	0.14	as fraction of TAW, above this leaf growth is inhibited
Leaf growth threshold p—lower	0.72	leaf growth stops completely at this p
Leaf growth stress coefficient curve shape	2.9	moderately convex curve
Stomatal conductance threshold p—upper	0.69	above this stomata begin to close
Stomata stress coefficient curve shape	6.0	highly convex curve
Senescence stress coefficient p—upper	0.69	above this early canopy senescence begins
Senescence stress coefficient curve shape	2.7	moderately convex curve
Reference harvest index	48%	common for good conditions
GDD from 90% emergence to start of anthesis	800	would be earlier for short season cultivars
Duration of anthesis, in GDD	190	–
Coefficient, inhibition of leaf growth on HI	7.0	HI increased by inhibition of leaf growth at anthesis
Coefficient, inhibition of stomata on HI	3.0	HI reduced by inhibition of stomata at anthesis
Total GDD from emergence to maturity, in GDD	1510–1840	less for shorter season cultivars

† GDD, growing degree days; HI, harvest index.

The same water productivity, normalized for both evaporative demand and atmospheric CO_2 of year 2000 (WP*) as given in Hsiao et al. (2009), was used but adjusted for the bulk atmosphere CO_2 concentration of the year of the specific study, using the procedure of Steduto et al. (2007), and based on the annual mean CO_2 concentration measured at Mauna Loa Observatory, Hawaii.

As most of the experiments report LAI rather than ground CC, the relationship between CC and LAI:

$$CC = 1.005\,[1 - \exp(-0.6\,LAI)]^{1.2} \qquad [2]$$

derived for maize in Hsiao et al. (2009), was also used to obtain CC in this study. The maximum canopy cover (CC_x) is adjusted by AquaCrop from plant density information; for the short season cultivar used in 1994 at Bushland, a smaller CC_x was obtained (Table 1) due to the lower leaf number per plant.

AquaCrop was run in growing degree day (GDD) calculated from the temperature data. As in Hsiao et al. (2009), the base temperature was 8°C, while the upper temperature (above which crop development no longer increases) was 30°C. A total of 800 GDD was the calibrated value needed for the crop to go from emergence to start of flowering and an additional 190 GDD for the duration of flowering.

User-Specific Parameters

For convenience, Hsiao et al. (2009) grouped site-, management-, and crop-specific parameters such as soil water characteristics, maximum rooting depth, plant density, sowing date, irrigations, and phenology all under the heading of *user-specific input parameters*. These parameters for the three locations (Texas, Florida, and Spain) are presented in Table 1. In addition, Table 1 also gives the WP* for the different years, and CC_x also because CC_x is density dependent. Some of these user-specific parameters are addressed here.

Emergence time. In AquaCrop, emergence time is taken as the date when 90% emergence has occurred, and on this date the crop canopy is assumed to start development. The rationale for this approach is based on the time of attainment of autotrophy by the seedlings, as explained in Steduto et al. (2009) and Hsiao et al. (2009). Because different experimenters use different criteria for determining the time of emergence, the date for 90% emergence was estimated by judging the number of days to be added to the stated emergence time until a good agreement between simulated very early CC agrees with the measured. These dates range from 7 to 10 d after sowing in most cases, as in Hsiao et al. (2009) for Davis, but longer for Bushland (Table 1). The longer emergence time in 1994 for Bushland was probably due to the colder temperature at sowing, which occurred more than a month earlier than at Davis. The version of AquaCrop used does not simulate germination in terms of GDD, only canopy development and biomass accumulation.

Canopy senescence and physiological maturity. The starting time of senescence was assumed to be the time when CC declined below a value corresponding to the LAI value of 4 (Hsiao et al., 2009). Physiological maturity was as stated in the studies, when CC declined to nearly zero or zero.

Rooting depth. As in Hsiao et al. (2009), the time for roots to reach maximum depth was assumed to be the same as that of starting of canopy senescence under nonstress conditions. The same curve-shape factor of 1.2 was used for the root deepening vs. time curve. The maximum rooting depths for the three locations (Table 1) were taken from the respective references as mentioned earlier. For the full season hybrid in Bushland, the rooting depth was 1.6 m, while a shallower maximum rooting depth of 1.5 m was assumed for the short-season hybrid. Soil depths given in ICASA Data Exchange at www.icasa.net (verified 25 Feb. 2009) for Gainesville and Zaragoza were assumed to be the rooting depths (1.8 m for Gainesville, and 1.5 m for Zaragoza soils).

Initial soil water content (SWO). These were given in DSSAT files for the Gainesville and Zaragoza studies. In the case of Bushland, the SWO for 1989 and 1990 was taken from the first neutron probe measurement for the seasons which were measured on 7 June 1989 and 24 May 1990. These SWOs turned out to be noncritical, as 36 mm of irrigation were applied over 2 d, 1 d after sowing for both years. The SWO for 1994 was extracted from Fig. 2 of Howell et al. (1998).

Data Analysis

The performance of the model was evaluated using the following statistical parameters: the root mean square error (RMSE), calculated as

$$RMSE = \sqrt{1/(N)\sum_{i=1}^{N}(O_i - S_i)^2} \qquad [3]$$

and the coefficient of efficiency (E) (Nash and Sutcliffe, 1970) is calculated as

$$E = 1 - \frac{\sum_{i=1}^{N}(O_i - S_i)^2}{\sum_{i=1}^{N}(O_i - \overline{O})^2} \qquad [4]$$

where S_i and O_i are the simulated and observed (measured) values as samples taken along the season (e.g., biomass and CC), or at the end of the season (e.g., grain yield), N is the number of observations, and $\overline{O}_i$ is the mean value of O_i.

The RMSE in Eq. 3 represents a measure of the overall, or mean, deviation between observed and simulated values, that is, a synthetic indicator of the absolute model uncertainty. In fact, it takes the same units of the variable being simulated, and therefore the closer the value is to zero, the better the model simulation performance.

The coefficient of efficiency (E, Eq. [4]) expresses how much the overall deviation between observed and simulated values departs from the overall deviation between observed values (O_i) and their mean value ($\overline{O}$). The added value of this statistical indicator (E) as compared to RMSE, is in its ability to capture how well the model performs over the whole simulation span, for example, along the season. In other words, while RMSE does not distinguish between large deviations occurring in some part of the season and small deviations in other part of the season, E accounts for the different deviations, as they depart from ($O_i - \overline{O}$) along the season and expresses an efficiency of the model

performance, that is, the smaller the departure from ($O_i - \overline{O}$), the higher the performing efficiency of the model. The E is unitless and may assume values ranging from $-\infty$ to +1, with better model simulation efficiency when values are closer to +1.

RESULTS AND DISCUSSION

The results are presented and discussed by location. For each location, comparisons were made between simulated and measured values of CC and cumulative biomass as sampled at intervals over the growing season, and the final biomass and grain yield. In addition, data of daily lysimeter measured ET were available for Bushland to compare with simulated daily ET. Similarly, dry mass of growing grain at different times were available for Gainesville and these were also compared with simulated values.

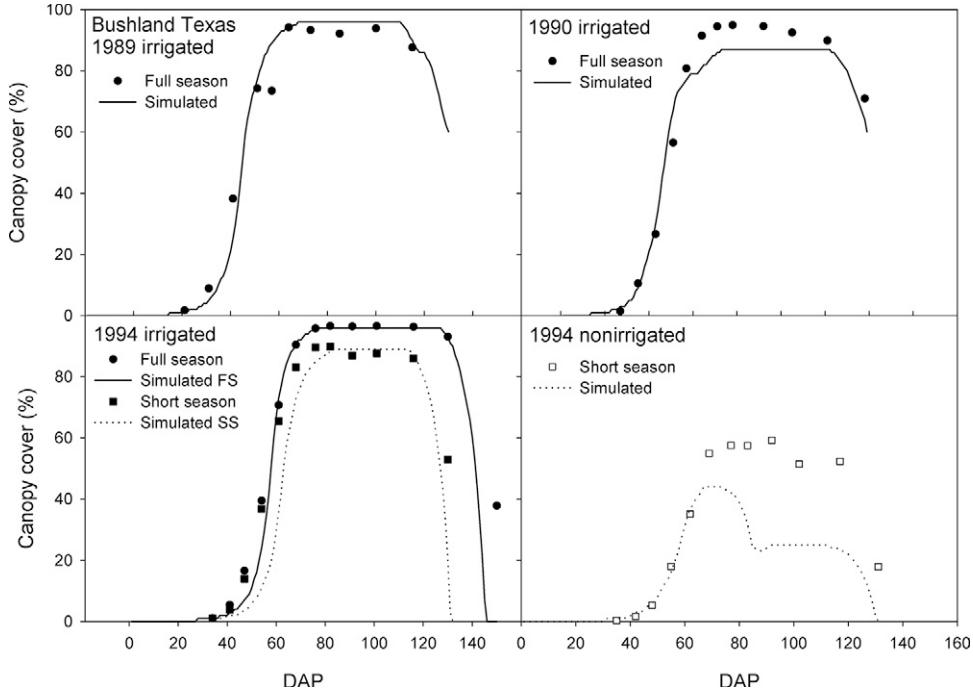

Fig. 2. Simulated (line) versus measured canopy cover (filled circles) of maize over three seasons (1989, 1990, and 1994) for Bushland, TX. In 1994, an irrigated (filled squares) and nonirrigated (open squares) short-season hybrid was also performed. FS, full season; SS, short season.

Bushland

AquaCrop was able to simulate accurately the CC development of 1989 and both the full and short seasons irrigated treatments in 1994 for Bushland (Fig. 2). There was a slight mismatch in the last senesced CC measurement in 1994, with the measured CC declining slightly faster compared with simulated CC for both the full and short season irrigated treatments. The good agreement between measured and simulated CC is also reflected in the statistical analysis given in Table 4, with high coefficient of efficiency (E) obtained for these treatments. On the other hand, the maximum CC in the 1990 irrigated treatment was slightly underestimated. The CC of the nonirrigated short-season treatment in 1994 was also not well simulated after Day 70, with simulated CC declining faster than measured CC values. As a result, lower E value was obtained for this nonirrigated treatment (Table 4).

The biomass production for the three seasons of irrigated treatments in Bushland was simulated accurately (Fig. 3). The model was able to properly simulate the 1989, 1990, and both the full- and short-season irrigated biomass in 1994. This is shown by the low RMSE and high E (close to 1.00) values (Table 4). Contrary to the underprediction in the CC in the nonirrigated short-season treatment in 1994,

Table 4. The root mean square error (RMSE) and coefficient of efficiency (E) between measured canopy cover (CC), biomass, grain yield, and evapotranspiration (ET) values and simulated results shown in Fig. 2, 3, and 4 for Bushland, Gainesville, and Zaragoza. Values in parentheses in the Zaragoza results were obtained when the simulation was rerun using a 15% higher ETo value.

	RMSE	E	RMSE	E	RMSE	E	RMSE	E
	%		t ha^{-1}		mm		t ha^{-1}	
Bushland	CC		Biomass		ET			
1989 irrigated	6.88	0.96	1.97	0.93	1.58	0.49		
1990 irrigated	7.01	0.99	1.24	0.98	2.15	0.87		
1994 irrigated FS†	5.33	0.98	0.79	0.99	2.22	0.89		
1994 irrigated SS	15.42	0.84	0.46	1.00	2.85	0.79		
1994 nonirrigated SS	7.16	7.16	1.76	0.62				
Gainesville	CC		Biomass				Grain Yield	
1982 full irrigation	11.63	0.81	0.86	0.99			1.57	0.89
Vegetative stress	7.06	0.91	2.90	0.75			0.65	0.97
Rainfed	34.53	–2.01	1.56	0.77			1.33	–0.47
Zaragoza	CC		Biomass					
1995 full irrigation	5.06 (4.67)	0.98 (0.98)	4.04 (4.43)	0.83 (0.83)				
1995 50% irrigation	5.52 (4.94)	0.98 (0.98)	1.39 (1.36)	0.97 (0.97)				
1995 33% irrigation	8.09 (5.52)	0.93 (0.97)	6.51 (4.98)	–4.88 (–2.44)				

† FS, full season; SS, short season.

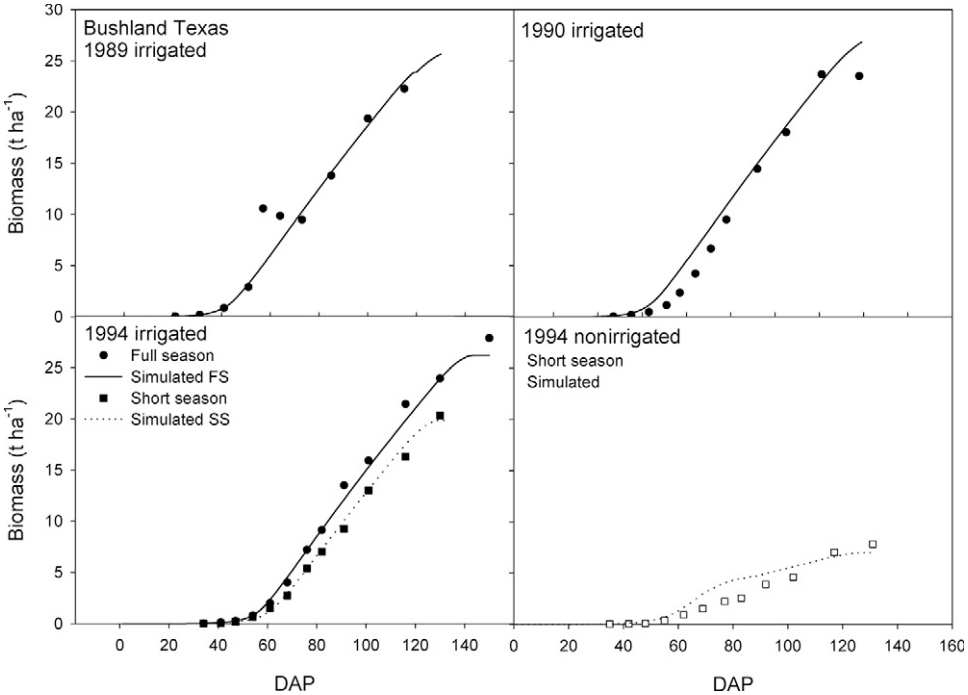

Fig. 3. Simulated (line) versus measured biomass accumulation (filled circles) of maize over three seasons (1989, 1990, and 1994) for Bushland, TX. The biomass of the irrigated (filled squares) and nonirrigated (open squares) short-season hybrid in 1994 was also presented.

the model simulated the biomass production that year fairly well.

Howell et al. (1996) reported that in 1989, 10 d after emergence of the crop, hail beat the plants to ground level. Although the crop was reported to recover and grow normally, crop development had to start from the beginning, delaying the emergence of the crop. This effect was accounted for in the simulation by adding 22 d to the emergence date given by Howell et al. (1996). The fact that the simulated CC closely matched the measured CC lends support to this approach and validates the algorithm used for canopy development (Steduto et al., 2009).

The observed and simulated final biomass and grain yields are given in Table 5. The comparison of the biomass yields shows that the majority has a deviation of less than 5%. And for the final grain yields, the comparison between measured and simulated values was also within 3% in three out of the four cases (no grain yield was given in the nonirrigated treatment in 1994). Simulated grain yield was within 2% of measured yields in 1989, while grain yield prediction was off by 12.4% in the 1994 irrigated full-season hybrid, although the final biomass was accurately simulated.

The model was also validated for its ability to simulate daily ET over the season as measured by weighing lysimeters for the 3 yr (Fig. 4). The model predicted some very high ET peaks at the start of 1990 and 1994 full season irrigated treatments due to the high input temperature and wind data, which seems to over predict measured values. Perhaps more detailed examination of input data is needed. It is also possible that under such high evaporative demand, stomata of the crop might have been partly closed and the effect of high ET_o on stomatal response (Steduto et al., 2009) as currently set needs adjustment. In general, the model gave better ET prediction in 1990 and for the two irrigated treatments in 1994, but predicted less accurately in 1989, as can be seen from the statistical analysis of Table 4. The measured and simulated total ET for the 3 yr is presented in Table 5.

Table 5. Measured and simulated final biomass, grain yield and canopy cover for all the experiments with AquaCrop. Values in parentheses are simulations using 15% higher ETo. Also presented is the total measured and simulated evapotranspiration (ET) and water use efficiency (WUE) in Bushland.

	Final biomass		Final grain yield		Total ET		WUE		Runoff/deep percolation
Treatment†	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated	Simulated
	t ha^{-1}				mm		kg m^{-3}		mm
Bushland									
1989 FI	22.3	25.6	12.4	12.1	625.0	598.0	1.98	2.02	15/90
1990 FI	26.2	26.8	13.1	12.7	730.8	778.3	1.79	1.63	9/3
1994 FI (FS)	27.8	26.2	13.2	12.3	882.1	808.0	1.50	1.52	1/134
1994 FI (SS)	20.4	19.9	11.3	9.5	696.0	687.0	1.63	1.38	1/70
1994 NI (SS)	7.8	7.0	NA‡	3.4	NA	369.0		0.92	0/2
Gainesville 1982									
FI	22.0	21.9	11.9	10.3	NA	449		2.29	127/367
Veg. Stress	17.1	20.4	9.3	9.6	NA	431		2.23	127/322
NI (rainfed)	7.2	7.3	3.1	0.14	NA	259		0.05	136/283
Zaragoza 1995									
FI	24.0	24.3 (24.3)	11.0	11.4 (11.7)	NA	–			0/209
50% FI	20.0	24.3 (24.2)	7.6	11.4 (11.6)	NA	–			0/49
33% FI	6.6	20.0 (16.7)	1.0	9.6 (8.0)	NA	–			0/27

† FI = full irrigation, NI = no irrigation, FS = full season, SS = short season.

‡ NA = not available.

The actual and simulated WUE of grain yield was calculated for the four treatments in Bushland. The regression line of simulated WUE (WUE_s) versus measured WUE (WUE_m) values fell close to the 1:1 line (Fig. 5) and with a reasonably small standard error of 0.17 kg m^{-3}. Simulated values of WUE were similar to other values reported from Bushland where WUE of maize tends to be less than at other locations due to the very high evaporative demand at Bushland. The values are slightly larger than values reported by Norwood and Dumler (2002) for limitedly irrigated maize at Garden City, Kansas, which is north of Bushland on the U.S. Great Plains. They are midway between values reported by Di Paolo and Rinaldi (2008) for irrigated maize in Italy. The WUE values are also quite similar to values reported for subsurface drip irrigated maize in Colby, KS (Lamm and Trooien, 2003), and for surface and subsurface drip irrigation maize at Bushland (Evett et al., 2000).

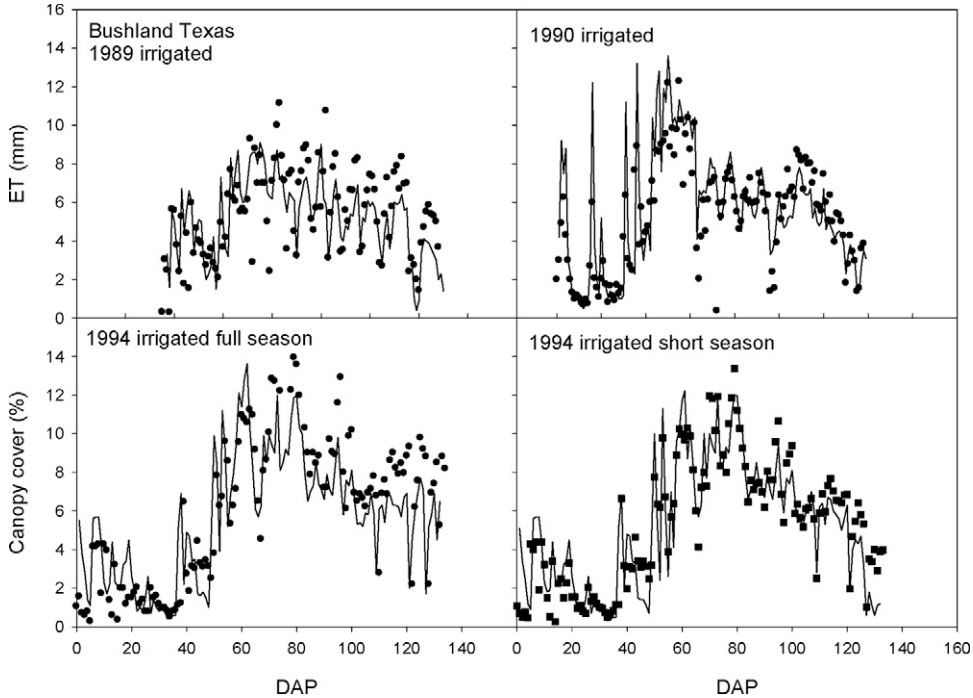

Fig. 4. Simulated (line) versus measured daily ET of maize over three full (filled circles) seasons (1989, 1990, and 1994) and that of a short season (filled squares) in 1994 for Bushland, TX.

Gainesville

For the Gainesville study, the simulated CC for fully irrigated and vegetative stress treatments agree well with measured values except during senescence, when the simulated CC tends to decline too early compared with measured CC (Fig. 6). For the rainfed treatment, the model was not able to simulate the drastic slowing down of the stress-induced early senescence due to the 40 mm of rain which fell around 86 DAP. The stress-induced decline in CC is a highly demanding test of the model since a small deviation in the simulated timing can lead to a marked difference in CC duration. Biomass production was well simulated in the fully irrigated treatment, but it was overpredicted through the whole season in the vegetative stress treatment, especially for the period after the stress was released by irrigation and later, rain. For the rainfed treatment, the biomass was substantially overpredicted up to 70 DAP, possibly because of the slight overprediction of CC over the same period and the actual stomatal conductance being less than the simulated. Fortuitously, the final biomass was virtually the same for the simulated and measured because actual biomass continued to accumulate after 86 DAP (when the simulated CC became zero), making up for the difference caused by the overprediction by the model up to 70 DAP. The accumulation of biomass in grain for the vegetative stress treatment was also relatively well-simulated but underpredicted in the fully irrigated treatment. The question of grain biomass is not relevant for the rainfed treatment simulation since the simulated CC died just when the grain began to gain mass. Table 4 presents the statistics of the above simulations. The lower E values and high RMSE for CC of the irrigated treatment were due to the last two CC data points, where the simulation model declined much too early compared with measured values.

Zaragoza

The 50% irrigation treatment involved omitting alternate irrigation of the full irrigation treatment throughout the season, while the 33% irrigation treatment applied one irrigation in each growth phase (i.e., 65 mm on 26 June, 52 mm on 28 July, and 57 mm on 5 September). The simulated CC for the full irrigation and 50% irrigation treatments in the 1995 Zaragoza study are in good agreement with measured values (Fig. 7), as reflected in the high E values (Table 4). However, CC for the 33% irrigation treatment was overpredicted. It was not possible to compare simulated CC with measured during

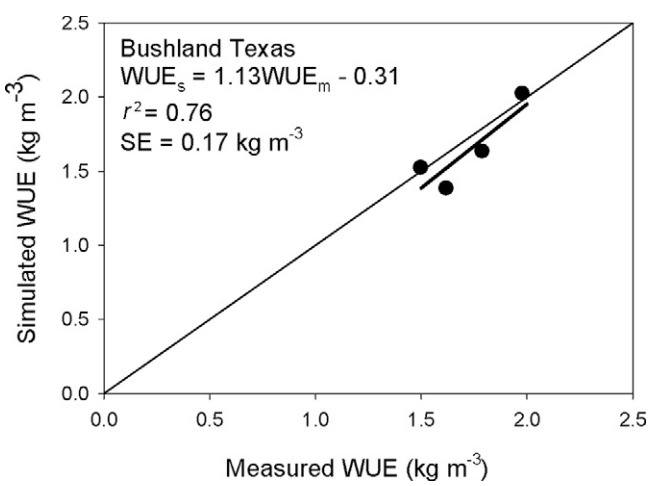

Fig. 5. Simulated WUE (WUE_s) and measured water use efficiency (WUE_m) of maize for the 1989, 1990, and 1994 (full and short) seasons in Bushland, TX.

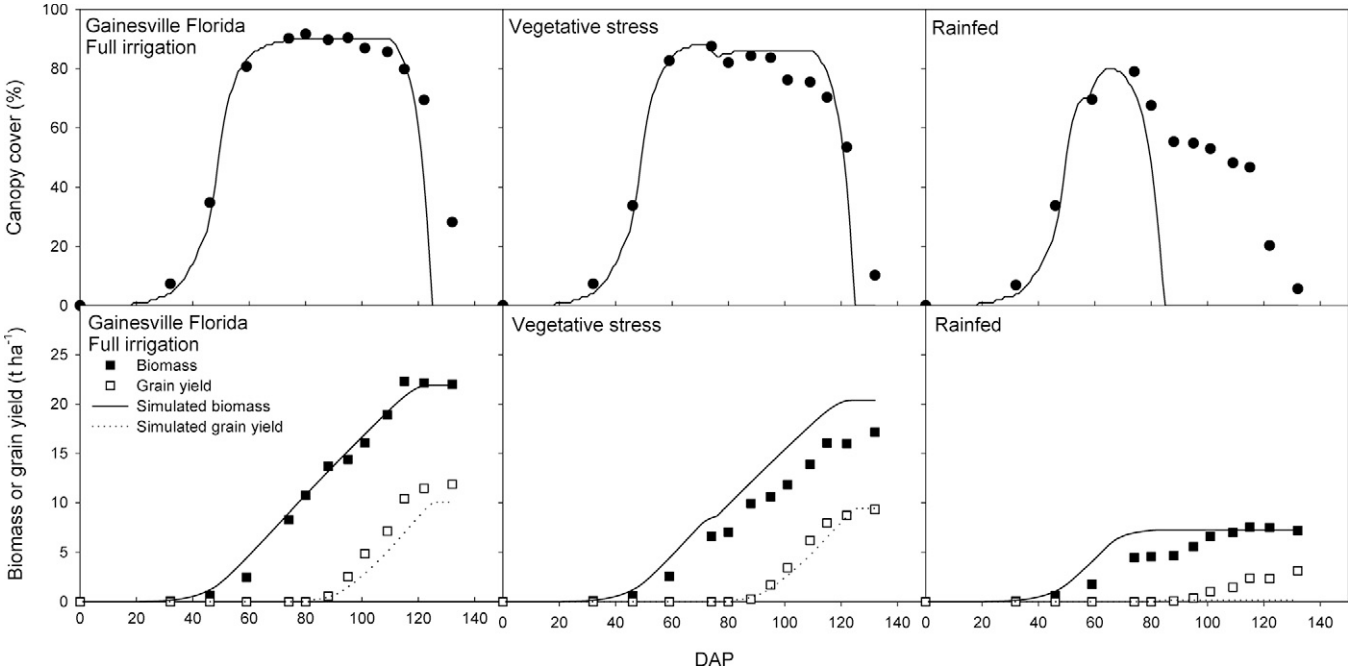

Fig. 6. Simulated (line) versus measured canopy cover (filled circles), biomass (filled squares), and grain yield (open squares) accumulation of maize for the full, vegetative stress and rainfed treatments in Gainesville, FL.

senescence decline, as no LAI data were given for that period in Fig. 4 of Cavero et al. (2000). The measured and simulated biomass accumulation in the Zaragoza study was also in close agreement for the fully irrigated and 50% irrigation treatments, but the model again overpredicted the 33% irrigation treatment. In addition to the three treatments depicted in Fig. 7, there were five other water stress treatments performed, with stress for each treatment occurred in one or more of the three growth phases (i, ii, or iii). For these treatments, only the measured final biomass and grain yield were given. In those cases, AquaCrop tends to overestimate both the final biomass and yield, for both 1995 and 1996 (Fig. 8).

Many studies have shown that the Hargreaves equation tends to overestimate ET_o in humid regions and underestimate ET_o in very dry regions (Jensen et al., 1990, Droogers and Allen, 2002). Since Zaragoza is semiarid, the use of the Hargreaves equation is likely to lead to underestimation of ET, making it possible for the simulated crop to have a higher productivity than the actual crop for the same amount of water consumed. When the above simulations were rerun with

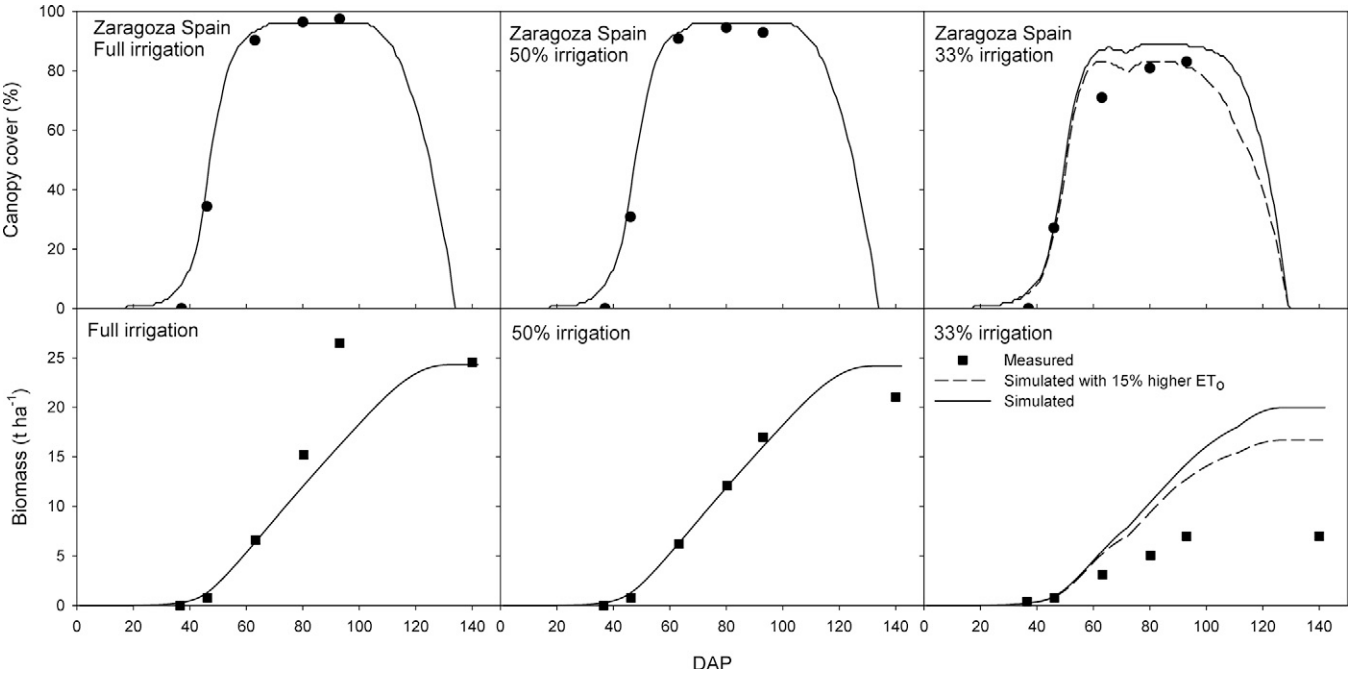

Fig. 7. Simulated (line) versus measured canopy cover (filled circles), and biomass (filled squares) accumulation of maize for the 1995 full, 50% and 33% irrigation treatments in Zaragoza, Spain. The dotted line represents the simulation using a 15% higher ET_o (see text for explanation).

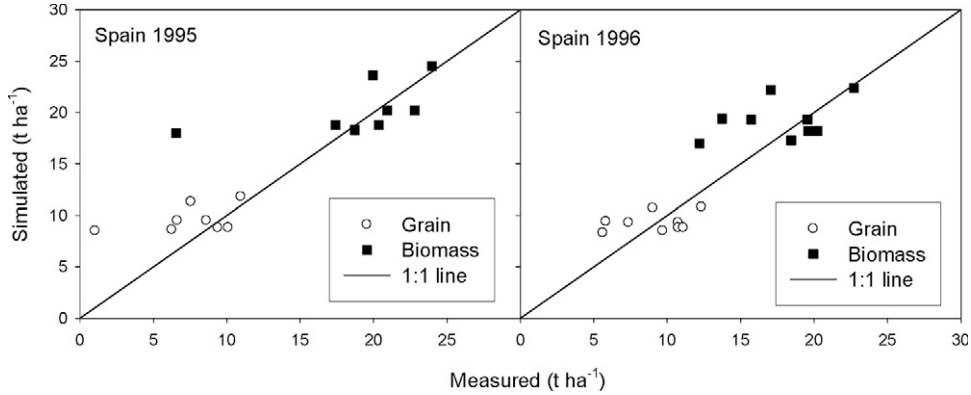

Fig. 8. Simulated and measured final biomass (filled squares) and grain yield (open circles) of all irrigation treatments in the 1995 and 1996 experiments conducted in Zaragoza, Spain.

15% added to the Hargreaves' ET_o estimate, good agreement between measured and simulated CC and improved biomass prediction was obtained in the 33% irrigation treatment, while the difference it made in the CC and biomass prediction of the 100 and 50% irrigation treatments was minor (Fig. 7). Nevertheless, the biomass was still overpredicted for the 33% irrigation treatment. The statistics obtained when using the 15% higher ET_o for CC and biomass are given in parentheses in Table 4. The corresponding final grain yield for the three treatments when using the higher ET_o is presented in Table 5. The discrepancy between measured and simulated results in the drier treatments could also be due to the variable soil depth as reported in Cavero et al. (2000). The spatial variability of the soil could cause some differences in measured values especially in the water stress treatments.

In all the above simulations, there were considerable uncertainties about the rooting depth estimates, especially for Florida and Zaragoza, as soil depths given in the ICASA Data Exchange were assumed to be the rooting depth, which might introduce some uncertainty. In addition, the ET_o data for Gainesville and Zaragoza were calculated by the Hargreaves equation instead of the desired FAO Penman–Monteith equation, which introduced further level of uncertainty. The use of a single set of soil characteristics in a spatially variable soil in the simulation irrespective of where the crops were grown on the experimental field can also generate substantial uncertainty. This uncertainty also applies to the estimation of SWO, which further increases the uncertainty in the simulation (Hsiao et al., 2009).

CONCLUSIONS

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, TX.

Considering that all the conservative parameters were taken from Hsiao et al. (2009), developed for maize in Davis, CA, and used without any adjustment, these results can be considered remarkable. The studies presented here also covered environments very different from that in Davis, that is, the extremely windy conditions of Bushland and consequently the very high ET_o, and the humid and rainy weather in Gainesville, FL. The seasonal rainfall ranged from 45 mm in Zaragoza to more than 670 mm in Gainesville. Within each location, different irrigation regimes were practiced. In the Bushland and Gainsville studies, irrigation was by overhead sprinklers, whereas in Zaragoza the crop was flood irrigated. Overall, this study involved five maize cultivars, including a comparison of a full- and a short-season hybrid. In Gainesville, FL, three water treatments (i.e., full irrigation, vegetative stress, and a rainfed) were performed. In Spain, the study consists of three water treatments where maize was flood irrigated to 33, 50, and 100% of potential ET over the whole season, and five other treatments with stress imposed at three different phases of growth. In addition, these studies also differ in their planting dates, ranging from February in Gainesville to April or May in Bushland and Zaragoza. Equally important, the three locations differed in soil types, with fine sand in Gainesville, sandy loam in Zaragoza, and clay loam in Bushland.

While some difficulties were encountered by AquaCrop in simulating strong water stress treatments, it could be the fault of the model, or it could also be errors in measurement (e.g., the Spanish data showed good canopy but very low biomass for the 33% irrigation treatment) or input data (ET_o from Hargreaves instead of Penman–Monteith). For water-deficient conditions, soil water characteristics are of critical importance, but it is not uncommon for field capacity and permanent wilting percentage to be estimated by different procedures with somewhat different outcome. AquaCrop strives to achieve a balance between accuracy and simplicity for nonresearch end users; bypassing many detailed processes. Nevertheless, even with the rather extensive simplification as discussed in Steduto et al. (2009) and Hsiao et al. (2009), the model has been shown to be robust in the simulation of most of the maize data examined here, as well as those from Davis, CA (Hsiao et al., 2009). AquaCrop also appears to be relatively insensitive in terms of biomass production to some inaccuracy in the simulation of the last portion of the canopy senescence phase.

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.

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