Agricultural Water Management 177 (2016) 274–283

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Simulation of crop evapotranspiration and crop coefficients with data in weighing lysimeters

Saseendran S. Anapalli[a,*], Lajpat R. Ahuja[b], Prasanna H. Gowda[c], Liwang Ma[b], Gary Marek[d], Steven R. Evett[d], Terry A. Howell[e]

[a] USDA-ARS, Crop Production Systems Research Unit, Stoneville, MS, United States
[b] USDA-ARS, Agricultural Systems Research Unit, Fort Collins, CO, United States
[c] USDA-ARS, Forage and Livestock Production Research Unit, El Reno, OK, United States
[d] USDA-ARS, CPRL, 2300 Experiment Station Road, Bushland, TX 79012, United States
[e] Retired USDA-ARS, P.O. Box 5649, Lago Vista, TX 78, United States

ARTICLE INFO

Article history:
Received 10 May 2016
Received in revised form 26 July 2016
Accepted 6 August 2016

Keywords:
Evapotranspiration
Crop coefficient
Lysimeter
Agricultural system model
Irrigation
Water management

ABSTRACT

Accurate quantification of crop evapotranspiration (ET) is critical to optimizing irrigation water productivity, especially, in the semiarid regions of the world where limited rainfall is supplemented by irrigation for crop production. In this context, cropping system models are potential tools for predicting ET or crop water requirements in agriculture across soils and climates and assist in developing decision support tools for irrigation. The objective of this study was to evaluate the accuracy of RZWQM2 simulated ET for fully irrigated silage (2006 and 2007) and grain corn (1990) against measured crop water use and soil evaporation with large weighing lysimeters in the Texas High Plains. An extended Shuttleworth and Wallace method was used to estimate potential crop ET (E and T) demand in RZWQM2. The Nimah and Hanks approach was used for crop water uptake and Richard's Equation for soil water redistribution modeling. Simulations of biomass, leaf area index, soil water storage, and ET were reasonably close to the measured data. Root Mean Squared Deviation (RMSD) for corn biomass was between 1 and 2.1 MT ha^{-1}, LAI between 0.33 and 0.88, water in the soil between 2 and 2.9 cm for a 190 cm soil profile, and actual daily crop ET between 1.0 to 1.5 mm across the three years of measured data. Arithmetic mean deviation (MD) for ET ranged from −0.10 to 0.40 mm. Fallow soil evaporation before and after corn planting was simulated within MD of −0.03–0.003 mm. The crop coefficients (Kc) calculated with measured ET and the short grass or alfalfa crop reference ET methods varied from year to year. The Kc values obtained by using the simulated ET and alfalfa reference ET were close to Kc values using measured ET, within RMSD of 0.17, and could be used to obtain long-term average Kc values for scheduling irrigation.

1. Introduction

The semi-arid regions of the world, like the western US, are crucial agricultural areas for feeding the world; however, much of agriculture in this region is water-limited. Water scarcity in these regions is expected to increase further not only from competing human enterprises (for example, drinking, sanitation, urban irrigation, industry, and ecosystem services) but also from global warming arising from increasing greenhouse gas (GHG) concentrations in the atmosphere (Solomon et al., 2007; Field et al., 2014). Many global climate models (GCM) project a more intense and variable hydrologic cycle in the future with altered precipitation patterns, and greater frequency of severe droughts in these areas (Field et al., 2014). Prolonged drought in the last decade in these semiarid regions has increased water scarcity for both dryland and irrigated production (Kahil et al., 2014). In the emerging scenario, there is widespread human concern that crop productivity will decline in the coming years when the demand for produces is virtually escalating. At this juncture, it is critical that we develop water management practices that are more water use efficient than what have been developed in the past. To obtain an optimum return from limited water (rainfall and irrigation) available for agricultural use, farm advisors and producers need whole-system based quantitative knowledge and information on crop water demands (evapotranspiration, ET) and available water supplies for precision

---

[*] Corresponding author.
E-mail addresses: Saseendransa@hotmail.com, saseendran.anapalli@ars.usda.gov (S.S. Anapalli).

http://dx.doi.org/10.1016/j.agwat.2016.08.009
0378-3774/

management on site-specific or field-specific bases (Hsiao et al., 2007).

Whereas field measurements can help us quantify ET directly in a crop-field, they are expensive for long-term data collection to capture location-specific climate variability impacts on ET for irrigation water management. In this context, state-of-the-science agricultural system models have been widely accepted tools for developing water management information for increased water productivity in agriculture (McNider et al., 2015; Saseendran et al., 2015; Okada et al., 2015). However, it is very critical that the ET processes simulated in the cropping system models used for water management research respond accurately to not only the current weather but also to the increased carbon dioxide, climate warming and greater weather variabilities associated with the climate change in the future. Bassu et al. (2014, unpublished data) found that for the same conditions, the simulated ET varied 2-fold among the 23 maize models developed around the world, and Rosenzweig et al. (2013, unpublished data) also made similar observations. These findings point towards the need for a more critical look at the ET simulations used in cropping system models and to evaluate them against precisely measured experimental data, such as in large weighing lysimeters.

The ET simulations have several major components: potential evapotranspiration (PET) that is imposed by the weather conditions (energy limited), partitioning of PET into potential transpiration (*PT*) and evaporation (*PE*), soil water, actual crop water uptake, actual transpiration (*AT*), actual soil water evaporation (*AE*), and water stress effects on leaf area growth which affects all the above components. For computations of PET, Monteith (1965) presented a single layer – an extended fully grass covered soil – Penman-Monteith (P-M) combination equation. Shuttleworth and Wallace (1985, S-W) extended this model for simulating PET from the entire range of canopy cover encountered, generally, in crop fields: partial canopy and bare soil by specifying resistances to energy exchanges at the canopy and bare soil surfaces, thus, opening a way for partitioning PET into PE and PT. Farahani and Ahuja (1996) extended the S-W model to include the effects of surface residue on soil evaporation, which was implemented in the USDA-ARS (United States Department of Agriculture – Agricultural Research Service) crop system model, called the Root Zone Water Quality Model (RZWQM2).

The RZWQM2 simulates other ET-related components as follows (see Ahuja et al., 2000 for details and references). The soil water is simulated by numerical solution of the extensively tested Green-Ampt approach during rainfall or irrigation water infiltration and by the state-of-the-science Richards equation during water redistribution in the soil profile. Root water uptake (AT) is simulated by the Nimah-Hanks approach (Nimah and Hanks, 1973) and is a sink term in the Richards equation solution. The Nimah-Hanks approach is a macroscopic approach to estimate root water uptake rate from each soil layer in the model. The uptake rate is directly proportional to water potential gradient between soil water and root water, multiplied by the soil water hydraulic conductivity, and divided by the root resistance to water flow. The soil evaporation (AE) is simulated as an upward surface flux in the Richards equation. The PT and PE are set as upper limits of AT and AE, respectively. The model contains the crop growth modules, such as the CSM-CERES-Maize v4.6 module, from the DSSAT cropping system model (Jones et al., 2003; http://arsagsoftware.ars.usda.gov/agsoftware/). The water stress effects on photosynthesis and leaf growth in the CERES-Maize module have been widely tested and improved (e.g., Saseendran et al., 2013). Although the RZWQM2 has been extensively used to simulate crop production (Ahuja et al., 2014; Islam et al., 2012; Ma et al., 2012; Nielsen et al., 2012; Saseendran et al. 2010, 2014a,b), details of the ET related modules described above need to be tested against precisely measured data and improved.

Using the original Penman-Monteith (P-M) equation to estimate PET for a crop with full canopy cover, as well as the Shuttleworth-Wallace (S-W) equation for incomplete cover, in the crop models requires dynamic crop growth information for the given crop and cultivar on a daily or hourly basis, besides the weather data, to calculate aerodynamic and canopy resistances and actual ET. This crop, cultivar, and growth stage specific detailed process level modeling approach advances our scientific understanding of the ET related processes and their interactions, needed for developing new ideas for increasing crop water use efficiency. However, this approach is too difficult to use for ET-based irrigation scheduling in the field for all the various crops. For practical irrigation water management, Doorenbos and Pruit (1977) published a simple and widely used two-step approach for estimating PET for a crop of interest, designated as ETc:

$$\mathrm{ETc} = \mathrm{ETr} \times \mathrm{Kc}$$

where ETr is the PET for a reference crop surface, such as fully irrigated short grass or alfalfa, and Kc (unitless) is the crop coefficient for the crop of interest, such as maize or corn (Allen et al., 1998). Thus, the Kc is calculated as:

$$\mathrm{Kc} = \frac{\mathrm{ETc}}{\mathrm{ETr}} \tag{1}$$

Again, ETc is the potential crop evapotranspiration, specific to a crop species and cultivar, traditionally estimated from water balance measurements in the field or lysimeters under fully irrigated conditions.

The ETr is computed from weather data by assigning fixed resistances for the reference crop surface in the P-M equation, and the Kc adjusts this ETr for given crop species, cultivar, canopy cover, and management characteristics to get the ETc. Fully irrigated short grass (0.12 m tall) or alfalfa (0.50 m tall) with full canopy cover are the accepted reference surfaces. The ASCE-Environmental and Water Resources Institute (ASCE-EWRI, 2005) and FAO Irrigation and Drainage Paper no. 56 (Allen et al., 1998) present ETr computation methods and Kc values for a variety of plants and conditions. It will be very useful to compare the Kc values derived in this two-step approach using the lysimeter measured ETc to Kc values estimated by using the ETc simulated with the extended S-W approach used in the RZWQM2 model.

The objective of this study was to evaluate the crop growth and ET components of RZWQM2 against precise data for fully irrigated corn grown in a large weighing lysimeter field in three different years (1990, 2006, and 2007) at the USDA-ARS Conservation and Production Research Laboratory in Bushland, Texas. We compared the ET values calculated by the RZWQM2 modules with the lysimeter measurements. We also explored how well the Kc values derived from using the simulated ET and short grass or alfalfa reference crops compare with those obtained from using lysimeter measured ET values with the reference crops. If successful, the former approach will make it easier to obtain average Kc values for different crops and cultivars for scheduling irrigation in the field.

2. Materials and methods

2.1. Lysimeter measurements

The lysimeter data for three different years (1990, 2006, and 2007) for fully irrigated corn was obtained from the USDA-ARS Conservation and Production Research Laboratory at Bushland, Texas (35° 11′ N, 102° 06′ W, 1170 m elevation above MSL) (Evett et al., 2015). The experiments were conducted in three large (3 × 3 × 2.5 m) high precision, weighing lysimeters, without replications. The lysimeter contains undisturbed monoliths of Pullman silty clay loam soil (fine, mixed, superactive, thermic Torrertic

Paleustoll). In the top 0.30 m of soil, the mean clay content is 0.33 g g^{-1}, the mean bulk density is 1.39 g cm^{-3} and the mean organic matter content is 0.018 g g^{-1}. A calcareous layer at about 1.4 m depth limits significant rooting below this depth. Each of the lysimeters is located in the center of a 4.4 ha, 210 m (E-W) by 210 m (N-S) field. There are four fields arranged in a square pattern, oriented to the cardinal points and contiguous and designated NE (northeast), SE (southeast), NW (northwest) and SW (southwest) plots/fields. Lysimeter mass is determined using a data logger (model CR7, Campbell Scientific, Inc., Logan, Utah) to measure and record the lysimeter load cell signal at 6-s intervals. The load cell signal is averaged for 5 min and composited to 30 min means (reported on the mid-point of the 30 min, i.e., data will be averaged from 0 to 30 min and reported at 15 min). Lysimeter mass resolution is 0.01 mm, and calibrated accuracy is 0.04–0.05 mm (Evett et al., 2012; Howell et al., 1995). A 15-min and daily ET values are determined as the difference between lysimeter mass losses (from evaporation and transpiration) and lysimeter mass gains (precipitation, or dew) divided by the lysimeter area (9 m^2). A pump regulated to 10 kPa vacuum provides drainage, and the drainage effluent is held in two tanks suspended from each lysimeter (their mass is part of the total lysimetric mass) and independently weighed by load cells. ET for each 24-h period is multiplied by 0.98 to adjust the lysimeter area to the mid-point between the two walls (10 mm air gap; 9.5 mm wall thickness; 9.18 m^2 area instead of 9.00 m^2 inside soil area). Lysimeters are operated as either irrigated or dryland depending on the experiment. Irrigated fields were equipped with a 10-span lateral-move sprinkler system (Lindsay Manufacturing, Omaha, NE). Irrigations were applied to field capacity based on weekly neutron probe measurements to maintain the soil water content always above the 50% level of maximum allowable depletion. Air temperature, wind speed, relative humidity, solar radiation, precipitation, and soil water contents were measured at each lysimeter.

The irrigated, for no water stress, corn data used in this study was obtained from the NE lysimeter for years 1990 and 2006, and from the SE lysimeter in 2007 (these three years have corn growth data adequate for modeling using the RZWQM2). In the lysimeter experiments, corn hybrid PIO 3124 was planted on May 9 in 1990, and hybrid NC + 7373RB (NC + Hybrids, Lincoln Neb.) was planted on May 11 in 2006 and May 17 in 2007, respectively, for silage harvesting only. The 2006 crop was damaged by a severe hailstorm and was replanted with a short-season hybrid (NC + 3723RB) on July 3. In the three years of this study (1990, 2006, 2007), the monthly mean daily minimum temperature varied between 8 °C in May 1990 and 18.2 °C in July 2006; similarly, monthly mean daily maximum temperature varied between 24.2 °C in May 1990 and 35.1 °C in June 1990 (Table 1). Total growing season rainfall varied between 16.5 cm in 1990 and 32.1 cm in 2006, total applied irrigation varied between 27.4 cm in 2006 and 58.5 cm in 1990, and total ET measured in the lysimeter varied between 67.4 cm in 2006 and 73.3 cm in 1990.

Quality control and assurance of lysimeter and weather data are maintained through daily graphing and visual inspection for obvious errors, missing values, and exceedance of physically possible values. Daily lysimeter ET data were computed as the difference between midnight centered, 5-min average lysimeter mass values, expressed as an equivalent depth of water in mm. When necessary, adjustments to daily ET values were performed to address gains in lysimeter mass corresponding to dew and frost accumulation, and precipitation and irrigation events using techniques detailed by Marek et al. (2014). These techniques provide reasonable daily ET values for use in modeling environments requiring continuous daily data. Field soil profile water contents were determined by neutron probe, periodically during the crop growing season, to 2.4 m depth with measurements in increments of 0.2 m beginning at 0.1 m depth using a depth control stand to ensure accuracy at the 0.1 m depth (Evett et al., 2003). Periodic measurements of biomass and leaf area index (LAI), pooled from four subsamples, were made using destructive sampling method. Summary of the weather data for three years of this study (1990, 2006, 2007) are given in Table 1.

Table 1

Corn growing season weather in 1990, 2006, and 2007: monthly mean daily min temperature (Tmin) and maximum temperature (Tmax), and monthly total precipitation and irrigations.

	1990				
	Tmin °C	Tmax °C	Rain cm	Irrigation cm	ET lysimeter cm
May	8.0	24.2	2.1	5.6	6.9
June	16.8	35.1	0.5	15.8	15.8
July	16.4	30.3	7.7	17.9	21.2
August	15.9	30.2	4.2	13.8	18.8
September	14.6	29.1	2.0	9.8	10.5
Total			16.5	62.9	73.3
	2006				
May	11.9	29.1	2.21	5.3	6.6
June	16.0	33.2	4.2	13.7	15.9
July	18.2	33.3	7.1	13.0	13.7
August	17.9	30.6	14.8	12.1	18.4
September	12.0	25.2	3.7	2.2	12.9
Total			32.1	46.4	67.4
	2007				
May	10.0	24.4	4.5	2.0	6.5
June	14.3	29.1	5.3	5.6	12.3
July	16.3	31.5	3.9	16.0	22.1
August	17.6	32.7	3.6	18.0	20.8
September	14.5	28.9	5.9	1.8	10.2
Total			23.2	43.4	71.9

2.2. ET simulation in RZWQM2

The daily PT and PE are calculated from the daily weather variables (solar radiation, temperature, relative humidity, and wind speed) and crop-soil characteristics by the extended S-W approach, described in the Introduction. The PET is obtained by summing up the PE and PT estimates during a given time interval: $PET = PT + PE$. The PT is determined as:

$$PT = \left(\frac{\Delta\left[(R_n - G) - R_{nsub}\right] + \rho C_p \left(VPD_o\right)/r_a^c}{\left(\Delta + \gamma\left(1 + \frac{r_s^c}{r_a^c}\right)\right)} \right) \left(1/\lambda\right) \tag{2}$$

where, Δ is the slope of the saturation vapor pressure versus temperature curve; λ is the latent heat of evaporation of water; R_n is the net incoming hemispherical radiation above the canopy; G is the heat flux into soil below the canopy with components G_s and G_r into the bare soil and into the residue-covered soil; R_{nsub} is the net radiation below the canopy (=$C_sR_{ns} + C_rR_{nr}$); ρC_p the volumetric heat capacity of air; VPD_o is the air vapor pressure deficit at the measurement height; r_a^c is the bulk boundary layer resistance of the canopy elements within the canopy; r_s^c is the bulk stomatal resistance of the canopy; and γ is the psychrometric constant.

The PE is composed of two components:

$$PE = C_S PE_s + C_r PE_r \tag{3}$$

where, C_S and C_r are fractions of bare soil and residue covered soil surface areas ($C_S + C_r = 1.0$); and PE_S and PE_r are evaporation fluxes from bare and residue covered soil areas, determined as:

$$PE_s = \left(\frac{\Delta\left(R_{ns} - G_s\right) + \rho C_p \left(VPD_o\right)/r_a^s}{\Delta + \gamma\left(1 + \frac{r_s^s}{r_a^s}\right)} \right) \left(1/\lambda\right) \tag{4}$$

Table 2
Soil parameters estimated from field measured soil water contents.

Soil Depth (cm)	Sand (fraction)	Silt (fraction)	Bulk Density, ρ_b (g cm^{-3})	θ_s (cm^3 cm^{-3})	Θ_{fc}(cm^3 cm^{-3})	Θ_{wp} (cm^3 cm^{-3})	h_b (cm)	λ
0–15	0.170	0.530	1.26	0.442	0.280	0.185	1.92	0.132
16–41	0.130	0.388	1.48	0.442	0.280	0.185	1.92	0.182
42–74	0.130	0.400	1.60	0.396	0.267	0.181	0.91	0.138
75–112	0.150	0.408	1.58	0.404	0.248	0.157	1.69	0.168
112–189	0.193	0.372	1.65	0.377	0.244	0.167	1.00	0.182

θ_s, θ_{fc} and θ_{wp} are soil water contents at field saturation, field capacity (drained upper limit) and plant wilting point (drained lower limit). h_b is the air entry water suction, and λ the pore size distribution index obtained by fitting the Brooks-Corey equation for obtaining the soil water retention curve (Brooks and Corey, 1964).

where, R_{ns} is the net radiation absorbed by a unit area of bare soil; G_s is the heat flux into the bare soil r_s^s; is the soil surface resistance; r_a^s is the aerodynamic resistance between the ground surface and the mean canopy height.

$$PE_r = \left(\frac{\Delta\left(R_{nr} - G_r\right) + \rho C_p\left(VPD_o\right)/r_a^s}{\Delta + \gamma\left[1 + \left(r_s^s + r_s^r\right)/r_a^s\right]} \right)\left(1/\lambda\right) \tag{5}$$

where, R_{nr} is the net radiation absorbed by a unit area of residue; G_s is the heat flux into the residue-covered soil; r_s^r is the residue evaporative resistance acting in series with r_s^s.

Derivations and estimations of the parameters and inputs required for Eqs. (2) through (5) can be found in Farahani and Ahuja (1996) and Ahuja et al. (2000). The PT and PE computed from this method set the upper limits for actual AT and AE, respectively, in RZWQM2.

2.3. Model calibration

The soil horizons and their characteristics of texture, bulk density, field capacity, and wilting point water content of the Pullman silty clay loam soil in the lysimeters were available from measurements made nearby on the same soil type (Unger and Pringle, 1981). The initial estimates of the Brooks and Corey (1964) hydraulic parameters of air-entry soil water pressure head (h_b), pore size distribution index (λ), saturated hydraulic conductivity, and the unsaturated hydraulic conductivity as function of soil water content or pressure head were obtained by the pedotransfer functions provided in the model (Ahuja et al., 2000). To account for often-large spatial variability of these characteristics in a given soil type, the above parameters for specific conditions of the lysimeters were refined by calibration using the measured soil water contents in the lysimeters for one of the three years (1990) by inverse modeling. These specific parameters are given in Table 2.

The crop growth parameters required for simulating the corn hybrids used in this study were calibrated manually by adjusting the cultivar parameters following the protocols given by Ma et al. (2011). Measured crop growth characteristics of phenology, LAI and final biomass for the PIO 3124 corn hybrid for silage planted in 2007 were used in the calibration (Table 3). The calibrated parameters for the corn hybrid in 2007, worked well for simulating the cultivars planted in 2006 and 1990, thus not recalibrated again. The simulation results showed that under fully irrigated conditions, the leaf and biomass growth of the three cultivars in three different years were described well by the same parameters. The ET and Kc values were also not apparently influenced by the cultivar differences.

2.4. Statistics for model calibration and evaluations

We evaluated the simulation results using: (i) Root Mean Squared Deviation (RMSD), Eq. (6), between simulated and observed values; (ii) relative RMSD (RRMSD) that varies between 0 and 100%, Eq. (7), and (iii) the mean deviation (MD) between measured and simulated values, Eq. (8). The mean deviation can be +ve (indicating a positive bias in prediction) or −ve (indicating a negative bias in prediction).

Table 3
Plant parameters calibrated for simulations of corn hybrids in the lysimeter experiments at Bushland, TX during 1990, 2006, and 2007.

Acronyms used and definitions of traits.	Parameter values
P1 – Degree days (base temperature of 8 °C) from seedling emergence to end of juvenile phase (thermal degree days).	380
P2 – Day length sensitivity coefficient [the extent (days) that development is delayed for each hour increase in photoperiod above the longest photoperiod (12.5 h) at which development proceeds at maximum rate].	0.80
P5 – Degree days (base temperature of 8 °C) from silking to physiological maturity (thermal degree days)	520
G2 – Potential kernel number	1200
G3 – Potential kernel growth rate (mg/(kernel d)	9.99
PHINT – Degree days required for a leaf tip to emerge (thermal degree days)	45

$$RMSD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Pi - Oi)^2} \tag{6}$$

$$RRMSD = \frac{RMSD}{O_{avg}} \tag{7}$$

$$MD = \frac{1}{n}\sum(Pi - Oi) \tag{8}$$

where, P_i is the ith simulated value, O_i is the ith observed value, O_{avg} is the average of the observed values, and n is the number of data pairs.

These statistics are the most commonly used and give adequate idea on the accuracies of simulated results compared to the field measured data. One other statistic that we prefer to have was (RMSD/Standard Deviation (SD) or Standard Error (SE) of the measured data) for each variable. It will be ideal to have this ratio less than 1.0; in other words have the RMSD within one SD or SE of the measured data. Having this ratio less than 2.0 will be acceptable, that is to have RMSD within two SD or SE (66%) of the data. However, the SD or SE of the measured data was not available for the variables of interest for this study. Further, based on this SD/SE concept, the acceptable ranges of RMSD will vary with the crop, variable of interest, method of measurement, and the type and spatial variabilities of soil, management, and plants. Therefore, no standardized ranges of RMSD are available in the literature for any of the variable of interest. In the presentation of results, we will provide references to the range of RMSD and/or RRMSD values obtained in previous studies fir each variable of interest.

3. Results and discussion

As described in the Materials and Methods, the calibrations of the model were carried out using the crop growth data collected in 2007 and validated using the data collected in 2006 and 1990; however, as the simulation results did not differ significantly between

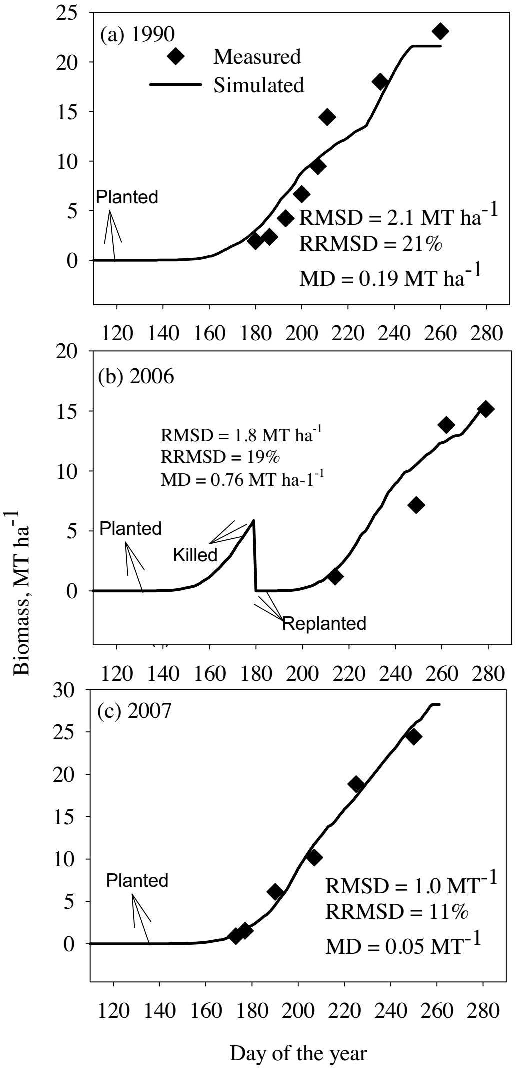

Fig. 1. Measured and simulated aboveground corn biomass in 1990, 2006, and 2007. RMSD = Root Mean Square Deviation; MD = mean difference between predicted and observed values.

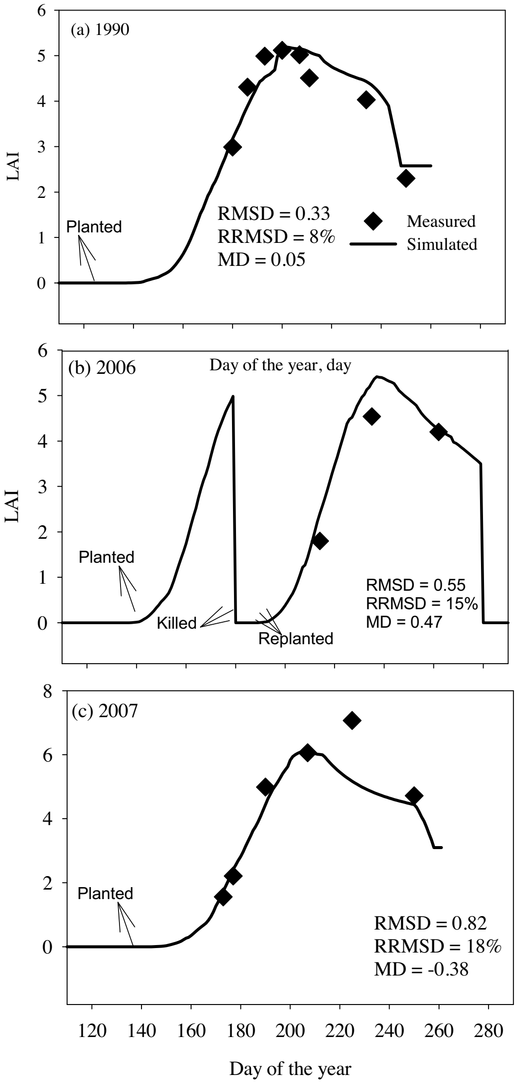

Fig. 2. Measured and simulated corn LAI in 1990, 2006, and 2007.

the calibration and validation years, all the three years (1990, 2006, 2007) results will be discussed together.

It should also be recalled that in 2006, the initial planting of corn failed, and it was replanted. The Root Mean Square Deviation (RMSD) between the simulated and observed biomass values were 2.1, 1.8, and 1.0 MT ha^{-1}, for 1990, 2006 (replanted crop), and 2007, respectively (Fig. 1a–c). These RMSD values for biomass simulation were within the range of values reported for corn in the literature (Nouna et al., 2000; Kozak et al., 2006). The mean deviation (MD) values were much smaller for the 1990 and 2007 normally planted crops, and relatively larger (but still smaller than the RMSD values) for the replanted crop in 2006 (Fig. 1a–c). Taking into account the uncertainties and errors in sampling of biomass in a spatially variable agricultural field, the model-simulated results for crop growth are acceptable. A similar comparison of the Leaf Area Index (LAI) data showed the RMSD values of 0.33, 0.55, and 0.82, for the three years, respectively (Fig. 2a–c). Similar RMSD values for corn and other crops have been reported by Yang et al. (2004) and Saseendran et al., 2005. The RMSD values for LAI are generally higher due to greater error and uncertainty in measurements by the currently used methods.

The simulated and measured changes in the total soil water in the root zone soil profile (0–190 cm; 170 cm profile in 1990) during the growing season are shown in Fig. 3a–c. The RMSD of the simulated data were within 4–6% of the observed mean values. Similar RMSD values for profile soil water contents have been reported earlier (Saseendran et al., 2005, 2010). However, two measurements on 258th and 278th days of the year for the replanted crop in 2006 were not simulated well for unknown reasons that we can pinpoint; whether it was the measurement error or a simulation error. Overall, the soil water contents of the lysimeters were under-simulated by about 3–4%. The ET results presented below indicate that slight over-simulation of the ET could partly account for this under-simulation of soil water content.

The observed and simulated daily ET values are shown in Figs. 4–6 along with the dates and amounts of precipitation and irrigation. For 1990 (Fig. 4), the lysimeter ET measurements were available only during the corn-growing season from planting to harvest. The RMSD between the daily simulated and measured data during the growing season was 1.5 mm. The mean deviation (MD), which is a good measure of the under- or over-prediction by the model, was 0.4 mm; thus, on average, the simulations were slightly higher than the observed data. For 2006 (Fig. 5), the daily simulations during the growing season of the initially planted damaged crop were higher than the measured because of the damage, whereas those of the replanted crop (July 3) were overall better, with the RMSD of 1.1 mm, and the mean deviation of 0.2 mm,

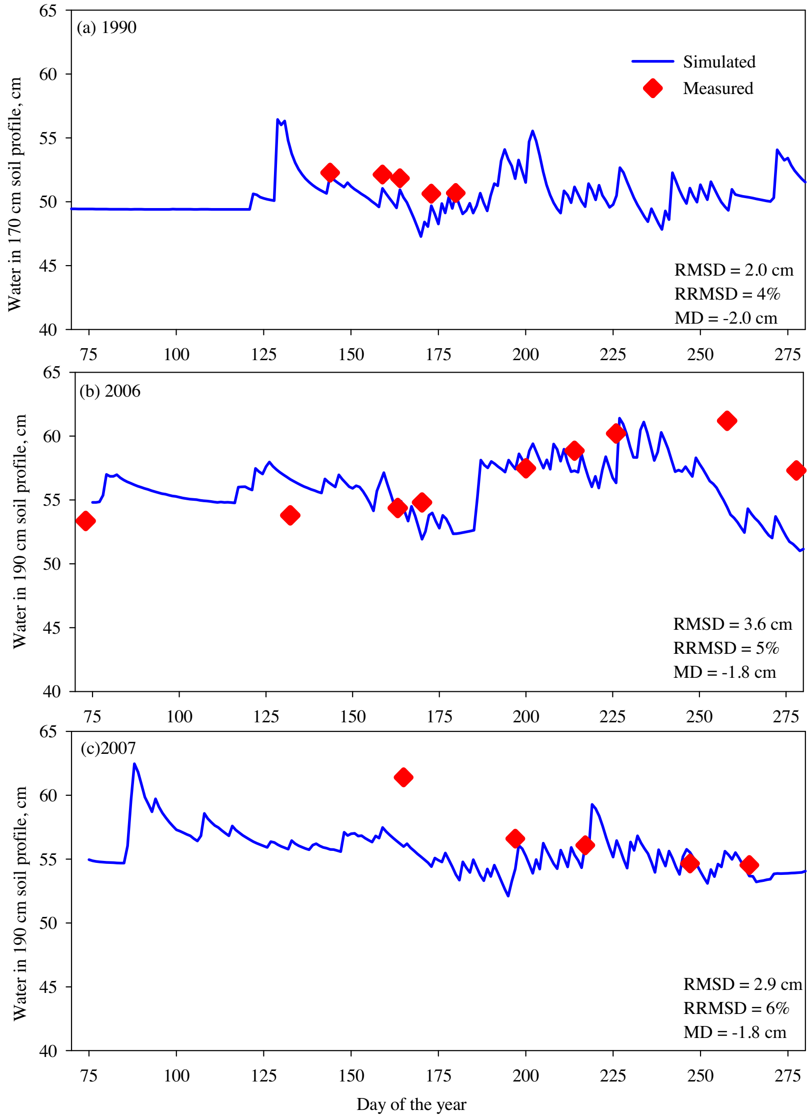

Fig. 3. Measured and simulated water in the soil profile in 1990, 2006, and 2007.

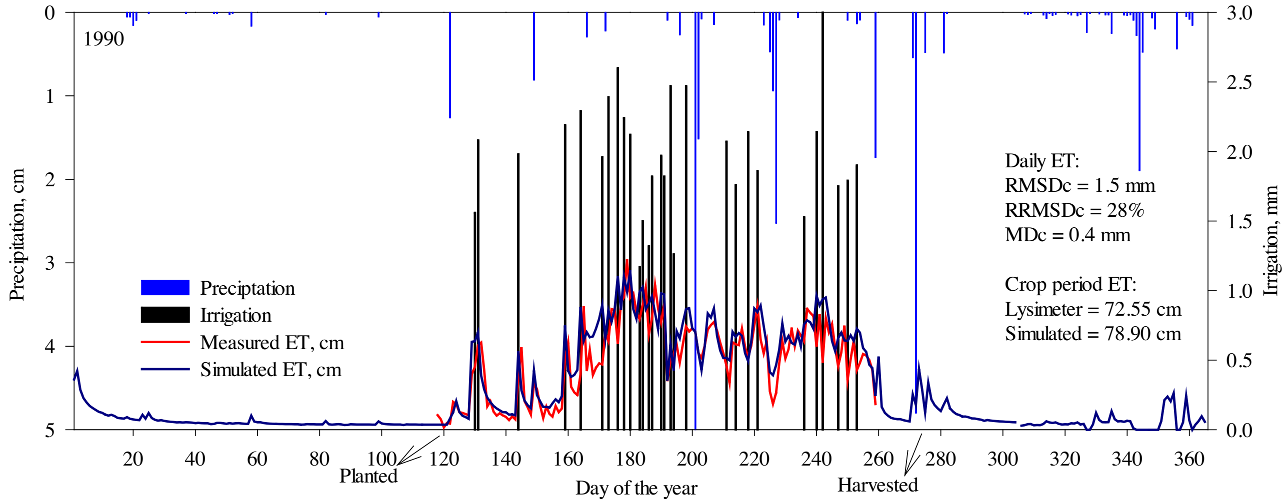

Fig. 4. Irrigation, precipitation, and lysimetric and simulated corn evapotranspiration (ET) in 1990. RMSD = Root Mean Square Deviation and MD = Mean Absolute Deviation. The subscript f denotes the total fallow days outside the crop period in a year, and the crop period is denoted by the subscript c.

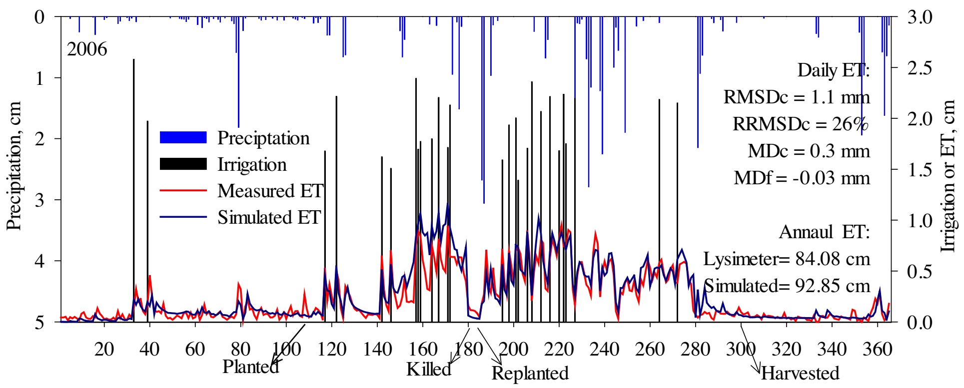

Fig. 5. Irrigation, precipitation, and lysimetric and simulated corn evapotranspiration (ET) in 2006. RMSD = Root Mean Square Deviation and MD = Mean Absolute Deviation. The subscript f denotes the total fallow days outside the crop period in a year, and the crop period is denoted by the subscript c.

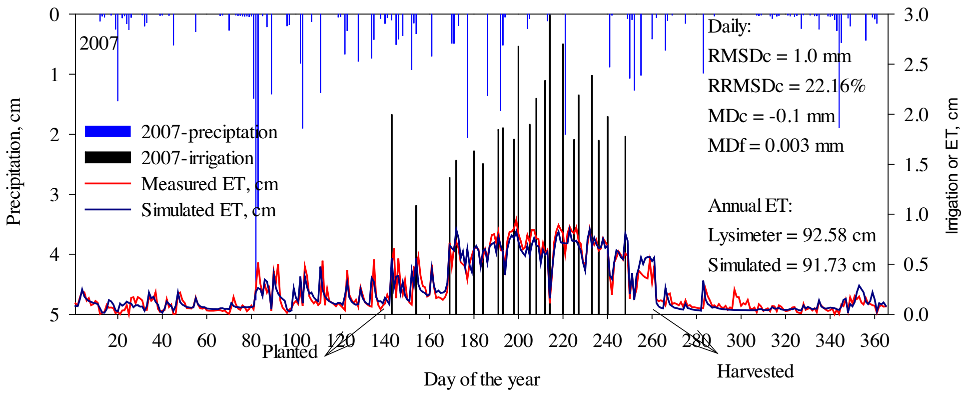

Fig. 6. Irrigation, precipitation, and lysimetric and simulated corn evapotranspiration (ET) in 2007. RMSD = Root Mean Square Deviation and MD = Mean Absolute Deviation. The subscript f denotes the total fallow days outside the crop period in a year, and the crop period is denoted by the subscript c.

slight over-prediction by the model. For this year, the measured ET data were also available for the non-crop seasons, before planting and after harvest. The mean deviation during these seasons was −0.03 mm, a slight under-prediction by the model. This indicated that the model predicted soil evaporation reasonably well. For 2007 (Fig. 6), the simulation results were closer to the measured data. During the crop season, the RMSD of the simulated ET values was 1.0 mm, and the mean deviation was −0.1 mm. The MD for the fallow seasons in this year was 0.003 mm.

Allen et al. (2011), the leading ET scientists, provided errors in measurement of ET by the various methods used in the literature, expressed as one standard deviation from the mean. For the working lysimeter, the typical error in measuring ET by a lysimeter were 5–15%. For a non-expert observer, the errors rose to 20–40%. In addition, errors caused by physical or equipment malfunction were 5–40%. The errors with the next best method of measurement, the Bowen Ratio method, were somewhat higher than the lysimeters. For the most often-used water balance method of estimating ET, the corresponding errors were 10–30%, 20–70%, and 10–40%, respectively. For other methods, the typical errors were similar or worse than the water balance method. Marek et al. (2014) have shown that even in lysimeters, the errors of measuring ET go up much higher on the days of rainfall or irrigation. Besides, the above error figures are for one standard deviation around the mean. In nature, the normal distribution of errors can extend to three standard deviations around the mean. The acceptable limit may be two standard deviations around the mean. Considering these ranges of errors, the overall error represented by the RMSD values for simulating ET in this study, varying between 22–28% of the mean values (RRMSDs in Fig. 4–6), were well within one standard deviation around the mean for lysimeters, and much below the errors of measuring ET by the commonly used methods. The MD values for the three years crop season ET were between −0.1 mm and 0.4 mm per day; and for the fallow periods between 0.003 mm and −0.03 mm per day.

The above results of simulating ET also show that the modeling of ET related processes in the RZWQM2 model, especially the extended S-W approach for computing PT and PE, are much better than many of the other maize models used in the study of Bassu et al. (2014), where the ET simulations varied within a factor of two. Nevertheless, there is certainly a room for further improvements in the methods of simulation of ET, by way of new knowledge of the dynamic canopy and surface resistances in the S-W approach for various crops, cultivars, management conditions and extreme climatic events, water stress effects on LAI and biomass growth at different crop growth stages, contribution of snow to water balance, and the like. ET is one of the most important information needed for further improving management of water and climate change in agriculture. The following results and discussion of the Kc are also important for a simpler approach to scheduling irrigations at this juncture in time.

Fig. 7 shows a comparison between the daily variation in Kc for corn-based ET measured in the lysimeters for each of the three years, calculated as daily lysimeter measured ET divided by the short grass reference ET. The figure also shows Kc calculated using the RZWQM2 simulated ET in place of the lysimeter measured ET. The Kc values obtained using simulated ET differed from the Kc values calculated using lysimeter measured ET with RMSDs between 0.24 and 0.20 in the three years (1990, 2006, and 2007). The simulated Kc for grass reference crop showed a negative bias in 1990 with an MD value of −0.14, and positive bias in the remaining two

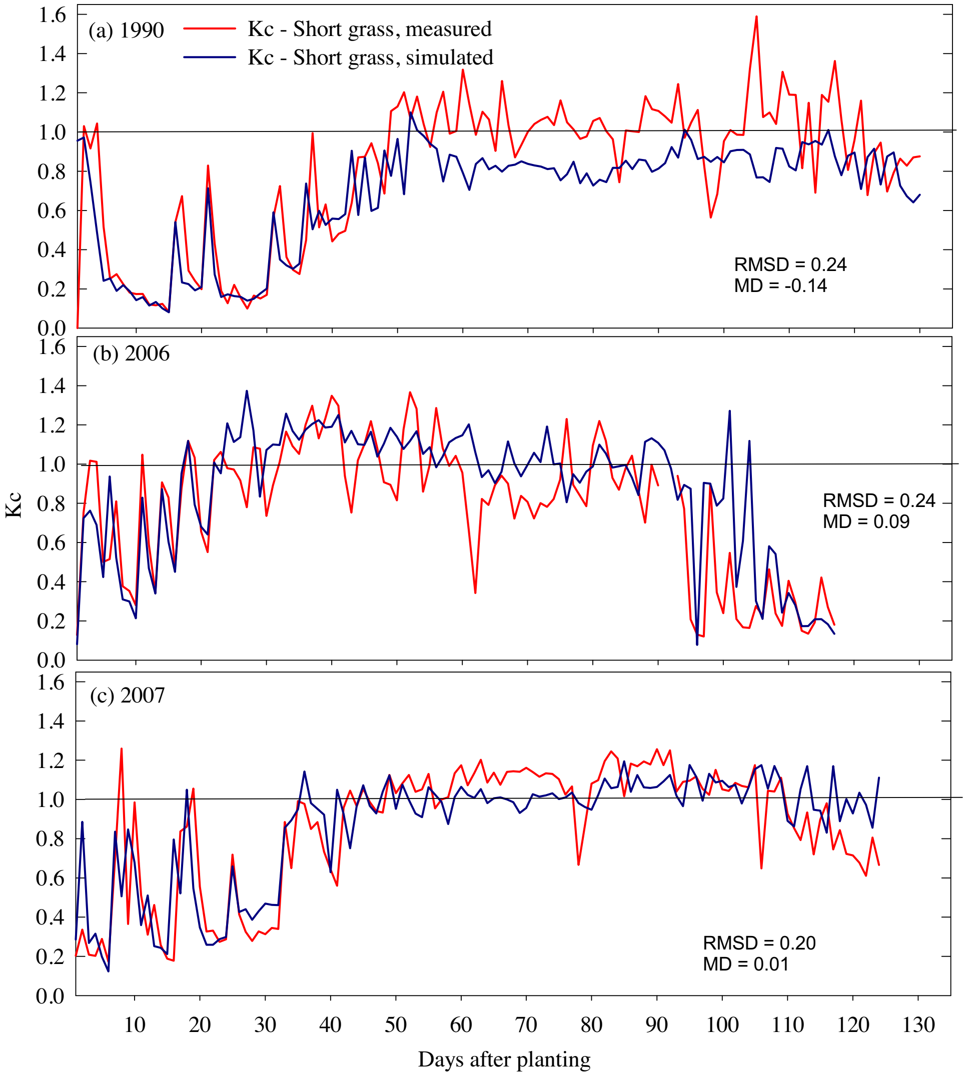

Fig. 7. Comparison between measured and simulated short grass reference crop ET-crop coefficients. Kc = ETm/ETr, ETr = short grass reference crop ET; ETm = ET measured in lysimeters or ET simulated using RZWQM2 for corn.

years: 2007 and 2008 with MD statistics of 0.09 and 0.01. The general temporal trends in Kc values during the growth period are similar between the two the two methods of estimation. At full canopy, both sets of Kc values are closer to 1.0.

Fig. 8 shows similar information for Kc computed with alfalfa reference ET. The RMSD values computed using the simulated values differed from the Kc values obtained by using the lysimeter measured Kc values, with the RMSDs between 0.15 and 0.17, and MDs between 0.00 and 0.08. Thus, the differences between the two are smaller than those for small grass reference ET (Fig. 7). Corn plant grows to heights of 2–3 m; for that reason, the aerodynamic resistances going into the computations of potential ET for the taller of the two reference crops –alfalfa- worked better in representing the corn aerodynamic characteristics and other micrometeorological conditions in the lysimeter. The Kc for the grass reference crop, as one would expect, is larger than those of the alfalfa reference for all three years. Though corn is normally taller than alfalfa and it can potentially transpire more water; it is a C_4 crop (C_4 photosynthetic pathway) and thus renders more resistances to transpirational water loss through its stomatae by opening them less than the C_3 alfalfa crop (Sage, 2004); therefore, it actually transpire less water than alfalfa. During the peak ET plateau period (full canopy period), which varied from year to year, the Kc for the grass reference crop (Fig. 7) were greater than 1.0, and those for the alfalfa reference (Fig. 8) were less than 1.0. These results for the two reference crops agree with those presented by Howell et al. (2008) for 2006 and 2007. However, there is fair amount of variation of crop coefficients from year to year (Fig. 7 and 8), even for the Kc values obtained by using lysimeter measured ET. The work of Howell et al., 1995 showed a large inter-annual variation of crop coefficients across different varieties and even for the same variety (Howell et al., 2006). This variability suggests that if the Kc approach is continued to be used for guiding irrigation scheduling, as it is done currently all over the world, we will need to consider obtaining longer term average (and preferably cultivar and site specific) Kc values. Long-term lysimeter or field studies for this purpose are not practical. Simulations with a well-tested model could be a good alternative. The results of this study and analysis showed that the Kc values obtained by using the RZWQM2 simulated ET and the alfalfa reference ET were better than the Kc values obtained by using simulated with the grass reference ET, and were reasonably close to Kc values obtained by using lysimeter measured ET based on RMSDs within 0.17 and MDs within 0.08, Long term simulations with a model like this could be good option for obtaining average Kc values for practical application.

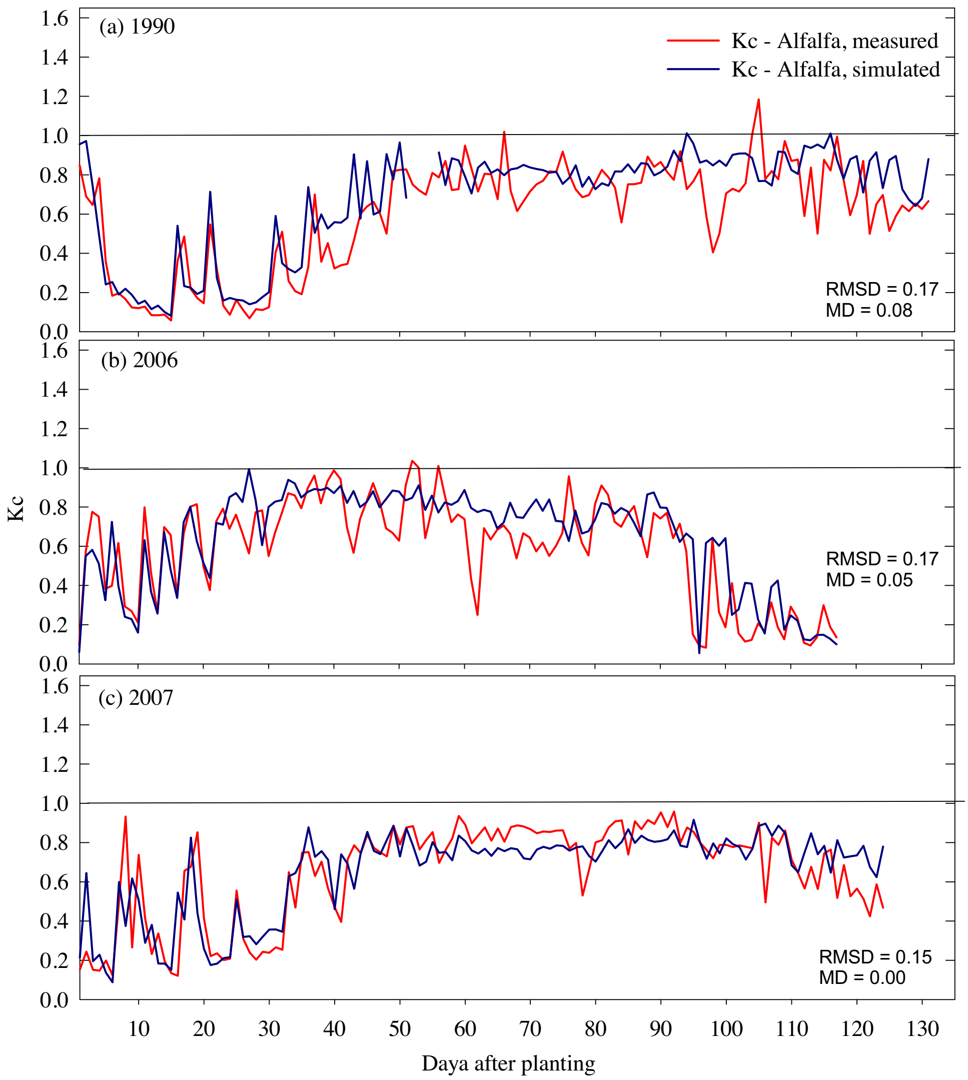

Fig. 8. Comparison between measured and simulated alfalfa reference crop ET-crop coefficients. Kc = ETm/ETr, ETr = is short grass reference crop ET; ETm = ET measured in lysimeters or ET simulated using RZWQM2 for corn.

Because of considerable variation of crop coefficients across crop cultivars and from year to year due to weather and management effects shown by Howell et al. (1995, 2006) (2012), supported by the results of this study, Lascano et al. (2010) and Lascano and Evett (2010) made a case for replacing the crop coefficient approach by direct solution of the P-M equation via full energy and water balance using the crop and variety specific canopy surface resistances. In this direction, the performance of the extended S-W formulation (Farahani and Ahuja, 1996) as presented in this study is encouraging for future practical applications in irrigation management.

4. Conclusions

Three-year corn ET (1990, 2006, and 2007) measured using large weighing lysimeters maintained with adequate fetch, along with daily weather data, at Bushland, TX was used for verifying the accuracies of the ET related simulation processes in the RZWQM2 model. Potential ET for short grass and alfalfa reference crops were also computed from the same weather data. The CSM-CERES-Maize crop growth module in RZWQM2 reproduced the corn biomass and LAI reasonably well, comparable to similar simulations in the literature. The extended S-W approach for potential crop ET combined with the Nimah and Hanks approach for crop water uptake and Richards equation formulation soil water redistribution provided simulations of the actual corn ET for three years within the established errors of measuring ET by the weighing lysimeters of one standard deviation around the mean, much below the errors of measuring ET by other commonly used methods. The mean deviation (MD) values for the three years crop season ET were between −0.1 mm and 0.4 mm per day. The soil evaporation for the fallow periods was measured with MD between 0.003 mm and −0.03 mm per day.

For practical field irrigation scheduling, the results of this study and analysis showed that the crop coefficient (Kc) values obtained by using the RZWQM2 simulated ET and the alfalfa reference ET were close to Kc values obtained by using the lysimeter measured ET and the alfalfa reference ET, with RMSDs within 0.17 and MDs within 0.08, They were also better than the corresponding Kc values based on using small grass reference ET. Because of high year-to-year variability of Kc values for a crop, simulations with a model like RZWQM2 could be a good option for obtaining long-term average Kc values for practical application.

Disclaimer

Mention of trade names or commercial products in this manuscript is solely for providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Acknowledgements

This research was supported in part by the Ogallala Aquifer Program, a consortium between USDA-Agricultural Research Service, Kansas State University, Texas A&M AgriLife Research, Texas A&M AgriLife Extension Service, Texas Tech University, and West Texas A&M University.

References

ASCE-EWRI., 2005. The ASCE standardized reference evapotranspiration equation, in: Allen, R.G., Walter, I.A., Elliot, R.L., Howell, T.A., Itenfisu, D., Jensen, M.E., Snyder, R.L. (Eds.), Standardization of Reference Evapotranspiration Task Committee Final Report, ASCE-EWRI, pp. 1–11.

Ahuja, L.R., Rojas, K.W., Hanson, J.D., Shafer, M.J., Ma, L., 2000. Root Zone Water Quality Model. Modeling Management Effects on Water Quality and Crop Production. Water Resources Publications, LLC, Highlands Ranch, CO.

Ahuja, L.R., Ma, L., Fang, Q.X., Saseendran, S.A., Islam, A., Malone, R.W., 2013. Computer modeling: applications to environment and food security. In: Van Alfen, Neal (Ed.), Encyclopedia of Agriculture and Food Systems, vol. 2. Elsevier, San Diego, pp. 337–358.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirement. United Nations Food and Agriculture Organization, Rome, Italy, Irrigation and Drainage Paper 56.

Allen, R.G., Pereira, L.S., Howell, T.A., Jensen, M.E., 2011. Evapotranspiration information reporting: 1. Factors governing measurement accuracy. Agric. Water Manag. 98, 899–920.

Bassu, S., Brisson, N., Durand, J.L., Boote, K., Lizaso, J., Jones, J.W., Rosenzweig, C., Ruane, A.C., Adam, M., Baron, C., Basso, B., Biernath, C., Boogaard, H., Conijn, S., Corbeels, M., Deryng, D., De Sanctis, G., Gayler, S., Grassini, P., Hatfield, J., Hoek, S., Izaurralde, C., Jongschaap, R., Kemanian, A.R., Kersebaum, K.C., Kim, S.-H., Kumar, N.S., Makowski, D., Müller, C., Nendel, C., Priesack, E., Pravia, M.V., Sau, F., Shcherbak, I., Tao, F., Teixeira, E., Timlin, D., Waha, K., 2014. How do various maize crop models vary in their responses to climate change factors? Glob. Change Biol. 20, 2301–2320, http://dx.doi.org/10.1111/gcb.12520.

Brooks, R.H., Corey, A.T., 1964. Hydraulic properties of porous media. In: Hydrology Paper 3. Colorado State University, Fort Collins, CO, USA.

Doorenbos, J., Pruit, W.O., 1977. Crop water requirements. In: Irrigation and Drainage Paper No. 24 (revised). Food and Agricultural Organization of the United Nations (FAO), Rome, Italy.

Evett, S.R., Tolk, J.A., Howell, T.A., 2003. A depth control stand for improved accuracy with the neutron probe. Vadose Zone J. 2 (4), 642–649.

Evett, S.R., Schwartz, R.C., Howell, T.A., Baumhardt, R.L., Copeland, K.S., 2012. Can weighing lysimeter ET represent surrounding field ET well enough to test flux station measurements of daily and sub-daily ET? Adv. Water Resour. 50, 79–90, http://dx.doi.org/10.1016/j.advwatres.2012.07.023.

Evett, S.R., Howell, T. A., Schneider, A.D., Copeland, K.S., Dusek, D.A., Brauer, D.K., Tolk, J.A., Marek, G.W., Marek, T.M., Gowda, P.H., 2015. The Bushland weighing lysimeters: A quarter century of crop ET investigations to advance sustainable irrigation, ASABE/IA Symposium: Emerging Technologies for Sustainable Irrigation, Paper No. 152141554, pages 1–12 (10.13031/irrig.20152141554). St. Joseph, Michigan.

Farahani, H.J., Ahuja, L.R., 1996. Evapotranspiration modeling of partial canopy/residue covered fields. Trans. ASAE 39, 2051–2064.

Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Howell, T.A., Schneider, A.D., Dusek, D.A., Marek, T.H., Steiner, J.L., 1995. Calibration and scale performance of Bushland weighing lysimeters. Trans. ASAE 38, 1019–1024.

Howell, T.A., Evett, S.R., Tolk, J.A., Copeland, K.S., Dusek, D.A., Colaizzi, P.D., 2006. Crop coefficients developed at Bushland, Texas for corn, wheat, sorghum, soybean, cotton, and alfalfa, in: Graham, R., (Ed.), Proc. ASCE-EWRI World Environmental and Water Resources Congress, Omaha, Nebraska, pp. 1–9.

Howell, T.A., Evett, S.R., Tolk, J.A., Copeland, K.S., Colaizzi, P.D., Gowda, P.H., 2008. Evapotranspiration of corn and forage sorghum for silage, in: Babcock, R.W. (Ed.), World Environmental and Water Resources Congress 2008: Ahupua's, Am. Soc. Civil Engineers., Reston, VA, pp. 1–14.

Hsiao, T.C., Steduto, P., Fereres, E., 2007. A systematic and quantitative approach to improve water use efficiency in agriculture. Irrig. Sci. 25, 209–231.

Islam, A., Ahuja, L.R., Garcia, L.A., Ma, L., Saseendran, S.A., 2012. Modeling the effect of elevated CO_2 and climate change on reference evapotranspiration in the semi-arid great plains. Trans. ASABE 55 (6), 2135–2146.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. Eur. J. Agron. 18, 235–265.

Kahil, M.T., Dinar, A., Albiac, J., 2014. Modeling water scarcity and droughts for policy adaptation to climate change in arid and semiarid regions. J. Hydrol. 522, 95–109.

Kozak, J.A., Ma, L., Ahuja, L.R., 2006. Evaluating various water stress calculations in RZWQM and RZ-SHAW for corn and soybean production. Agron. J. 98, 1146–1155.

Lascano, R.J., Evett, S.R., 2010. Calculation of canopy resistance with a recursive evapotranspiration model. In: Symposium 2.1.1 of 19th World Congress of Soil Science, Soil Solutions for a Changing World, 1–6 August 2010, Brisbane, Australia, pp. 20-–23.

Lascano, R.J., van Bavel, C.H.M., Evett, S.R., 2010. A field test of recursive calculation of crop evapotranspiration. Trans. ASABE 53 (4), 1117–1126.

Ma, L., Ahuja, L.R., Saseendran, S.A., Malone, R.W., Green, T.R., Nolan, B.T., Bartling, P.N.S., Flerchinger, G.N., Boote, K.J., Hoogenboom, G., 2011. A protocol for parameterization and calibration of RZWQM2 in field research. In: Ahuja, L.R., Ma, L. (Eds.), Methods of Introducing System Models into Agricultural Research. ASA-SSSA-CSSA, Madison, WI, pp. 1–64.

Ma, L., Trout, T.J., Ahuja, L.R., Bausch, W.C., Saseendran, S.A., Malone, R.W., Nielsen, D.C., 2012. Calibrating RZWQM2 model for maize responses to deficit irrigation. Agric. Water Manag. 103, 140–149.

Marek, G.W., Evett, S.R., Gowda, P.H., Howell, T.A., Copeland, K.S., Baumhardt, R.L., 2014. Post-processing techniques for reducing errors in weighing lysimeter evapotranspiration (ET) datasets. Trans. ASABE 57 (2), 499–515.

McNider, R.T., Handyside, C., Doty, K., Ellenburg, W.L., Cruise, J.F., Christy, J.R., Moss, D., Sharda, V., Hoogenboom, G., Caldwell, P., 2015. An integrated crop and hydrologic modeling system to estimate hydrologic impacts of crop irrigation demands. Environ. Modell. Softw. 72, 341–355.

Monteith, J.L., 1965. Evaporation and the environment. Proc. XIXth Symposium: The state of movement of water in living organisms. Cambridge, U.K. Cambridge Univ. Press.

Nielsen, D.C., Saseendran, S.A., Ma, L., Ahuja, L.R., 2012. Simulating the production potential of dryland spring canola in the central great plains. Agron. J. 104, 1182–1188.

Nimah, M.N., Hanks, R.J., 1973. Model for estimating soil water, plant and atmospheric interrelations: I. description and sensitivity. Proc. Soil Sci. Soc. Am. 37, 522–527.

Nouna, B.B., Katerji, N., Mastrorilli, M., 2000. Using the CERES-maize model in a semi-arid Mediterranean environment: evaluation of model performance. Eur. J. Agron. 13, 309–322.

Okada, M., Iizumi, T., Sakurai, G., Hanasaki, N., Sakai, T., Okamoto, T., Yokozawa, M., 2015. Modeling irrigation-based climate change adaptation in agriculture: model development and evaluation in Northeast China. J. Adv. Model. Earth Syst. 7, 1409–1424, http://dx.doi.org/10.1002/2014MS000402.

Rosenzweig, C., Jones, J.W., Hatfield, J.L., Ruane, A.C., oote, K.J., Thorburn, P., Antle, A.M., Nelson, G.C., Porter, C., Janssen, S., Asseng, S., Basso, B., Ewert, F., Wallach, D., Baigorria, G., Winter, J.M., 2013. The Agricultural Model Intercomparison and Improvement Project (AgMIP). Protocols and pilot studies Agricultural and Forest Meteorology 170, 166–182.

Sage, R.F., 2004. The evolution of C4 photosynthesis. New Physiol. 161, 341–370.

Saseendran, S.A., Ma, L., Nielsen, D.C., Vigil, M.F., Ahuja, L.R., 2005. Simulating planting date effects on crop production using RZWQM and CERES-maize models. Agron. J. 97, 58–71.

Saseendran, S.A., Nielsen, D.C., Ma, L., Ahuja, L.R., Vigil, M.F., 2010. Simulating alternative dryland rotational cropping systems in the Central Great Plains with RZWQM2. Agron. J. 102, 1521–1534.

Saseendran, S.A., Ahuja, L.R., Ma, L., Trout, T.J., McMaster, G., Andales, A.A., Chaves, J., Ham, J., 2014a. Enhancing the water stress factors for simulation of corn (*Zea mays* L.) in RZWQM2. Agron. J. 106, 81–94, http://dx.doi.org/10.2134/agronj/2013.0300.

Saseendran, S.A., Ahuja, L.R., Ma, L., Trout, T.J., 2014b. Modeling the effects of irrigation frequencies, initial water, and nitrogen on corn yield responses for best management. Practical Applications of agricultural system models to optimize the use of limited water. Adv. Agric. Syst. Model. 5, 25–52.

Saseendran, S.A., Trout, T.J., Ahuja, L.R., Ma, L., McMaster, G., Andales, A.A., Chaves j. Ham, J., 2015. Quantification of crop water stress factors from soil water measurements in limited irrigation experiments. Agric. Syst. 137, 191–205.

Shuttleworth, W.J., Wallace, J.S., 1985. Evaporation from sparse crops-an energy combination theory. Quart. J. R. Meteorol. Soc. 111, 839–855.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Unger, P.W., Pringle, F.B., 1981. Pullman Soils: Distribution, Importance, Variability, and Management. The Texas Agricultural Experiment Station, Neville, P., Clarke, Director, College Station, Texas in cooperation with United States Department of Agriculture, Agricultural Research Service, and Soil Conservation Service.

Yang, H.S., Dobermann, A., Lindquist, J.L., Walters, D.T., Arkebauer, T.J., Cassman, K.G., 2004. Hybrid-maize—a maize simulation model that combines two crop modeling approaches. Field Crops Res. 87, 131–154.