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MEASURED AND SIMULATED EVAPOTRANSPIRATION OF GRAIN SORGHUM GROWN WITH FULL AND LIMITED IRRIGATION IN THREE HIGH PLAINS SOILS

J. A. Tolk, T. A. Howell

ABSTRACT. *Water conservation in irrigated agriculture of the semi–arid Great Plains relies on accurate prediction of crop water use to gain the greatest benefit from declining irrigation water supplies. One method for estimating crop water use applies crop specific coefficients to adjust reference evapotranspiration (ET_o). We compared daily measured evapotranspiration (ET_m) of limited and fully irrigated grain sorghum to simulated ET (ET_c) calculated using single and dual crop coefficients (K_c) and a grass–referenced ET_o. We also compared simulated and actual applied irrigation water requirements that were based on full replacement of ET. The dual K_c procedure contained separate coefficients for crop transpiration, soil water evaporation, and water stress, as compared with one coefficient in the single K_c procedure. Short–season grain sorghum was grown in weighing lysimeters containing monolithic soil cores of Pullman, Ulysses, or Amarillo soil located in a rain shelter facility. With the dual K_c procedure, the difference during the season between cumulative ET_c and ET_m varied from 2 mm to around 70 mm, and by the end of the season the maximum difference in all treatments was about 60 mm, or 10%. The single K_c procedure underestimated final cumulative ET_m in the fully irrigated treatments by as much as 120 mm. Simulated and actual applied irrigation amounts in the fully irrigated treatments were similar using the dual K_c methodology, but the single K_c methodology under–simulated irrigation needs by more than 100 mm in all treatments. The dual K_c procedure improved water use predictions compared with the single K_c procedure.*

Keywords. *Crop coefficient, Model evaluation, Irrigation scheduling, Lysimeters.*

Agricultural producers in the semi–arid Great Plains must minimize water application losses as irrigation water supplies decline and pumping costs increase. One approach has been to schedule irrigation timing and amounts based on accurate predictions of crop water use. Measured crop evapotranspiration (ET_m) routinely has been estimated from reference evapo– transpiration (ET_0) combined with crop coefficients (K_c) (Jensen et al., 1970). The crop coefficient is an empirical ratio of ET_m to ET_0. It relates ET_0, which is based on ET of a reference crop, to ET_m by integrating the crop– and soil–specific characteristics that differ from those used for the reference crop, such as crop height (which affects crop aerodynamic resistance to heat and vapor transport), crop–soil resistance to water loss (affected by crop stomatal characteristics and soil texture), and soil albedo. Calculation of ET by this method often used procedures outlined by Doorenbos and Pruitt (1975) in a publication commonly known as FAO–24 (United Nations Food and Agriculture Organization's Irrigation and Drainage Paper Number 24).

This procedure was updated in FAO–56 (Allen et al., 1998), and uses the Penman–Monteith combination reference ET_0 equation with grass as the reference crop. The equation as presented in FAO–56 is:

$$\lambda ET = \frac{(R_n - G) + \rho_a c_p \dfrac{e_s - e_a}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_a}\right)} \qquad (1)$$

where

R_n = net radiation (MJ m^{-2} day^{-1})
G = soil heat flux (MJ m^{-2} day^{-1})
ρ_a = mean air density at constant pressure (kg m^{-3})
c_p = specific heat of the air (MJ $kg^{-1}{}^{\circ}C^{-1}$)
$(e_s - e_a)$ = saturation vapor pressure (e) deficit between the evaporating surface (s) and the air (a) (kPa)
Δ = slope of the saturation vapor pressure–temperature relationship (kPa $^{\circ}C^{-1}$)
γ = psychrometric constant (kPa $^{\circ}C^{-1}$)
r_s = evaporating surface's resistance to water loss (s m^{-1})
r_a = aerodynamic resistance (s m^{-1}).

The parameters used for r_a and r_s provide the "reference" to which other crops are compared. In this case, the reference is a hypothetical grass surface with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1}, and an albedo of 0.23 (Allen et al., 1998). While ET_0 is a measure

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The authors are **Judy A. Tolk**, Plant Physiologist, and **Terry A. Howell**, ***ASAE Fellow Engineer***, Research Leader, Agricultural Engineer; Water Management Research Unit, Conservation and Production Research Laboratory, USDA Agricultural Research Service, Bushland, Texas. **Corresponding author**: Judy A. Tolk, USDA–ARS, Water Management Research Unit, Conservation and Production Research Laboratory, P.O. Drawer 10, Bushland, TX 79012; phone: 806–356–5736; fax: 806–356–5750; e-mail: jtolk@cprl.ars.usda.gov.

of climatic demand, K_c varies with specific crop/soil characteristics that control water loss upon which climatic conditions have a limited impact, thus enabling the transfer of standard crop coefficients between climates.

In addition to containing the single K_c approach, which combines crop transpiration and soil water evaporation into one value, the updated procedure includes procedures for calculating a dual K_c, which has separate coefficients for crop transpiration (K_{cb}, or basal crop coefficient), soil water evaporation (K_e), as well as water stress (K_s). The need to have separate coefficients for soil water evaporation and water stress was recognized early in the development of the crop coefficient procedure (Jensen et al., 1971).

The dual K_c procedure is recommended for daily calculations of ET, which require more accurate values of K_c. The procedure adjusts the K_{cb} for crop growth stage and daily variations in meteorological conditions, and combines it with fluctuations in K_e due to rainfall and irrigation and K_s due to a reduction in soil water content below the level that induces crop water stress. Calculation of K_e requires specification of soil water holding characteristics such as field capacity (FC), permanent wilting point (PWP), readily evaporable water (potential evaporation) and, from the specified soil surface depth from which surface evaporation occurs, the total evaporable water. Calculation of K_s additionally requires rooting depth which, when combined with FC and PWP, determines total available water, and the percentage of the total available water that can be used before the crop experiences water stress, or readily available water.

The performance of the FAO–56 dual crop coefficient rests not only upon the representativeness of the crop coefficients for transpiration and soil water evaporation but also on the ability of the ET_o equation to accurately predict a reference water use in a particular environment as well. Howell et al. (2000) compared ET_o simulated using the FAO–56 equation to lysimetrically measured ET of irrigated fescue and found that the equation tended to over–simulate during the spring and fall, and under–simulate during the summer, especially on days of high ET. De Bruin and Stricker (2000) reported that, when all equation inputs were measured, the FAO–56 ET_o equation also under–simulated ET measured by energy balance–Bowen ratio techniques. Hunsaker (1999) used FAO–56 guidelines to develop basal crop coefficients for early maturity cotton and determined that recommended K_{cb} values were higher than those measured, which would lead to an over–simulation of ET. Both Allen (2000) and Kite and Droogers (2000) concluded that FAO–56 methodology could potentially be used for estimating ET over larger land areas if limitations are taken into account and appropriate crop coefficients developed.

The objectives of this research were: (1) to compare daily ET_c simulated by both single and dual crop coefficient procedures with lysimetrically measured ET_m of short–season grain sorghum grown under full and limited irrigation in three soil types, and (2) to compare irrigation requirements simulated by the single and dual K_c methodologies with actual applied irrigations that were based on replacement of measured ET for the fully irrigated treatments. This would help determine if the more complicated dual K_c procedure improved prediction of crop water use and irrigation water requirements compared with the simpler single K_c procedure.

MATERIALS AND METHODS

AGRONOMY

A short season grain sorghum hybrid PIO–8699 was grown at a plant density of 16 plants m^{-2} in 1997, 1998, and 1999 at the USDA–ARS Soil–Plant–Environment Research (SPER) facility at Bushland, Texas. The facility had lysimeters (1 m wide by 0.75 m long by 2.4 m deep) that contained monolithic cores of Pullman clay loam, Ulysses clay loam, or Amarillo fine sandy loam. Deck scales (Weigh–Tronix Model DS30x40–10K) under the lysimeters were used in the analysis to measure daily changes in mass balance. There were two replicates of each soil type/irrigation treatment combination in 1997 and 1998, and three in 1999. All treatments received 19 g N m^{-2} prior to planting. Soil water content was monitored using neutron thermalization. At the beginning of the experiments, the Pullman and Amarillo soil cores were at about 100% of field capacity in 1997 and 1998 and at about 65% in 1999. The Ulysses cores were at about 75% of field capacity in 1997 and 1998 and 50% in 1999. The SPER facility had a rain shelter (Schneider et al., 1993), which allowed precise control of the lysimeter water balance. The shelter remained 15 m north of the research area until needed. Wind direction was predominately from the south–southwest. The lysimeter area was surrounded by similarly cropped grain sorghum for about 30 to 35 m in the prevailing wind direction. About 450 m of dryland grain sorghum was south of the SPER facility, and a heterogeneous landscape of grassland, playa, and irrigated and dryland cropland extended more than 1700 m to the southwest.

IRRIGATION TREATMENTS

Irrigation treatments were 110% and 70% of measured ET in 1997, and 100% and 50% of measured ET in 1998 and 1999. The reductions in ET replacement simulate deficit irrigation (does not meet crop water use demands) that results from limited water availability such as reduced well capacities. Irrigations were volumetrically measured and applied by hand using buckets, with large irrigations (>50 mm) resulting in ponding on the soil surface. Daily ET_c for the dual K_c procedure was simulated using two different irrigation inputs. The first irrigation input was the measured irrigation values. The second irrigation input was irrigation as scheduled by the simulated ET_c, which was also at the same levels of ET replacement for the irrigation treatments. Simulated irrigations were applied on the same schedule as measured irrigations, which was generally weekly from the day after sowing (DAS) until the beginning of the late season crop development phase, at which time all irrigation ceased. Irrigation applications simulated by the single K_c procedure were also terminated at the beginning of the late season crop development stage.

CROP COEFFICIENTS

Input parameters for calculation of ET_c for both full and limited irrigation treatments using the dual K_c procedure are shown in table 1. Additional required inputs were length of the four crop growth stages (initial, development, mid–season, late season) and the K_{cb} for each growth stage. The K_{cb} values were adjusted for climatic effects. Lengths of the crop growth stages were established by plotting measured K_c (ET_m/ET_o) vs. day of year (DOY), as shown in FAO–56

Table 1. Soil parameters used in calculating the dual K_c (parameters defined in text).

Soil	FC (m^3/m^3)	PWP (m^3/m^3)	Z_r (m)	Z_e (m)	TEW (mm)	REW (mm)	TAW (mm)	RAW (mm)	p (mm/mm)
Amarillo	0.25	0.12	2.0	0.10	20	9	260	143	0.55
Pullman	0.34	0.22	2.0	0.15	33	10	240	121	0.55
Ulysses	0.32	0.14	2.0	0.15	38	10	360	288	0.80

(Allen et al., 1998, p. 158). Soil parameters required included permanent wilting point (PWP), field capacity (FC), readily evaporable water (REW), and depth of soil contributing to soil water evaporation (Z_e). The parameters FC, PWP, and Z_e determined total evaporable water (TEW), and FC, PWP, and crop rooting depth (Z_r) the total available water (TAW). The parameters TAW and its fraction of water that can be depleted before water stress occurs (p) were used to calculate readily available water (RAW). Many of these parameters were determined in prior tests associated with the SPER facility, and were similar to those recommended in FAO–56. The use of 0.80 as the p value for the Ulysses soil is the highest value in the range of p recommended by FAO–56. This value is supported by the grain yield vs. percent remaining plant available water (%PAW) at harvest relationships for the crops grown in that soil in 1998 and 1999 (data not shown). The crops in that soil were able to produce yields near maximum until %PAW dropped below about 20%. Yield reductions began at much higher %PAW in the other two soils, especially in 1998.

Daily ET_C and irrigation requirements of the full irrigation treatments were also simulated using the single K_c procedure in FAO–56. Crop coefficients used in establishing the crop coefficient curve for the four crop growth stages were those recommended in FAO–56 for grain sorghum. The initial K_c value was calculated from the dual K_c procedure as the sum of the soil water evaporation and basal crop coefficient of 0.15. The mid–season K_c was set at 1.1 and the end season K_c at 0.55, and both were adjusted for climatic effects during those growth stages.

CALCULATION OF ET_O

Data for the calculation of ET_O were gathered at a weather station with irrigated, cool season grass about 1000 m from the SPER facility. Weather station instrumentation was described fully in Dusek et al. (1987). Calculation of ET_O followed FAO–56 guidelines.

EVALUATION OF MODEL PERFORMANCE

The performance of the models was evaluated using the coefficient of determination (R^2), mean ($\overline{X}$), standard deviation (SD), root mean square error (RMSE), and the modified coefficient of efficiency (Legates and McCabe, 1999), given as:

$$E = \frac{1.0 - \sum_{i=1}^{N} \left| O_i - P_i \right|}{\sum_{i=1}^{N} \left| O_i - \overline{O} \right|} \qquad (2)$$

where O is the observed data and P is the model–simulated data. The statistic E examines whether the difference between the model simulations and the measured data is as large as the variability in the observed data. For interpretation, if E = 0 then the observed mean $\overline{O}$ is as good a predictor as the model, and if E > 0 then the larger the positive number, the better the model fit. The coefficient of efficiency represents an improvement over R^2 in that it is sensitive to differences in the observed and model–simulated means and variances, and will always be lower than that value. In the unmodified form of E, the differences are squared, which makes it overly sensitive to extreme values, as is R^2 (Legates and McCabe, 1999).

Table 2. Measured and simulated daily and total seasonal ET using single and dual crop coefficients (K_c) and, for the daily values, the mean ($\overline{X}$), the standard deviation (SD), root mean square error (RMSE), the coefficient of determination (R^2), and the model coefficient of efficiency (E). Irrigation amounts used in the dual crop coefficient methodology simulations were either the actual applied amounts based on measured ET (measured) or application amounts based on simulated ET (simulated).

	Measured			Single K_c						Dual K_c (measured irrigation)						Dual K_c (simulated irrigation)					
		Daily			Daily						Daily						Daily				
Soil	Total (mm)	$\overline{X}$ (mm)	SD (mm)	Total (mm)	$\overline{X}$ (mm)	SD (mm)	RMSE (mm)	R^2	E	Total (mm)	$\overline{X}$ (mm)	SD (mm)	RMSE (mm)	R^2	E	Total (mm)	$\overline{X}$ (mm)	SD (mm)	RMSE (mm)	R^2	E
Amarillo																					
1997	581	4.9	2.9	558	4.7	2.5	1.7	0.67	0.52	584	5.0	2.8	1.4	0.77	0.56	584	5.0	2.9	1.4	0.77	0.56
1998	613	6.7	3.3	517	5.7	2.3	1.9	0.65	0.33	550	6.1	2.5	1.8	0.71	0.42	550	6.1	2.5	1.8	0.71	0.42
1999	547	5.3	3.4	468	4.5	2.6	1.7	0.77	0.57	504	4.8	2.8	1.5	0.81	0.63	514	4.9	2.8	1.5	0.81	0.60
Pullman																					
1997	665	5.6	3.3	578	4.9	2.4	2.1	0.60	0.42	635	5.4	2.8	1.7	0.72	0.52	638	5.4	2.8	1.7	0.72	0.52
1998	653	7.2	3.0	542	6.0	2.0	2.0	0.57	0.19	604	6.6	2.2	1.7	0.68	0.36	604	6.6	2.2	1.7	0.68	0.36
1999	559	5.4	3.2	474	4.6	2.5	1.5	0.76	0.52	526	5.1	2.7	1.2	0.85	0.65	557	5.4	2.7	1.2	0.85	0.58
Ulysses																					
1997	710	6.0	3.5	588	5.0	2.4	2.5	0.47	0.27	659	5.6	2.7	2.3	0.57	0.39	664	5.6	2.8	2.3	0.57	0.38
1998	659	7.2	3.3	546	6.0	1.9	2.3	0.50	0.16	614	6.8	2.1	2.1	0.60	0.30	626	6.9	2.1	2.3	0.51	0.26
1999	577	5.6	3.4	481	4.6	2.4	1.6	0.77	0.51	536	5.2	2.6	1.4	0.83	0.62	577	5.6	2.6	1.9	0.68	0.52

RESULTS AND DISCUSSION

FULLY IRRIGATED TREATMENTS

Total seasonal ET_c simulated by both the single and dual K_c procedures in the fully irrigated treatments typically was lower than total seasonal ET_m in all three years (table 2). Using the single K_c procedure, the difference between total seasonal ET_m and ET_c ranged from −4% (23 mm) in the Amarillo soil to −17% (122 mm) in the Ulysses soil, both in 1997. In general, cumulative ET_c simulated using the single K_c procedure remained below cumulative ET_m throughout the season.

The difference between total seasonal ET_m and ET_c as simulated by the dual K_c procedure ranged from +1% (3 mm) to −10% (62 mm) calculated from measured irrigation amounts, and 0% to −10% (63 mm) calculated from simulated irrigation amounts (table 2). A typical example of the performance of the dual K_c procedure is for the 1999 crop grown in the Ulysses soil (fig. 1). The dual K_c procedure tended to overestimate K_c during the initial growth stage period, and then underestimate it during the mid–season growth stage (fig. 1a), which could result in similar simulated and measured seasonal ET totals (fig. 1b).

During the initial growth stage, soil water evaporation, which made up the bulk of ET, generally was over–simulated after an irrigation (fig. 1c). Both actual applied and simulated irrigations typically equaled or exceeded the amounts specified for total evaporable water (TEW) for the three soil types (table 1), filling the top soil to field capacity. Model simulations called for soil water evaporation to proceed through stage one, or energy limiting, evaporation during which the readily evaporable water (REW) is evaporated, followed by stage two, or falling rate, stage, during which TEW is evaporated. The over–simulation of ET during this stage suggests that the complete evaporation of TEW between irrigations did not occur.

Higher ET_m than ET_c during the mid–season growth stage may have been related to increases in both evaporation and transpiration compared with simulated values. During the mid–season growth stage, the model simulates almost complete elimination of soil water evaporation due to shading from the crop. However, actual evaporation may have been greater than that simulated due to the ponded irrigation water (Garatuza–Payan et al., 1998). Increases in measured transpiration compared with simulated values may have been due to advected energy coming from the arid areas upwind, and the low minimum relative humidity (<25%) and higher mean wind speeds (>2.5 m/s) that commonly occur during that time of year.

The model simulated similar total seasonal ET_c with either measured or simulated irrigation amounts except in 1999. In 1999, the use of simulated irrigation amounts improved crop water use predictions, and brought ET_m and ET_c totals to within less than 1% for the crops in the Pullman and Ulysses soils.

LIMITED IRRIGATION TREATMENTS

The difference between total seasonal ET_c and ET_m of the limited irrigation treatments modeled by the dual K_c procedure ranged from <+1% (1 mm) to 15% (72 mm) (table 3). The dual K_c procedure tended to produce K_c values similar to measured ones throughout most of the season (fig. 2a), resulting in comparable cumulative ET during the season (fig. 2b) as it did for the crop in the Ulysses soil in 1999. This is unlike the fully irrigated treatments, in which errors in simulating soil water evaporation of the larger irrigation application amounts in both unshaded and shaded conditions resulted in large differences in simulated and measured K_c values (fig. 1a) in the initial and mid–season growth stages. The smaller irrigation applications and the lack of ponded water reduced the contributions from soil water evaporation in the limited irrigation treatments and resulted in mid–season ET_c and ET_m values that were similar (fig. 2c) in spite of advective weather conditions.

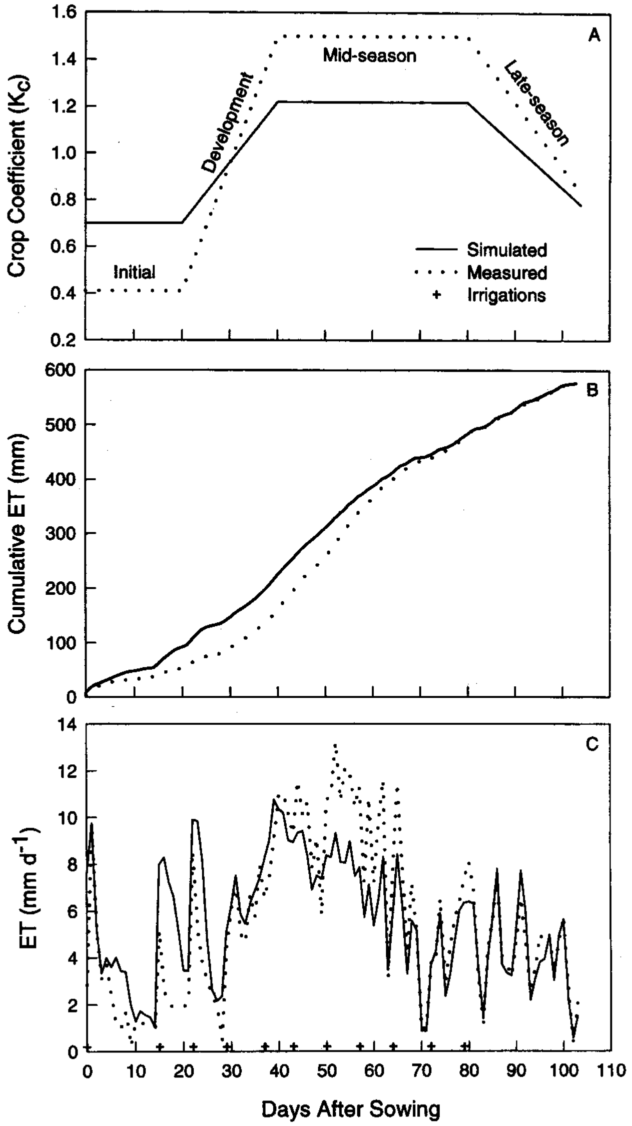

Figure 1. Fully irrigated treatment in the Ulysses soil in 1999: (A) measured and simulated (dual crop coefficient) K_c time–averaged for the initial, development, mid–season, and late–season crop growth stages; (B) cumulative measured and simulated evapotranspiration (ET); (C) simulated and measured daily ET and irrigations (+).

Greater reductions in K_c were simulated than those measured at the end–season growth stage (fig. 2a), resulting in final seasonal ET_c that was generally lower than ET_m (fig. 2b). During that growth stage, the limited irrigation amounts resulted in a gradual depletion of TAW in the profile to the threshold value needed to begin the reduction of K_c due to water stress through the application of the water stress coefficient, K_s. FAO–56 uses a straight–line function (Kerr et

Table 3. Measured and simulated daily and total seasonal ET of the limited irrigation treatments using the dual crop coefficient (K_c) methodology and, for the daily values, the mean ($\overline{X}$), the standard deviation (SD), root mean square error (RMSE), the coefficient of determination (R^2), and the model coefficient of efficiency (E).

	Measured			Simulated					
		Daily			Daily				
Soil	Total	$\overline{X}$	SD	Total	$\overline{X}$	SD	RMSE	R^2	E
	mm			mm					
Amarillo									
1997	613	5.2	3.3	566	4.8	2.9	1.6	0.77	0.56
1998	471	5.2	2.5	472	5.2	2.6	1.4	0.70	0.42
1999	432	4.2	2.6	397	3.8	2.6	1.1	0.81	0.59
Pullman									
1997	595	5.1	3.0	584	5.0	3.0	1.6	0.72	0.53
1998	527	5.6	2.3	510	5.6	2.5	1.2	0.75	0.47
1999	475	4.6	2.6	402	3.9	2.3	1.2	0.79	0.50
Ulysses									
1997	694	5.9	3.5	633	5.4	2.8	2.1	0.65	0.43
1998	511	5.6	2.9	512	5.6	2.6	1.5	0.72	0.49
1999	467	4.5	2.7	422	4.1	2.7	1.1	0.83	0.60

al., 1993) to reduce K_c once the threshold soil water content is reached. Errors in the simulations during this growth stage may be related to the shape of the soil water depletion function, which best represents the effects of water stress (Kerr et al., 1993), or errors in the calculating soil water evaporation.

PREDICTING CROP WATER REQUIREMENTS

The crop coefficient methodology was developed to predict crop water requirements so that irrigations can be applied most efficiently. Table 4 compares irrigation application amounts calculated by the single and dual crop coefficient methodologies with the actual applied amounts based on percent replacement of measured ET for the fully irrigated treatments. Both actual and simulated irrigation applications were stopped near the beginning of the end–season crop growth stage in all three years. The single K_c methodology under–simulated irrigation water requirements by 100 mm or more, with the maximum amount being 170 mm. The irrigation water requirements simulated by the dual K_c methodology were similar to the actual amount applied except in 1998, when the crop irrigation needs were under–simulated by almost 100 mm for the crop in the Amarillo soil. These results suggest that irrigations scheduled using the single K_c methodology might not meet crop water requirements, resulting in yield reductions.

The improvement of model simulations by using the dual K_c methodology is also shown in its somewhat higher coefficient of determination (R^2), higher modified coefficient of efficiency (E), and lower root mean square error (RMSE) compared with those of the single K_c methodology (table 3). The overall performance of the dual K_c methodology in predicting crop water use was poorest in 1998, in which the region experienced a drought with high winds and very low humidity during the cropping season. The lower standard deviations (SD) of the simulated values compared with measured values shows that the model was unable to simulate the extremes in measured values.

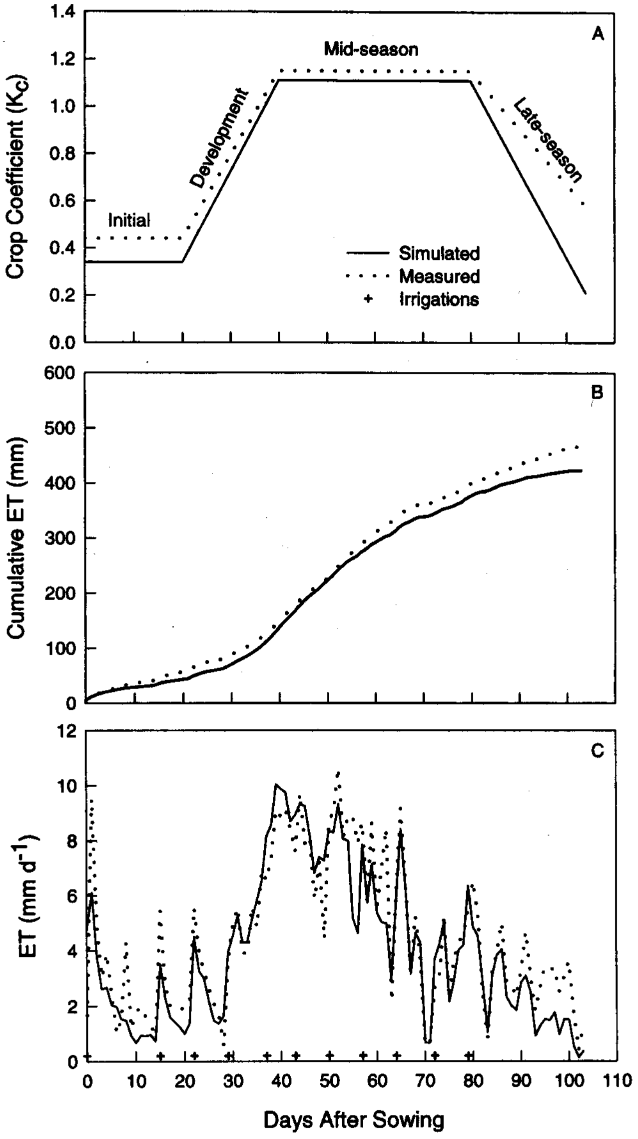

Figure 2. Limited irrigation treatment in the Ulysses soil in 1999: (A) measured and simulated (dual crop coefficient) K_c time–averaged for the initial, development, mid–season, and late–season crop growth stages; (B) cumulative measured and simulated evapotranspiration (ET); (C) simulated and measured daily ET and irrigations (+).

CONCLUSIONS

The dual crop coefficient methodology as outlined in FAO–56 (Allen et al., 1998) improved the prediction of the water use and irrigation requirements of grain sorghum in a range of soil types and irrigation treatments compared with the single crop coefficient methodology. Irrigations scheduled using the single K_c methodology potentially could not meet crop water use demands, resulting in yield reductions. Irrigations scheduled to meet but not exceed crop water needs can also preserve limited irrigation water supplies. Although the FAO–56 dual crop coefficient methodology does contain adjustments for differences in local climate from the sub–humid minimum relative humidity and wind speeds for which it was developed, these adjustments may need to be modified for the semi–arid climate of the Great Plains to achieve the best results.

Table 4. Measured and simulated total seasonal irrigation using the single and dual crop coefficients (K_c) for the Amarillo, Pullman, and Ulysses soil series. All measurements are in mm; the percent difference between measured and simulated values is in parentheses.

	Amarillo			Pullman			Ulysses		
		Simulated			Simulated			Simulated	
Year	Measured	Single K_c	Dual K_c	Measured	Single K_c	Dual K_c	Measured	Single K_c	Dual K_c
1997	516	404 (–22)	507 (–2)	569	424 (–26)	561 (–1)	604	434 (–28)	584 (–3)
1998	537	418 (–22)	543 (–18)	573	443 (–23)	497 (–13)	546	446 (–18)	516 (–6)
1999	522	372 (–29)	496 (–5)	512	384 (–25)	516 (+1)	510	385 (–25)	541 (+6)

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