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Simulation for Irrigation Management of Corn in South Texas

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ABSTRACT Interest is growing in applying simulation models for the South Texas conditions, to better assess crop water use and production with different crop management practices. The Environmental Policy Integrated Climate (EPIC) model was used to evaluate its application as a decision support tool for irrigation management of corn (*Zea mays* L.) in South Texas of the U.S. We measured actual crop evapotranspiration (ETc) using a weighing lysimeter, soil moisture using a neutron probe, and grain yield by field sampling. The model was then validated using the measured data. Simulated ETc using the Hargreaves-Samani equation was in agreement with the lysimeter measured ETc. Simulated soil moisture generally matched with the measured soil moisture. The EPIC model simulated the variability in grain yield with different irrigation regimes with r^2 value of 0.69 and root mean square error of 0.5 ton ha^{-1}. Simulation results with farm data demonstrate that EPIC can be used as a decision support tool for corn under irrigated conditions in South Texas. EPIC appears to be effective in making long term and pre-season decisions for irrigation management of crops, while reference ET and phenologically based crop coefficients can be used for in-season irrigation management.

Keywords : corn, crop model, EPIC, ET, irrigation management

The traditional solution to water shortages for plants has been irrigation, which has made agriculture possible in many otherwise nonproductive areas (Kramer & Boyer, 1995). In the Winter Garden area of Texas in the U.S., irrigation is also one of the major limiting factors in producing corn and other crops as more than 90% of the water for urban and agricultural use in this region depends on the Edwards aquifer. Irrigation management of crops is becoming an important issue as the water supplies shrink and competition with urban centers in the region grows. For efficient water use, the irrigation amount should not exceed the maximum amount that can be used by plants through evapotranspiration (ET), which is the sum of the amount of water returned to the atmosphere through the processes of evaporation and transpiration (Hansen *et al.*, 1980).

ET is very difficult to measure but several methods have been developed. One of the direct measuring techniques is a method using a weighing lysimeter, which constantly weighs the soil/vegetation mass and estimates gains and losses in water (Watson & Burnett, 1995). Because direct measurement of ET can be a difficult task, a wide rage of models have been developed for use in environments that lack either sufficient radiometric, meteorological, or lysimetric data. ET models tend to be categorized into three basic types: temperature, radiation, and combination (Jenson *et al.*, 1990; Dingman, 1984; Watson & Burnett, 1995). Temperature models (e.g., Thornthwate, 1948; Doorenbos & Pruitt, 1977) generally require only air temperature data as the sole meteorological input; Radiation models (e.g., Turc, 1962; Doorenbos & Pruitt, 1977; Hargreaves & Samani, 1985), designed to use some component of the energy budget concept, usually require some form of radiation measurement; and combination models (e.g., Penman, 1948) combine elements from both the energy budget and mass transfer models (Jensen *et al.*, 1990).

Interest is growing in applying simulation models for conditions of the South Texas, to better assess crop water use and production with different crop management practices. One of these simulation models is EPIC, which was developed to determine the relationship between soil erosion and soil productivity in the U.S. (Williams *et al.*, 1984). EPIC includes physiologically based components to simulate erosion, plant growth, and related processes. Model components include weather, hydrology, erosion, nutrient cycling, soil temperature, crop growth, tillage, pesticide fate, economics,

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and plant environmental control. The generic crop-growth subroutine in EPIC (Williams *et al.*, 1989) facilitates the simulation of complex rotations and fallow-cropping systems, making the model useful for evaluating alternative crop management scenarios in South Texas. A variety of scenarios can be simulated with the model, such as evaluating crop water use.

The EPIC hydrology component includes runoff, percolation, lateral subsurface flow, ET, and snow melt. EPIC comes with five ET equations from which the user of EPIC has to make a single choice for a simulation exercise. The equations include: Penman (Penman, 1948), Penman-Monteith (Penman, 1965), Priestley-Taylor (Priestley & Taylor, 1972), Hargreaves-Samani (Hargreaves & Samani, 1985), and Baier-Robertson (Baier & Robertson, 1965). A critical step in constructing crop water management scenarios for EPIC is to determine an ET option. The objectives of this research were 1) to determine an appropriate EPIC ET model, and 2) to validate and evaluate the model as a decision support tool in irrigation scheduling.

MATERIALS AND METHODS

Field Experiment for Model Validation

Field studies for validation of EPIC crop model (Williams *et al.*, 1990) were conducted at the Texas A&M AgriLife Research Center in Uvalde, Texas (N 29° 13' 03", W 99° 45' 26"; elevation 283 m) in 2002, 2003, and 2004. Corn was grown in two similarly managed fields, one from a center-pivot-irrigated field with a low energy precision application (LEPA) system and the other from a linear-irrigated lysimeter field with a LEPA system. Soil type of both fields was an Uvalde clay soil (fine-silty, mixed, hyperthermic Aridic Calciustolls with a pH of 8.1). A corn variety planted was 30 G54 from Pioneer (Johnston, IA). Summarized cropping practices are presented in Table 1. The field experiment under the center pivot was arranged in a randomized split-block design with each block replicated three times. A 90° wedge of the center pivot field was divided equally into 10° regimes, which were maintained at 100, 75, and 50% crop evapotranspiration (ETc) values.

The lysimeter units used in this study had monolithic cores where soil structure and associated parameters remain unchanged (Marek *et al.*, 2006). The size of the monoliths was 1.52×2.03×2.13 m and the soil monolith boxes were constructed of 9.5 mm thickness mild steel plate. The lysimeter showed detectable resolution values of ~113 g on the 18 Mg scales measured with a Campbell Scientific CR23X (Logan, UT). The lysimeter field was managed under full irrigation based on daily crop water use. On the other hand, irrigation scheduling and ET regimes for the center pivot field were imposed according to daily calculations of the modified Penman-Monteith equation (Allen *et al.*, 1998). Actual crop water use requirements for corn were determined based on the relation to a well-watered reference grass. The equation was as follows:

$$ET_c = K_c \times ET_0 \qquad (1)$$

where K_c is crop coefficient and ET_0 is reference evapotranspiration. ET from a tall fescue grass (*Festuca arundinacea* Schreb.) with a height of 0.12 m and a surface resistance of 70 s m^{-1} was the ET_0 surface employed in K_c. The total amounts of irrigation for each year were presented in Table 1. Rainfall was highest in 2004.

A neutron probe (530 DR Hydroprobe Probe Moisture Depth

Table 1. Summary of cropping practices at Texas A&M AgriLife Research Center in Uvalde, Texas in 2002, 2003, and 2004.

Year	Plant	Fertilization		Irrigation applied†		Rainfall	Maturity
		N	P_2O_5	Lysimeter	IFC		
	--- date ---	--------- kg ha^{-1} ---------		--------------------- mm ---------------------			--- date ---
2002	March 25	118.2	20.9	358.1	422.4	99.6	June 20
2003	March 18	77.3	0.0	370.8	417.8	136.7	June 24
2004	March 10	168.0	44.8	293.6	231.1	232.4	June 24

†Total amounts of irrigation applied using in-field calculated (IFC) using the modified Penman-Monteith equation and lysimeter measured.

Gauge, Campbell Pacific Nuclear Corp. Int. Inc., Martinez, CA) was used to quantify soil moisture at various depths during the crop growing season in 2003 and 2004. After planting, neutron probe access tubes were installed at the center of each planting treatment plot. Volumetric water content (θ) was determined using a linear equation as follows:

$$Water\ Content\ (Vol.) = a \times CR + b \qquad (2)$$

where a and b are coefficients, and CR is the count ratio (count divided by standard count). The coefficients were determined for each soil depth by experimentation measuring the soil moisture at different water contents with the neutron probe and measuring it also by taking a soil sample (Table 2). The soil samples were weighed and dried at 104℃ for 24 h and again weighed to calculate the dry weight moisture contents. The θ values determined by the neutron probe were also determined from the dry weight contents of the soils times the apparent specific gravity of the soils or bulk densities. The bulk densities were determined by measuring the volume of dry soil and the dry weight of that volume. Measurements in 2003 were done on 8 and 29 April; 6, 15, 21, and 27 May; 6, 9, 18, and 26 June; and 8 and 27 July. Measurements in 2004 were done on 28 April; 6, 13, 18, and 24 May; 2, 11, 17, 23 June; and 14 and 22 July. Crop grain yields were determined by randomly sampling and harvesting 3 m^2 for each plot.

Model Validation and Application

Parameters for the model validation were ETc, soil moisture, and grain yield. In-field and simulated ET were calculated under unstressed crop conditions. Modified Penman-Monteith (Allen *et al.*, 1998) ET_0 method in conjunction with crop coefficients developed at Bushland, TX (2002-03) and Uvalde, TX (2004) were used to calculate in-field ETc. EPIC makes users select one ET equation from five options. After preliminary test runs of the EPIC model, Penman-Monteith (Monteith, 1965) and Hargreaves-Samani (Hargreaves & Samani, 1985) ET_0 methods were selected to simulate ETc in this study.

Table 2. Linear relationships between soil moisture and neutron probe (NP) ratio, x, at each depth (n=12). The x is a target NP count divided by a standard NP count.

Soil depth (cm)	Linear equation	R^2
20	48.2 x - 43.9	0.94
40	28.2 x - 19.9	0.99
60	24.6 x - 14.2	1.00
80	19.6 x - 6.8	0.99
100	23.1 x - 10.8	0.98

The model was applied to simulate 2006 crop yield in South Texas (Fig. 1). Information regarding the farms and their cropping practices is presented in Table 2. In addition, the model was used to simulate the grain yield of corn with various irrigation scenarios. These were 229, 306, 381, 457, 533, and 610 mm of irrigation, respectively.

In this study, water use efficiency (WUE) is defined with the following equations:

$$WUE_{ETc} = Y/ETc \qquad (3)$$

where WUE_{ETc} (g m^{-2} mm^{-1}) is water use efficiency calculated with seasonal crop water use in terms of crop evapotranspiration (ETc in mm) and Y (g m^{-2}) is the crop yield.

$$WUE_{I+R} = Y/(I+R) \qquad (4)$$

where WUE_{I+R} (g m^{-2} mm^{-1}) is water use efficiency cal-

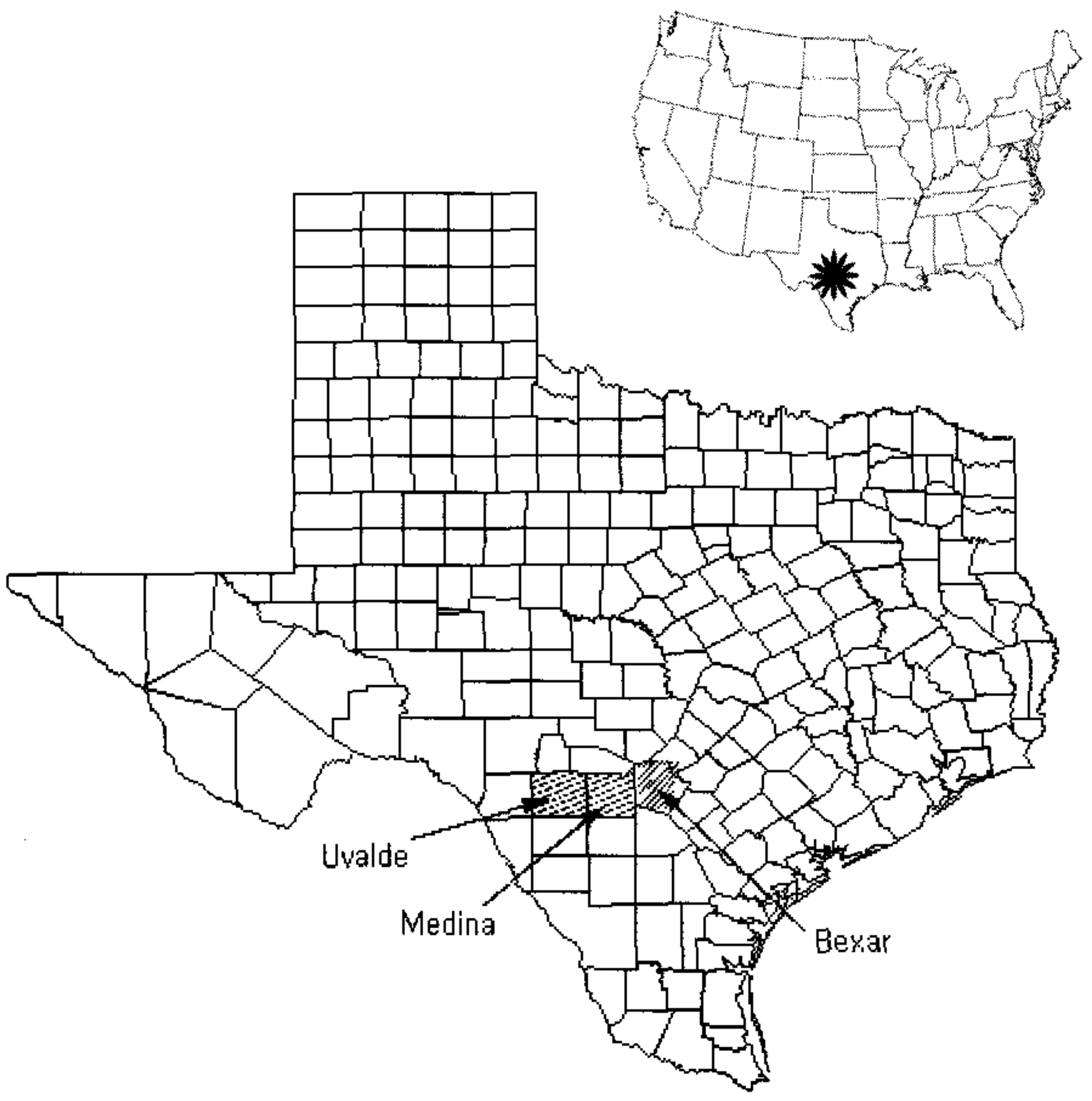

Fig. 1. Map of the region where corn data were obtained for parameterization and simulation.

Table 3. Summarized information of farms and their cropping practices in 2006 used in crop simulation.

Grower	County	Latitude (N), longitude (W); elevation (m)	Soil type	plant to harvest (M/D)	N-P[†] (kg ha^{-1})	Irrigation (mm)
Boyle, Duane	Medina	29.397, 98.893; 252	Knippa clay 0-1%	3/11-7/22	163-19	622
Clary, Austin[‡]	Medina	29.335, 99.365; 315	Montell clay 0-1%	3/03-8/01	101-90	427
Crawford, Jimmy	Uvalde	29.176, 99.760; 268	Uvalde silty clay loam 0-1%	3/03-7/30	168-56	610
Parker, Jimmy	Uvalde	29.255, 99.764; 303	Uvalde silty clay loam 0-1%	3/08-8/10	168-45	495
Shirmer, Ernie	Bexar	29.359, 98.723; 192	Brayton clay 0-1%	3/10-8/26	163-46	533

[†]Nitrogen-Phosphate applied.
[‡]Two fields were used from these farms.

culated with seasonal water input (mm), or irrigation (I) + rainfall (R).

Weather data used in the simulations were collected with a standard Campbell Scientific meteorological station (Campbell Scientific Inc., Logan, UT) at each location, available at the Texas AgriLife Research and Extension Center website (http://uvalde.tamu.edu/weather/weather.php). Data were analyzed by analyses of paired t-test using PROC TTEST and simple linear regression using PROC REG (SAS version 9.1, Cary, NC). Paired t-test was used to determine any statistical differences of the calculated and simulated data from the measured lysimeter data. Simple linear regression was used to compare yields of simulation and measurement.

RESULTS AND DISCUSSION

Crop water use of lysimeter measured under unstressed crop conditions was compared to different methods of irrigation calculation, which was performed as a preliminary validation of the EPIC model (Table 4). No statistical differences were found between end-of-season measured lysimeter data and crop evapotranspiration (ETc) methods of in-field calculated or EPIC Hargreaves-Samani. However, EPIC Penman-Monteith method overestimated cumulative growing season ETc. Our result generally corresponds to the following findings. ET methods tend to perform the best in the climates in which they were designed. This has been demonstrated with many studies to examine how other grass-reference methods perform against Penman-Monteith (Amatya *et al.*, 1995; de Bruin & Lablans, 1998; Xu & Sigh, 1998; de Bruin & Sticker, 2000; Barnett *et al.*, 1998; Irmak *et al.*, 2003). It is not surprising that the Hargreaves-Samani method fits well in this study as it was initially designed using data from Davis, California, which is the closest to our study site. On the other hand, George *et al.* (2002) reported that the Hargreaves-Samani method performed best in situations

Table 4. Comparison of crop water usage among different methods of irrigation calculation under unstressed crop conditions in 2002, 2003, and 2004. The methods include lysimeter measured (LM), in-field calculated (IFC) using the modified Penman-Monteith (PM), and two options of EPIC simulation (EPIC-H, set with the Hargreaves equation, and EPIC-PM, set with the original PM equation).

Year	LM	IFC	EPIC-H	EPIC-PM
	------	------ mm	------	------
2002	457.71	491.24	509.27	511.56
2003	507.49	523.24	502.41	560.07
2004	526.03	477.52	509.52	541.53
3-year mean	497.08	497.33	506.98	537.72
Diff. LM[†]	---	0.25	9.91	40.64*

[†]Diff. LM, differences from lysimeter measured.
*indicates that the crop ET is significantly different from the measured lysimeter crop ET at the 0.1 alpha level.

where only maximum and minimum air temperature data were available, on their research to select the best ET_0 method using a decision support system. Irmak *et al.* (2003) similarly described that method choice depended on the availability and quality of meteorological data.

Cumulative ETc during the growing seasons varied year to year among the three methods of lysimeter measured, in-field calculated, and EPIC simulated using Hargreaves-Samani (Fig. 2). However, cumulative ETc varied during the growing season among the three methods of measurements. In-season differences among ETc methods were larger possibly due to inexact simulation growth curves or growth stage specific crop coefficients. However, it is considered that the variations were within an acceptable range. This allows us to determine to use the Hargreaves-Samani from the EPIC ETc calculation options.

Seasonal simulated soil moisture at various depths was generally in agreement with the measured soil moisture in 2003 while disagreement was found in the deeper soil depths (Fig. 3). For each month during the season, simulated soil moisture was in agreement with the measured soil moisture from the surface to the depths of 20 cm in April, 40 cm in May, and 30 cm in July, while agreement in June was found in the soil depths between 40 and 100 cm. As Kiniry *et al.* (1995) pointed out, overestimation of the amount of plant-available water at field capacity can cause EPIC to overestimate yield in dry years. It is considered to be helpful to measure maximum depth of water extraction using ap-

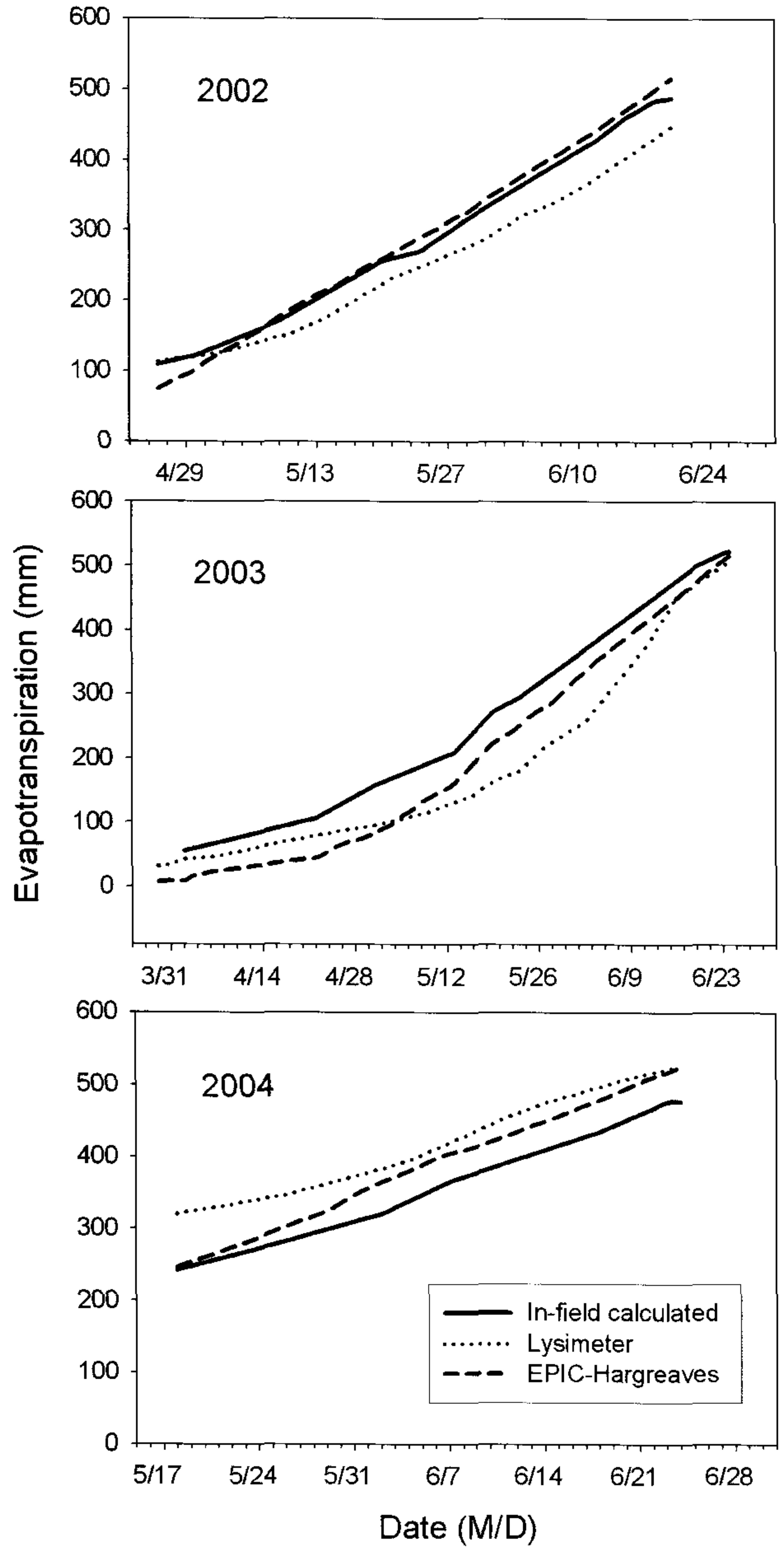

Fig. 2. Lysimeter measured crop evapotranspiration (ETc) vs. two methods of estimating ETc (in-field calculated and EPIC simulated using Hargreaves-Samani) in 2002, 2003, and 2004 at the Texas A&M AgriLife Research Center in Uvalde, Texas.

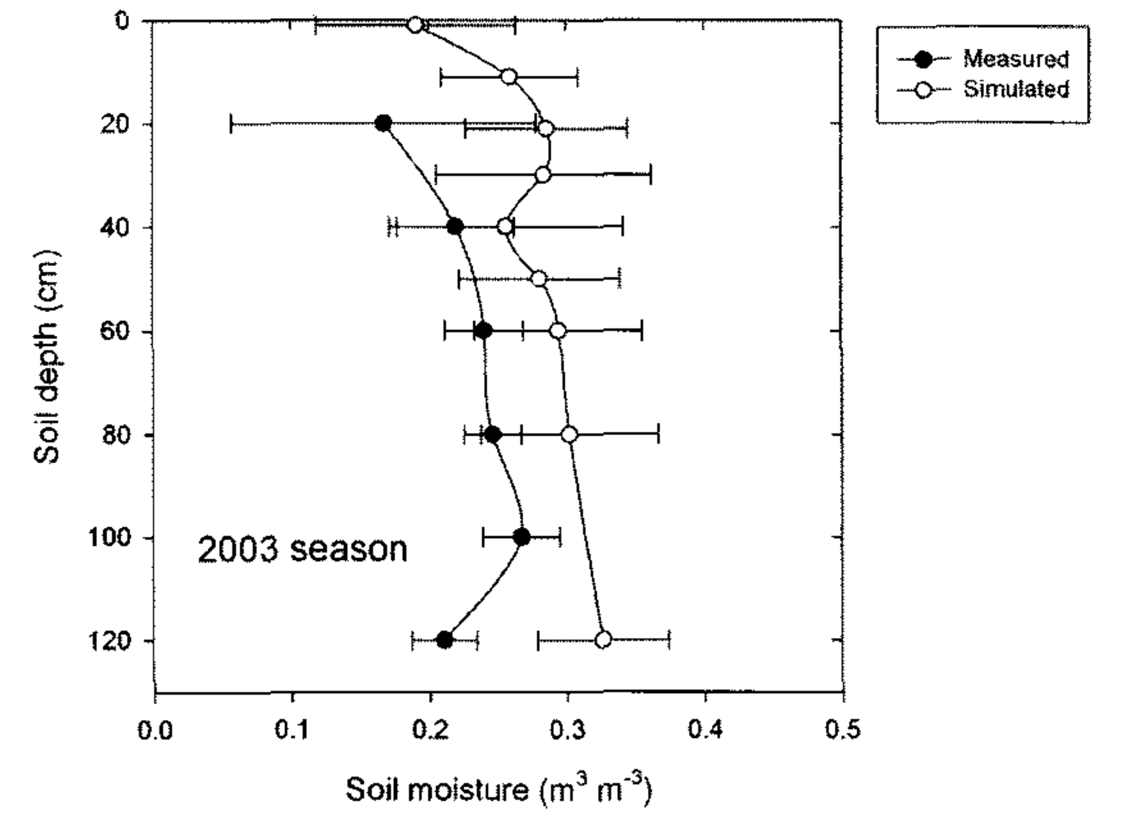

Fig. 3. Measured vs. simulated soil moisture at each soil depth within each month (top) and during the crop growing season (bottom) in 2003. Horizontal bars represent monthly and seasonal variations.

propriate cultivars in the region.

The EPIC model simulated the variability in grain yield within the field with different irrigation regimes, with r^2 value of 0.69 and root mean square error (RMSE) of 0.50 Mg ha^{-1} (Fig. 4). The regression slope was 0.73 (±SE of 0.19) and the y-intercept was 1.82. The regression line was close to the 1:1 line. For the three years, the measured yield ranged from 4.71 to 7.62 Mg ha^{-1} while simulated yield ranged from 4.68 to 7.56 Mg ha^{-1}. The upper 95% confidence interval of the means ranged from 6.08 to 8.14 Mg ha^{-1} while the lower 95% confident interval ranged from 4.50 to 6.67 Mg ha^{-1}. Previously, Williams *et al.* (1989) reported that EPIC could accurately simulate corn responses to irrigation at locations in the western USA. Kiniry *et al.* (2004) recently demonstrated that corn yields grown under irrigated conditions in the Texas High Plains could be simulated using the ALMANAC simulation model. Our validation results also demonstrate that the EPIC model can be used as a decision support tool for irrigation management of corn in South Texas.

The crop model simulated the variability in grain yield of corn from different farms at different irrigation regimes (Fig. 5). Measured yield ranged from 6.91 to 9.42 Mg ha^{-1} while simulated yield ranged from 5.45 to 9.23 Mg ha^{-1}. While present data were not statistically significant due to narrow ranges of measured crop yield, simulated yield was arithmetically in agreement with the measured yield. Assuming that EPIC reproduced the crop yield variation from the farms, the model was applied to simulate yield responses with various irrigation scenarios.

Yield responses at various irrigation scenarios (Fig. 6A) show that the yields in dry years linearly increased with the increased irrigation amounts while those in wet years already reached a plateau. When the yields were plotted as a function of total amounts of water (irrigation + rainfall), grain yield as a function of irrigation + rainfall linearly increased until 700 mm and reached a plateau after that (Fig. 6B). With this result, we assume that the amount of water necessary to achieve 9 to 9.5 Mg ha^{-1} for corn is ~ 700 mm. In addition, yield versus ETc shows that grain yield linearly increased up to ~ 650 mm, which is considered to be a saturated ETc for corn in this region (Fig. 6C). Values of water use efficiency (WUE) versus grain yield curve-linearly increased until ~ 8 Mg ha^{-1} (Fig. 7A). WUE_{I+R} generally reached a plateau at ~ 8 Mg ha^{-1}. Our result shows that there is a positive correlation between WUE and grain corn yield up to a certain range of yield, which was ~ 8 Mg ha^{-1}. When the WUE values were plotted against values of ETc and water input, WUE generally increased as ETc or water input increased until ~ 600 mm (Fig. 7B). WUE_{I+R} versus water input de-

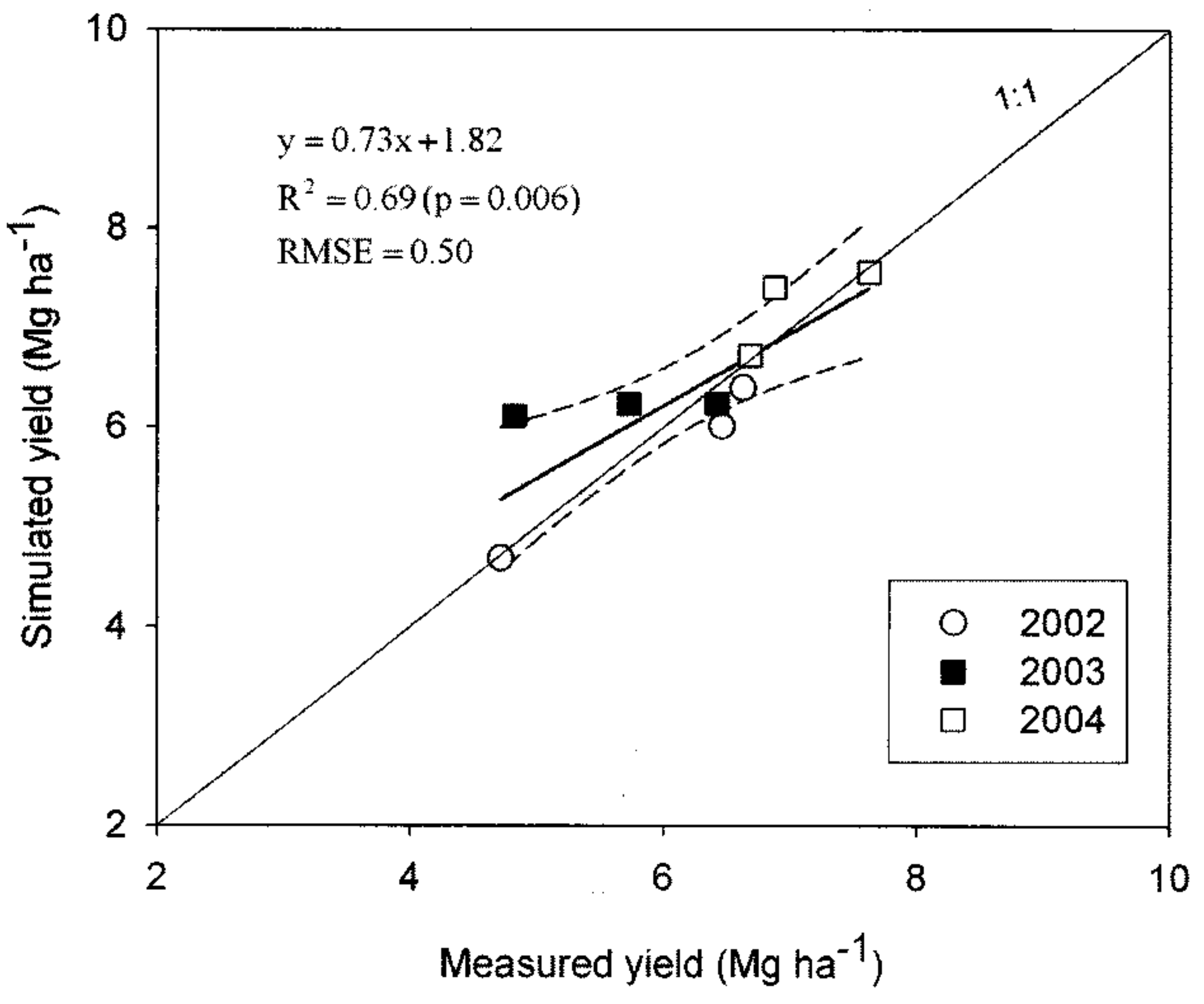

Fig. 4. Measured vs. simulated grain yield using the data obtained in 2002, 2003, and 2004 at the Texas A&M AgriLife Research Center in Uvalde, Texas. Dashed lines are 95% confidence interval for the mean of the simulated values.

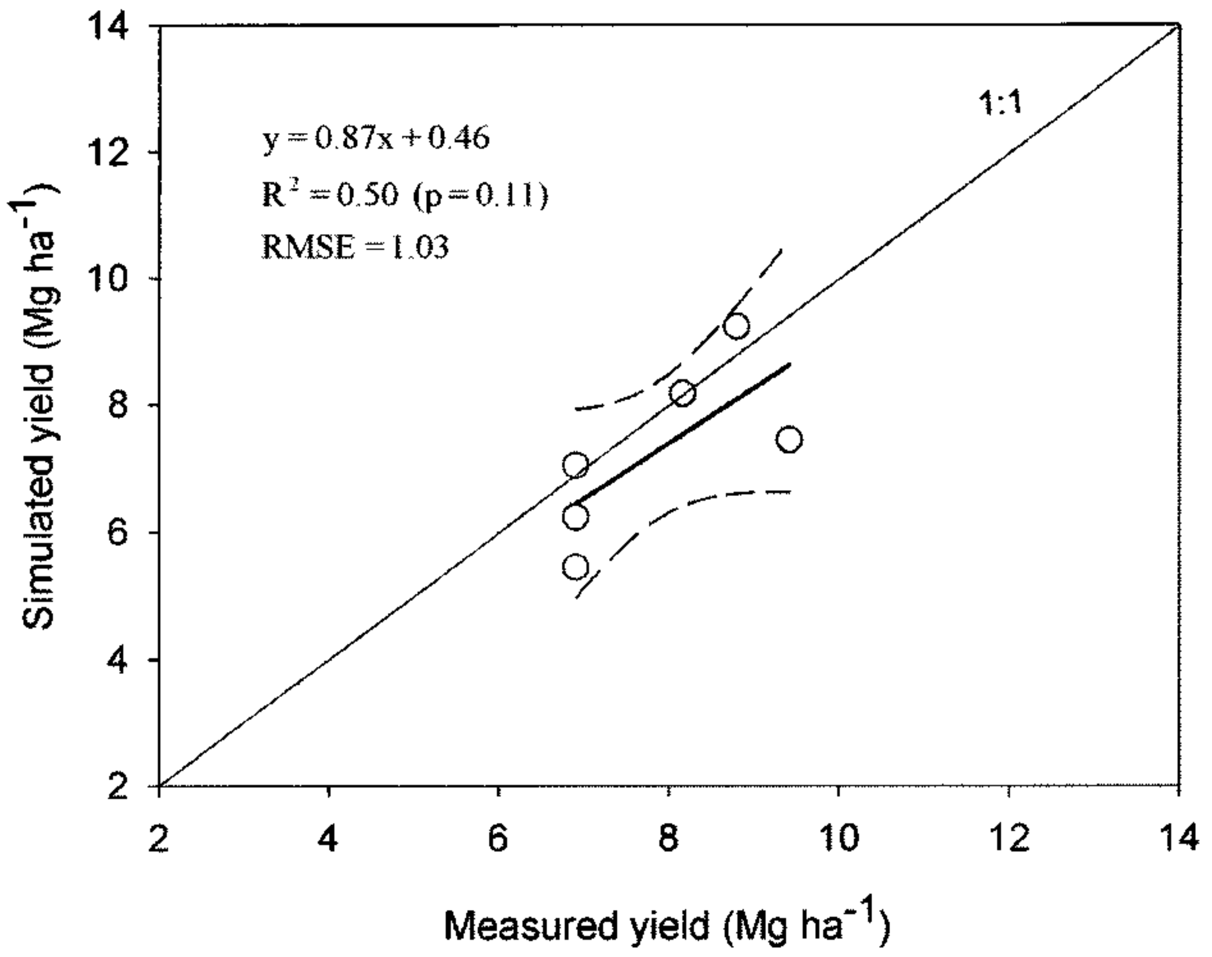

Fig. 5. Measured vs. simulated grain yield using farm data, obtained at four Counties of South Texas (Bexar, Medina, and Uvalde) in 2006. Dashed lines are 95% confidence interval for the mean of the simulated values.

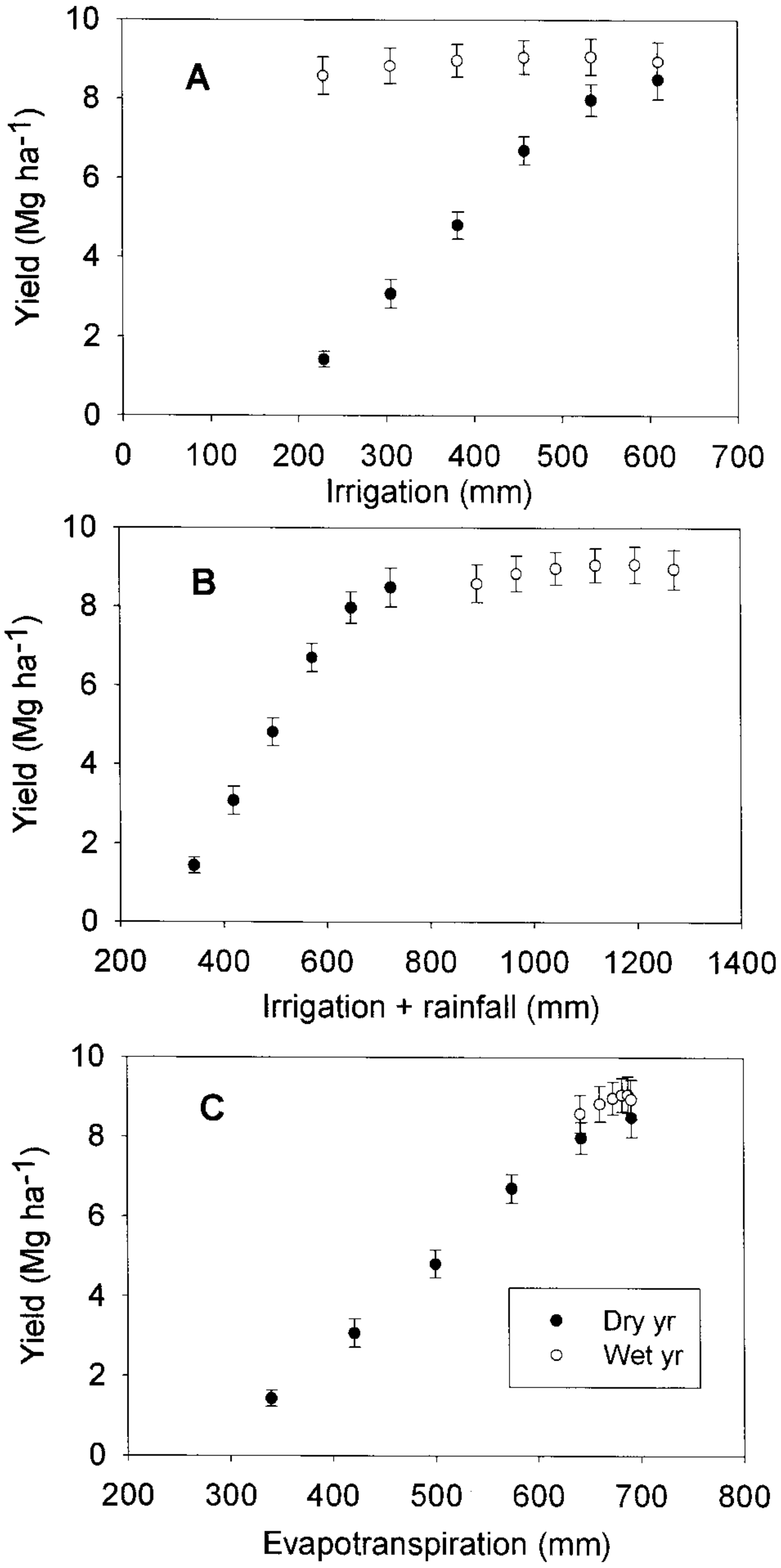

Fig. 6. Yield responses as a function of irrigation (A), irrigation + rainfall (B), and crop evapotranspiration (C). Data were normalized using the yield responses from 20-yr (1987-2006) simulations for each farm. Vertical bars represent standard errors at 95% confidence interval for the mean of each data point (n=6).

creased with a slow linear phase after ~ 650 mm. Therefore, it is considered that there are positive correlations between WUE_{I+R} versus water input and WUE_{ETc} versus ETc until ~ 600 mm while there is a negative correlation between WUE_{I+R} and water input after ~ 650 mm. This value was determined to be the amount of ETc needed to achieve the range of the highest grain corn yield in this study.

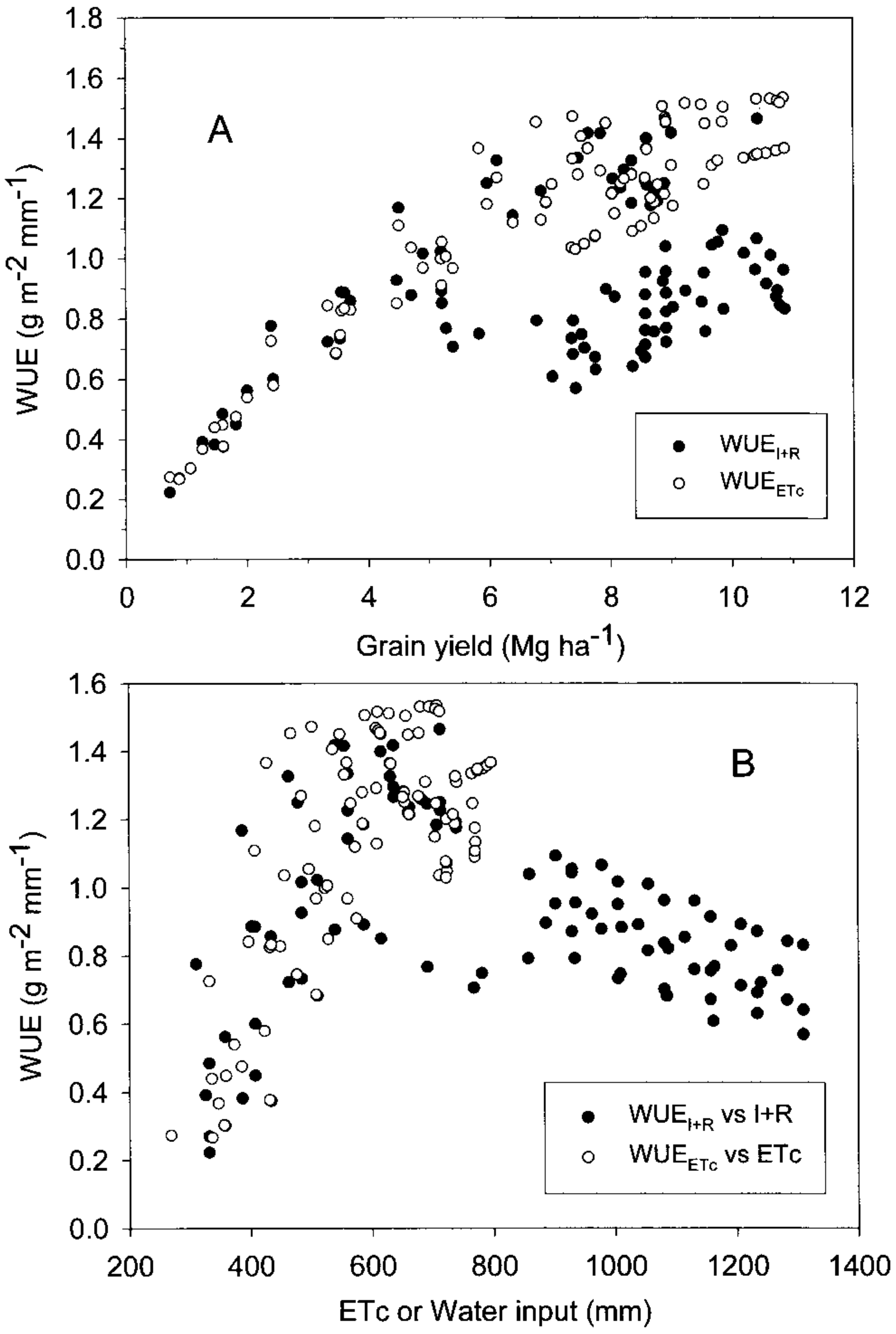

Fig. 7. Water use efficiency, WUE, in relation to corn grain yield, Y, (A) and WUE in relation to crop evapotranspiration, ETc, and water input, or irrigation, I, + rainfall, R, (B). WUE_{I+R} = Y/(I+R) and WUE_{ETc} = Y/ ETc.

The EPIC crop simulation model can be used to assess the impact of weather and management strategies on agricultural production as well as soil and water resources. The model has been used extensively in the U.S. and other counties. Studies reported that EPIC can be one of the most recommendable models for simulating long-term average crops (Bryant *et al.*, 1992; Kiniry *et al.*, 1995; Moulin & Beckie, 1993; Touré *et al.*, 1995; Williams *et al.*, 1989). In this study, we used EPIC to evaluate the possibility of using it as a decision support tool for irrigation management of crops under South Texas conditions. The effectiveness of crop simulation models depends on practical accuracy in simulating variables of interest. The validation result of corn shows reasonable agreement between simulation and measurement in terms of crop water use and crop yield. However, Wang *et al.* (2005) noted that 'while models could be well calibrated and perform adequately under many conditions, there is still uncertainty about the values of many of their parameters', resulting in the overall uncertainty in the simulation results. It was reported that the model tended to overestimate low yields (Cabelguenne *et al.*, 1990; Ceotto *et al.*, 1993; Martin *et al.*, 1993; Warner *et al.*, 1997). Overestimation of the amount of plant-available water at field capacity can cause EPIC to overestimate yield in dry years (Kiniry *et al.*, 1995). Therefore, efforts with intense investigation of the parameters for EPIC are needed to adequately simulate yield in low and high yielding years.

While many studies focused on the evaluation of EPIC to simulate biomass and yield for various crops, some evaluated the model as a decision support tool in irrigation allocation and scheduling (Bryant *et al.*, 1992, 1993; Cabelguenne *et al.*, 1995, 1997; Santos *et al.*, 2000). Meanwhile, the simulation results with farm data in this study also demonstrate that the EPIC model can be used as a decision support tool for crops under full and deficit irrigation conditions in South Texas. We could determine that corn required ~ 700 mm of water input and ~ 650 mm of ETc to achieve a maximum yield of 9 to 9.5 Mg ha^{-1}. The differences between water input and ETc can be attributed to water losses due to 97% irrigation system efficiency as well as deep percolation. The relationships between yield and water use for corn have been reported to be linear (Irmak *et al.*, 2000; Oktem *et al.*, 2003; Payero *et al.*, 2006; Yazar *et al.*, 2002). Simulation result in this study agreed to the findings.

CONCLUSIONS

We compared measured crop evapotranspiration (ETc) to two methods of estimating ETc, and evaluated the EPIC crop model to use as a decision support tool for management of corn experiencing various irrigation conditions in South Texas of the U.S. The validation results of corn show reasonable agreement between simulation and measurement in terms of crop water use, soil moisture, and grain yield. The simulation results with farm data allow us to use the EPIC model as a decision support tool for corn under full and deficit irrigation conditions in South Texas. EPIC specifically appears to be effective in long term and pre-season decision making for irrigation management of crops. Using growth stage specific crop coefficients and/or the EPIC simulation model indicate the possibility of being effective tools in irrigation scheduling.

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