Agricultural Water Management 96 (2009) 1698–1704

Contents lists available at ScienceDirect

Agricultural Water Management

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

Determination of growth-stage-specific crop coefficients (K_C) of maize and sorghum

Giovanni Piccinni [a,1], Jonghan Ko [b,1,*], Thomas Marek [c], Terry Howell [d]

[a] Monsanto Company, 700 Chesterfield Pkwy West, Chesterfield, MO 63017, USA
[b] USDA-ARS, Agricultural Systems Research Unit, 2150 Centre Avenue, Building D, Suite 200, Fort Collins, CO 80526, USA
[c] Texas A&M University, Texas AgriLife Research and Extension Center, 6500 Amarillo Blvd. West, Amarillo, TX 79106, USA
[d] USDA-ARS, Conservation and Production Research Laboratory, P.O. Drawer 10, Bushland, TX 79012, USA

ARTICLE INFO

Article history:
Received 7 January 2009
Accepted 26 June 2009
Available online 5 August 2009

Keywords:
Crop coefficient
ET measurement
Weighing lysimeter

ABSTRACT

A ratio of crop evapotranspiration (ET_C) to reference evapotranspiration (ET_O) determines a crop coefficient (K_C) value, which is related to specific crop phenological development to improve transferability of the K_C values. Development of K_C can assist in predicting crop irrigation needs using meteorological data from weather stations. The objective of the research was conducted to determine growth-stage-specific K_C and crop water use for maize (*Zea Mays*) and sorghum (*Sorghum bicolor*) at Texas AgriLife Research field in Uvalde, TX, USA from 2002 to 2008. Seven lysimeters, weighing about 14 Mg, consisted of undisturbed 1.5 m × 2.0 m × 2.2 m deep soil monoliths. Six lysimeters were located in the center of a 1-ha field beneath a linear-move sprinkler system equipped with low energy precision application (LEPA). A seventh lysimeter was established to measure reference grass ET_O. Crop water requirements, K_C determination, and comparison to existing FAO K_C values were determined over a 3-year period for both maize and sorghum. Accumulated seasonal crop water use ranged between 441 and 641 mm for maize and between 491 and 533 mm for sorghum. The K_C values determined during the growing seasons varied from 0.2 to 1.2 for maize and 0.2 to 1.0 for sorghum. Some of the values corresponded and some did not correspond to those from FAO-56 and from the Texas High Plains and elsewhere in other states. We assume that the development of regionally based and growth-stage-specific K_C helps in irrigation management and provides precise water applications for this region.

Published by Elsevier B.V.

1. Introduction

Agricultural water users must plan an annual water budget in semiarid and arid lands and areas where water usage is regulated due to ecological protection programs, limited resources, and competitive demand (Barrett, 1999). Water for agricultural, urban and industrial use in the Austin – San Antonio – Uvalde corridor is pumped from the Edwards aquifer. This karst aquifer is unique in terms of containment, recharge, and political sensitivity as a sole-source water supply for many small towns and the much larger metropolitan city of San Antonio. The regulation of this aquifer, however, is portent to the possible regulation of all aquifers in Texas. In 2007, Senate Bill 3 of the 80th session of legislature imposed a maximum withdrawal of 705.5 million m^3 (705.5 GL) of water per year from the Edwards aquifer. Since 50% of the water withdrawn from the aquifer is for agricultural use, agricultural water conservation strategies are of utmost importance in the Edwards region. Mild climatic conditions in this region allow for a variety of economically important crops to be grown year-round under irrigation, including maize, cotton, grain sorghum, wheat, and vegetable crops. Determining crop water requirements specific to each crop is key in providing growers with information to (a) select which crops to grow and (b) determine the timing and quantity of irrigation events.

The Wintergarden region of Texas is located on the South Texas Plains, receives approximately 660 mm $year^{-1}$ of precipitation and has a growing season of approximately 214–275 d. In 2000, growers in this region irrigated 40,000 ha (Texas Water Development Board, 2001). From preliminary studies carried on at the Texas AgriLife Research Center at Uvalde, it is estimated that approximately 62 million to 74 million m^3 (74 GL) of groundwater could be conserved each year by implementing proper irrigation techniques and scheduling. To optimize irrigation events, crop water requirements throughout the growing season must first be determined.

Abbreviations: ASCE, American Society of Civil Engineers; ET_O, reference evapotranspiration; ETc, crop evapotranspiration; K_C, crop coefficient; K_{co}, crop coefficient based on the ASCE Penman–Monteith equation for grass; LEPA, low energy precision application.

* *Corresponding author.* Tel.: +1 970 492 7370; fax: +1 970 492 7310.
E-mail address: Jonghan.Ko@ars.usda.gov (J. Ko).
[1] Previously, Texas A&M University, Texas AgriLife Research and Extension Center, 1619 Garner Field Road, Uvalde, TX 78801, USA.

0378-3774/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.agwat.2009.06.024

The use of on-site microclimatological data and crop coefficients enables the determination of crop water use and dissemination of such information to growers in a reliable, usable, and affordable format. The concept of 'crop coefficient' (K_C) was introduced by Jensen (1968) and further developed by the other researchers (Doorenbos and Pruitt, 1975, 1977; Burman et al., 1980a,b; Allen et al., 1998). K_C is the ratio of the evapotranspiration of the crop (ET_C) to a reference crop (ET_O) (Allen et al., 1998). ET_O may be measured directly from a reference crop such as a perennial grass (Pruitt and Doorenbos, 1977; Watson and Burnett, 1995) or computed from weather data using (a) temperature models (Thornthwate, 1948; Doorenbos and Pruitt, 1977), (b) radiation models (Doorenbos and Pruitt, 1977; Hargreaves and Samani, 1985), and (c) combination models (Allen et al., 1998). Weighing lysimeters are employed to measure ET_O and ET_C directly by detecting changes in the weight of the soil/crop unit (Howell et al., 1995; Schneider et al., 1998; Marek et al., 2006). Weather data are used to compute ET_O via equations such as the ASCE Penman–Monteith (ASCE-EWRI, 2005). By utilizing the following equation

$$ET_C = K_C \times ET_O \tag{1}$$

where all that is needed to provide growers with real time irrigation recommendations (ET_C) are local weather stations to provide data to determine ET_O. According to Allen et al. (1998), crop type, variety, and developmental stage affect ET_C.

Potential evapotranspiration (PET) network is a group of meteorological stations to acquire weather data to compute PET and to disseminate it in an automated process providing timely, accurate data on ET for various crops (Howell, 1998). PET networks (Brock et al., 1995; Howell, 1998; Snyder, 1983) and crop simulation models (Guerra et al., 2005, 2007; Santos et al., 2000) have proven to be reliable, inexpensive, and effective tools for estimating crop water needs in research settings. The PET networks provide a 'uniform' and 'dependable' source of information on crop water use (Marek et al., 1996; Seymour et al., 1994). Recently, networks of weather stations have been established in many parts of Texas for the purpose of supporting predictions of crop ET. It is estimated that, in the northern Texas panhandle, yearly fuel cost savings would exceed 18 million dollars if all irrigators used the PET network data. However to support predictions of crop evapotranspiration, generic crop coefficients will not fulfill the need for precise irrigation applications. The objective of this research was to determine crop water use (ET_C) and develop crop coefficients (K_C) specific to multiple phenological stages for maize and sorghum grown in the Wintergarden region of Texas.

2. Materials and methods

2.1. Lysimeter facility

The lysimeter facility at the Texas AgriLife Research Center in Uvalde, TX (29°13′N, 99°45′W; elevation 283 m), includes seven weighing (~14 Mg) lysimeters constructed between 2001 and 2006. Six lysimeters were established to measure crop evapotranspiration (ET_C) and a seventh lysimeter was established to measure reference grass evapotranspiration (ET_O). Construction details and resolution are described by Marek et al. (2006). Each lysimeter is 1.5 m × 2.0 m in surface area and 2.2 m deep. The surface area of the lysimeters accommodates the common row spacing utilized in the region. The soil monoliths of a Uvalde silty clay soil (fine-silty, mixed, hyperthermic Aridic Calciustolls with a pH of 8.1) in the lysimeters represent soils within an 80 km radius of the research center.

Microclimatological data were collected by a standard Campbell Scientific, Inc. (Logan, UT) weather station every 6 s with 15 min output. These include solar irradiance, wind speed, air temperature, relative humidity, precipitation, and barometric pressure (Dusek et al., 1987; Howell et al., 1995). The mass of each lysimeter was sampled at a frequency of 1 Hz and averaged for every 5 min. Changes in lysimeter mass were measured as changes in load cell output from a platform scale (Avery Weigh Tronix scale model #: HSDS 6060, Fairmont, MN) in $mV\,V^{-1}$ beneath each lysimeter and the lysimeter mass calibration. The calibration of the scale output ($mV\,V^{-1}$) to mass (kg) and then to water depth (mm) was described in Marek et al. (2006). The load cell signal was composited to 30-min means and the lysimeter mass resolution was 0.01 mm. Daily evapotranspiration (ET) was determined as the difference between lysimeter mass losses and lysimeter gains divided by the lysimeter area (3 m^2). A pump (−10 kPa) provided vacuum drainage and the drainage effluent was weighed by load cells (drainage rate data are not reported here). ET for each 24-h period was divided by 1.02 to adjust the lysimeter area to the midpoint between the two walls (10 mm air gap; 9.5 mm wall thickness; 3.05 m^2 area instead of the inside 3.00 m^2 lysimeter surface area, according to Howell et al. (2004).

2.2. Lysimeter field data

A tall fescue grass (*Festuca arundinacea*) seed brand, Emerald III (Sharp Bros. Seed Co., Healy, KS) was hydro-mulched in the late fall of 2001 on the weather station plot after completing installation of a lysimeter, located in the center of ~1.0 ha, and a subsurface drip irrigation system. The irrigation system used 1.9 $L\,h^{-1}$ Geoflow turbulent flow emitters spaced every 0.46 m along laterals (14 mm ID) placed at 0.15 m depth. The lysimeter had a dense network of lines (64 arranged in a 0.19 m^2 grid) with 3.8 $L\,h^{-1}$ emitters that allowed 25 mm of water to be applied in 15 min. In 2008, the irrigation system was replaced with a rotary sprinkler system, which used a 3.8 $L\,h^{-1}$ high pressure pop-up, rotating stream sprinkler spaced every 6.0 m along the laterals. Irrigation was scheduled based on measured daily evapotranspiration (ET) and normally applied at 20 to 25 mm one to three times a week. Fertilizers (N and P) were applied through the irrigation water. The grass was regularly mowed with a rotary mower and hand-clipped around and on the lysimeter, and the clippings were bagged and removed. The grass height was ~0.1 m after mowing and varied from 0.12 to 0.15 m before mowing.

Maize and sorghum were grown between 2002 and 2008 in crop lysimeter fields, each located in the center of ~1.0 ha, which were used in the determination of K_C (Table 1). Growth and yield of the crops on the lysimeters was comparable to those of the surrounding crops in the field. All field operations were performed with standard 1.0 m wide four row-crop field equipment, except at each lysimeter where hand-cultural methods were applied. Row direction was east to west. Fertility and pest control practices were uniformly applied to the fields. The fields were furrow diked (dike spacing at ~1.5 m) in all years to minimize field runoff and rainfall and irrigation redistribution. Irrigation, equipped with a North-South-aligned sprinkler system, was applied East-West or West-East with a 3-span lateral move sprinkler system from Lindsay Manufacturing Co. (Lindsay, NE). The system was equipped with gooseneck fittings and spray heads (Senninger Super Spray 360E, Clermont, FL) with medium grooved spray plates on drops located ~1.5 m above the ground and 1.0 m apart. The drops could be converted to low energy precision application (LEPA) heads placed ~0.3 m above the ground. The fields were managed under full irrigation, which was scheduled based on measured daily crop water use (ET).

Daily ET measured with the lysimeters was determined as the difference between lysimeter mass losses (evaporation and transpiration) and lysimeter mass gains (irrigation, precipitation,

Table 1
Crops grown at the Texas AgriLife Research – Uvalde for determination of crop coefficient and associated seasonal data.

Crop	Variety[†]	Planting year	Plant-harvest (M/D)	Rainfall (mm)	Irrigation (mm)	ET_C (mm)	Temperature (°C)		GDD[‡]
							Max	Min	
Maize	32H39	2002	03/29–08/07	489	405	609	30.7	18.8	2426.8
	30G54	2003	03/18–08/11	322	349	641	31.2	18.2	2542.3
	30G54	2004	03/10–08/18	350	92	441	27.9	17.6	2598.7
Sorghum	DKS54	2006	03/24–07/19	64	439	491	33.4	19.6	1947.2
	DKS54	2007	03/21–08/09	524	20	533	29.1	19.1	1979.2
	DKS54	2008	03/26–08/05	87	443	521	33.3	20.0	1998.7

[†] 32H39 and 30G54 from Pioneer (Johnston, IA), DKS54 from DeKalb Genetics Co. (DeKalb, IL).
[‡] GDD, growing degree days, was determined using a base temperature of 8.0 °C for corn and 10.0 °C for sorghum.

or dew) as shown in Fig. 1. Crop coefficient (K_C) was calculated using the following equation:

$$K_C = ET_C/ET_O \quad (2)$$

where ET_O was determined from direct measurement using the lysimeter (Lys ET_O) and calculation using the ASCE Penman–Monteith equation (ASCE-EWRI, 2005) for grass (ASCE ET_O). K_C curves were fitted to third-order polynomials. Other studies demonstrate that K_C curves can be fitted to third and up to fifth-order polynomials (Ayars and Hutmacher, 1994; Sammis and Wu, 1985; Stegman, 1988). Lys K_C was the ratio of the lysimeter crop ET_C to the grass lysimeter ET_O. ASCE K_{co} was the ratio of the lysimeter ET_C to the ASCE computed ET_O.

2.3. The ASCE-standardized reference evapotranspiration equation

The ASCE ET_O (mm day^{-1}) was estimated using the following formula (ASCE-EWRI, 2005):

$$ET_O = \frac{0.408\Delta(R_n - G) + \gamma(C_n/T + 273)u2(e_s - e_a)}{\Delta + \gamma(1 + C_d u2)} \quad (3)$$

where R_n (MJ m^{-2} day^{-1}) is the measured net irradiance at the crop canopy; G (MJ m^{-1}) is the soil heat flux density; T (°C) is the measured mean daily air temperatures; $u2$ is the mean daily wind speed at 2-m height (m s^{-1}); e_s (kPa) is the saturated vapor pressure; e_a (kPa) is the mean actual vapor pressure; Δ (kPa °C^{-1}) is the slope of the saturation vapor–pressure temperature curve; γ (kPa °C^{-1}) is the psychrometric constant; C_n (K mm s^3 mg^{-1} d^{-1}) is the numerator constant; and, C_d (s m^{-1}) is the denominator constant and both change with crop reference type and calculation time-step. The units for the coefficient 0.408 are m^2 mm MJ^{-1}.

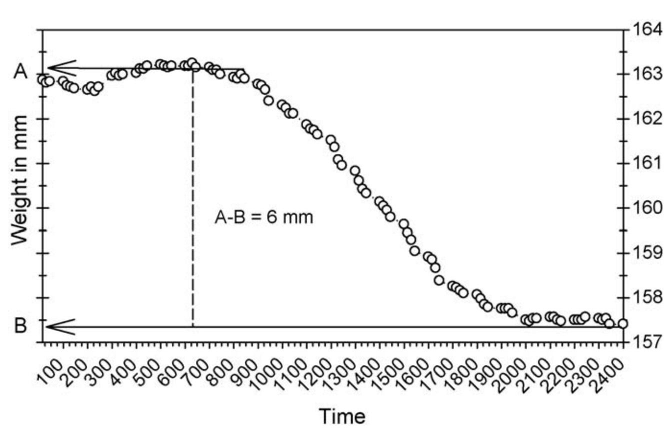

Fig. 1. An example of daily evapotranspiration (ET) determination using a 15-min weighing lysimeter chart. The difference between lysimeter mass losses and lysimeter mass gains represents daily ET.

2.4. Statistical analysis

The data were analyzed by paired t-test using PROC TTEST and analysis of correlation using PROC CORR (SAS version 9.2, Cary, NC). These were used to determine statistical differences of the measured lysimeter data from the calculated data. Goodness-of-fit estimators used were p value from the paired t-test. In addition, two statistics were used: (i) root mean square error (RMSE), Eq. (4), (ii) mean relative error (MRE), and (iii) d statistics (Nash and Sutcliffe, 1970), Eq. (5).

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{n}(C_i - M_i)^2\right]^{1/2} \quad (4)$$

$$MRE_i = \frac{1}{n}\sum_{i=1}^{n}\frac{(C_i - M_i)}{M_i}100\% \quad (5)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(C_i - M_i)^2}{\sum_{i=1}^{n}(M_i - M_{avg})^2} \quad (6)$$

where C_i is the ith calculated value, M_i is the ith measured value, M_{avg} is the averaged measured value, and n is the number of data pairs. d values are equivalent to the coefficient of determination (R^2), if the values fall around a 1:1 line of calculated versus measured data, but d is generally lower than R^2 when the predictions are biased, and can be negative.

3. Results and discussion

3.1. Maize

Lysimeter-measured reference evapotranspiration (Lys ET_O) over the maize growing seasons in 2002, 2003, and 2004 varied from 1 to 10 mm d^{-1} and typically ranged between 2 and 7 mm d^{-1} (Fig. 2A). Lys ET_O values in 2004 were relatively smaller than those in 2002 and 2003. Crop evapotranspiration (ET_C) of maize during the growing seasons ranged between 1 and 12 mm d^{-1} and peaked at ~85 days after planting (DAP) in 2002, ~98 DAP in 2003, and ~110 DAP in 2004 (Fig. 2B). The maximum maize ET_C closely corresponds to the one (12.4 mm d^{-1}) reported by Howell et al. (1997) at Bushland, TX. Accumulated amounts of maize ET_C in 2002, 2003, and 2004 were 609, 641, and 441 mm, respectively (Table 1). The disagreement between the total water amount applied and that consumed through ET_C in 2002 can be explained by a runoff due to a heavy rain (193 mm) on July 1. In addition, the discrepancies in ET_C between 2004 and the

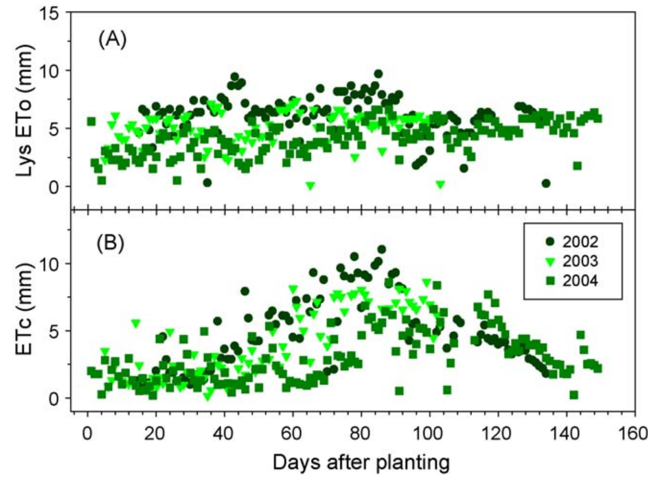

Fig. 2. (A) Lysimeter-measured reference evapotranspiration (Lys ET_O) and (B) maize crop evapotranspiration (ET_C) as a function of days after planting for crop growing seasons from 2002 to 2003.

other years are probably due to lower air temperatures (Table 1) and more frequent rainfalls (consequent higher humilities) in 2004 than the other years. In comparison with those from the Texas High Plains, our ET_C values are within the value range of 328 and 617 mm reported by Tolk et al. (1998) and a bit larger or smaller than those of 418 and 671 mm by Howell et al. (2008). In addition, our values are smaller than the value range of 670 and 790 mm reported by Musick and Dusek (1980b) and those of 741 and 802 mm by Howell et al. (1997). Meanwhile, reference evapotranspiration (ET_O) during the corresponding crop seasons ranged between 2 and 7 mm d^{-1} for both Lys ET_O and calculated ET_O using ASCE Penman–Monteith equation for grass (ASCE ET_O) (Fig. 3A). A *t*-test shows that the ASCE ET_O was significantly different from the Lys ET_O ($p < 0.0001$). However, the other evaluation statistics show that the ASCE ET_O agreed with root mean square error (RMSE) of 0.52 mm d^{-1}, mean relative error (MRE) of −4.0%, and *d* statistics of 0.89 (Fig. 4A). The ASCE ET_O also correlated with the Lys ET_O with Pearson's correlation coefficient (r) of 0.95 ($p < 0.0001$).

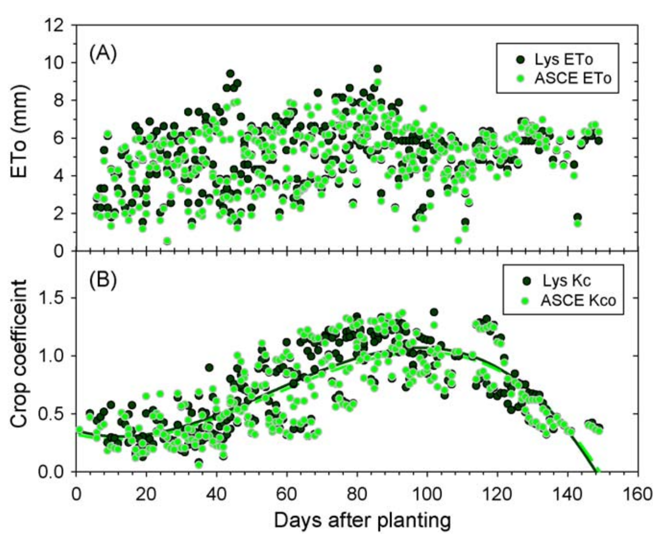

Fig. 3. (A) Lysimeter-measured reference evapotranspiration (Lys ET_O) and (B) maize crop coefficient as a function of days after planting for measured K_C using lysimeter (Lys K_C) and calculated K_C based on ASCE Penman–Monteith equation for grass (ASCE K_{co}). Data were obtained at Texas AgriLife Research Center in Uvalde, TX from 2002 to 2004. A third polynomial equation for each K_C is as follows: Lys $K_C = 0.36 - 8.89 \times 10^{-3}\text{DAP} + 4.02 \times 10^{-4}\text{DAP}^2 - 2.42 \times 10^{-6}\text{DAP}^3$. ASCE $K_{co} = 0.32 - 7.84 \times 10^{-3}\text{DAP} + 3.75 \times 10^{-4}\text{DAP}^2 - 2.26 \times 10^{-6}\text{DAP}^3$

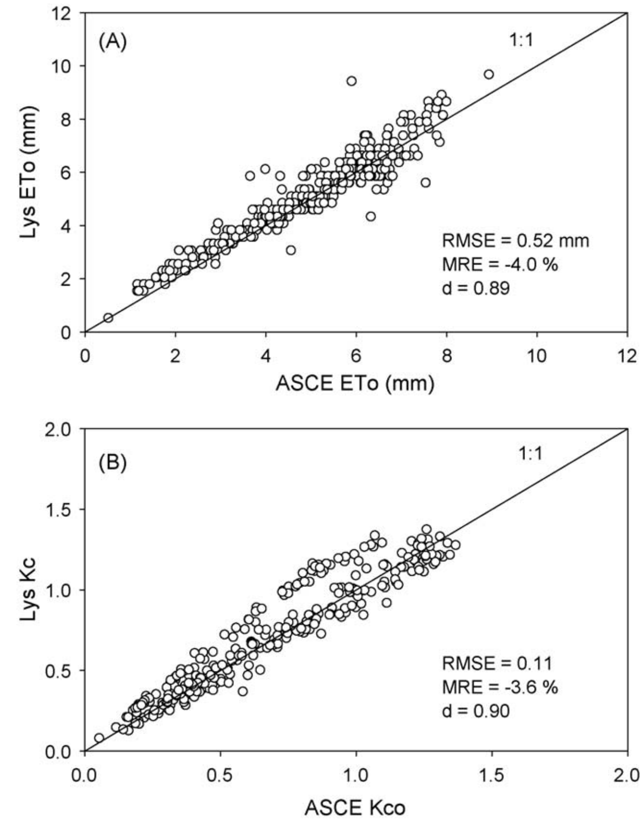

Fig. 4. (A) Lysimeter-measured ET_O (Lys ET_O) vs. calculated ET_O using ASCE Penman–Monteith equation for grass (ASCE ET_O) and (B) maize K_C based on lysimeter measurement (Lys K_C) vs. maize K_C based on ASCE Penman–Monteith equation for grass (ASCE K_{co}).

Maize K_C in the 3 years varied from 0.1 to 1.3 for both of lysimeter based K_C (Lys K_C) and ASCE ET_O based K_C (K_{co}) (Fig. 3B). According to a *t*-test, there was significant difference between the Lys K_C and the ASCE ET_O ($p < 0.0001$). However, the Lys K_C corresponded to the ASCE ET_O K_C with RMSE of 0.11, MRE of −3.6%, *d* value of 0.90 (Fig. 4B). The calculated and measured data also correlated with *r* value of 0.95 ($p < 0.0001$). Seasonal K_C values in 2002, 2003, and 2004 typically ranged between 0.2 and 1.2 without

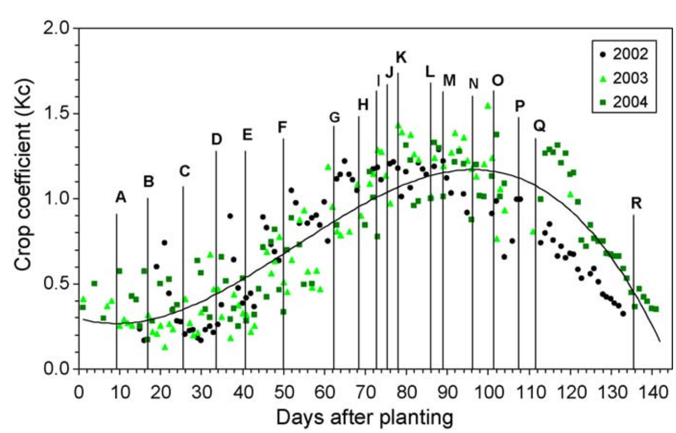

Fig. 5. Growth-stage-specific crop coefficients (K_C) of maize determined as a function of the days after planting in 2002, 2003 and 2004 at Uvalde, TX. Vertical lines represent 3-year-average growth stages: A – emergence; B – 2 leaf; C – 4 leaf; D – 5 leaf; E – 6 leaf; F – 8 leaf; G – 10 leaf; H – 12 leaf; I – 14 leaf; J – tassel; K – silk; L – blister; M – milk; N – dough; O – dent; P – 1/2 mature; Q – black layer; R – harvest. A third polynomial equation for the Lys K_C is as follows: Lys $K_C = 0.36 - 8.89 \times 10^{-3}\text{DAP} + 4.02 \times 10^{-4}\text{DAP}^2 - 2.42 \times 10^{-6}\text{DAP}^3$.

Table 2
Maize crop coefficients (K_C) determined at Uvalde, TX (A) in comparison to those from FAO-56 (Allen et al., 1998) (B).

Growth stage	DAP†	K_C
(A)		
Emergence	8	0.35
2-Leaf	9–20	0.35
4-Leaf	21–26	0.40
6-Leaf	27–39	0.55
8-Leaf	40–47	0.70
10-Leaf	48–58	0.80
12-Leaf	59–66	0.90
14-Leaf	67–72	1.00
Tassel	73–75	1.05
Silk	76–83	1.10
Blister	84–87	1.15
Milk	88–93	1.20
Dough	94–98	1.20
Dent	99–105	1.15
1/2 Mature	106–110	1.10
Black layer	111–137	0.90
(B)		
K_C ini	0–30	0.30
K_C mid	70–120	1.20
K_C end	120–170	0.35

† DAP, days after planting.

much year-to-year variation (Fig. 5). Our growth-stage-specific K_C values were determined based on a third-order polynomial K_C curve that represents the distribution of K_C over time throughout the season (Wright, 1982). Growth-stage-specific K_C for maize determined in this study was 0.35 at emergence, 1.00 at tassel, and 0.90 at black layer stages (Table 2). The K_C values in this study are smaller at mid growth stage and larger at late growth stage than those from FAO-56 (Allen et al., 1998). In comparison with the basal crop coefficients (K_{cb}) derived from Davis, California (Burman et al., 1980a; Jensen et al., 1990), our K_C values are somewhat larger at the most growth stages but nearer to the peak K_{cb} of 1.17. Meanwhile, our values are larger than the K_{cb} value of 0.1 at initial growth stage but generally match with the maximum K_{cb} of 1.10 at mid growth stage determined from the Texas High Plains (Howell et al., 1998, 2006).

3.2. Sorghum

Lys ET_O during the sorghum growing seasons in 2006, 2007, and 2008 varied from 1 to 13 mm d^{-1} (Fig. 6A). Lys ET_C of sorghum

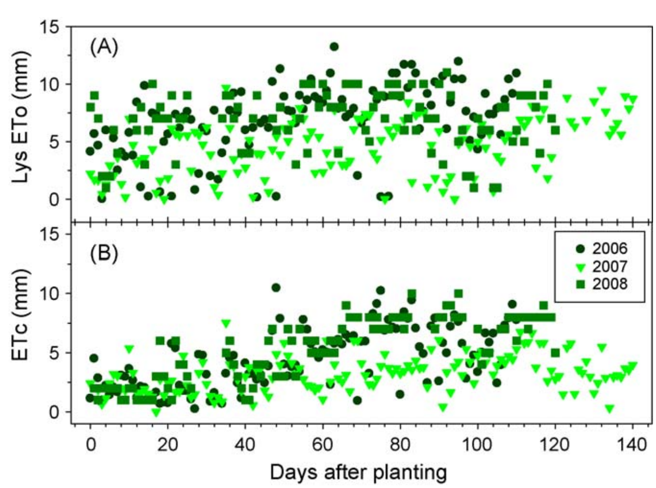

Fig. 6. (A) Lysimeter-measured reference evapotranspiration (Lys ET_O) and (B) sorghum crop evapotranspiration (ET_C) as a function of days after planting for crop growing seasons from 2006 to 2008.

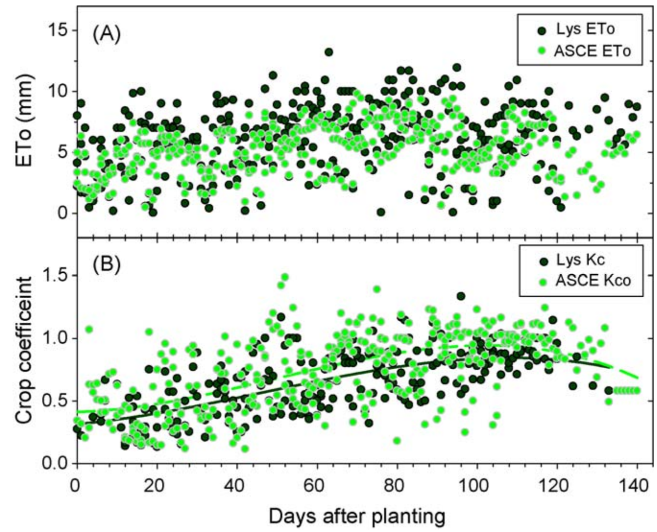

Fig. 7. (A) Lysimeter-measured reference evapotranspiration (Lys ET_O) and (B) sorghum crop coefficient as a function of days after planting for measured K_C using lysimeter (Lys K_C) and calculated K_C based on ASCE Penman–Monteith equation for grass (ASCE K_{co}). Data were obtained at Texas AgriLife Research Center in Uvalde, TX in 2006, 2007 and 2008. A third-order polynomial equation for each K_C is as follows: Lys $K_C = 0.32 + 3.28 \times 10^{-3}DAP + 5.49 \times 10^{-5}DAP^2 - 4.10 \times 10^{-7}DAP^3$. ASCE $K_{co} = 0.43 - 4.80 \times 10^{-4}DAP + 1.46 \times 10^{-4}DAP^2 - 9.28 \times 10^{-7}DAP^3$.

(medium-full hybrid; ~72 d to flower) during the 3 years ranged between 1 and 9 mm d^{-1} and peaked at ~80 DAP in 2006, ~110 DAP in 2007, and ~90 DAP in 2008 (Fig. 6B). Most values of the Lys ET_O and the Lys ET_C in 2007 were typically smaller than those in 2006 and 2007. This can be attributed to lower temperatures and more rainfalls in 2006 (Table 1). Meanwhile, our values in daily ET_C variation generally match with those (e.g., 10 mm d^{-1} for the typical maximum ET_C rate) reported by Howell et al. (1997) at Bushland, TX. Seasonal accumulations of sorghum ET_C in 2006, 2007, and 2008 were 491, 533, and 521 mm, respectively (Table 1). These values are somewhat smaller than that of 578 mm reported by Howell et al. (1997) and those of 559 mm (Jensen and Sletten, 1965b) and 629 mm (Stewart et al., 1983) at Bushland, TX. The major reason for this can be found from comparatively higher daily temperatures during the crop season in South Texas, which causes faster growing degree days (GDD) accumulation resulting in a shorter crop season. ET_O during the corresponding crop seasons was between 2 and 11 mm d^{-1} for both Lys ET_O and ASCE ET_O (Fig. 7A). Even though there was significant difference between the Lys ET_O and the ASCE ET_O according to a t-test ($p < 0.0001$), the other statistics show that the ASCE ET_O agreed with the Lys ET_O with RMSE of 1.43 mm d^{-1}, MRE of 14.4%, and d value of 0.57 (Fig. 8A). The calculated and measured ET_O values correlated with r value of 0.86 ($p < 0.0001$).

Sorghum K_C in the 2 years varied from 0.2 to 1.0 for both of Lys K_C and ASCE K_{co} (Fig. 7B). According to a t-test, the ASCE K_{co} was significantly different from the Lys K_C ($p < 0.0001$). However, according to the other statistics, the Lys K_C corresponded to the ASCE K_C, with RMSE of 0.12, MRE of 16.7%, and d values of 0.50 (Fig. 8B). The calculated and measured data also correlated with r value of 0.88 ($p < 0.0001$). While there was great daily K_C variation within each growth stage over the crop seasons in 2006, 2007, and 2008, there was not much year-to-year K_C variation (Fig. 9). Likewise for maize, we also determined growth-stage-specific K_C values for sorghum based on a third-order polynomial K_C curve. The Growth-stage-specific K_C for sorghum determined in this study was 0.40 at emergence, 0.80 at heading, and 0.75 at black layer stages (Table 3). The values are somewhat larger at initial and

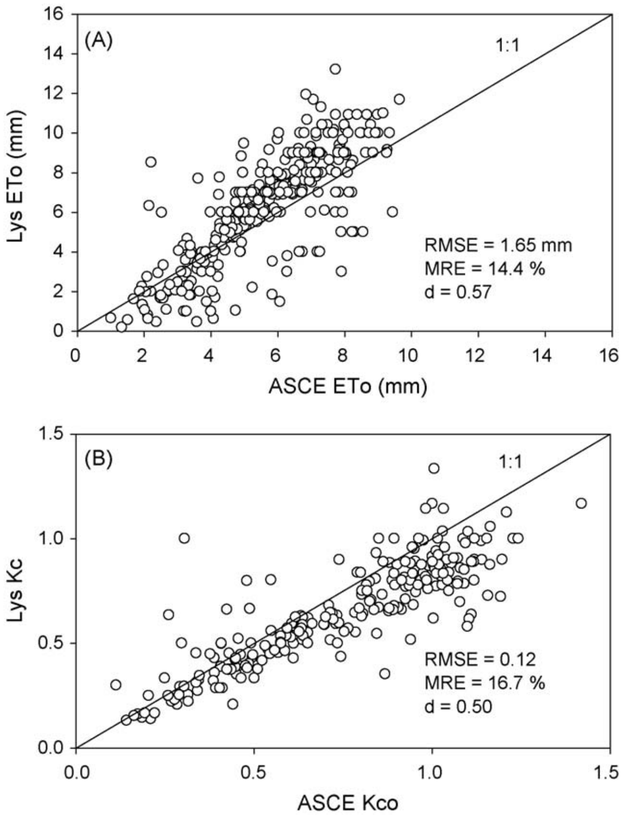

Fig. 8. (A) Lysimeter-measured ET_O (Lys ET_O) vs. calculated ET_O using ASCE Penman–Monteith equation for grass (ASCE ET_O) and (B) sorghum K_C based on lysimeter measurement (Lys K_C) vs. sorghum K_C based on ASCE Penman–Monteith equation for grass (ASCE K_{co}).

late growth stages and smaller at mid growth stage than those from FAO-56 (Allen et al., 1998). Our values are larger at early growth stage and smaller at mid- and late-growth stages than the K_{cb} values (e.g., the peak of 1.08) derived from Davis, CA (Burman et al., 1980a; Jensen et al., 1990). In comparison with the K_{cb} values reported at the Texas High Plains (Howell et al., 2006, 2007, 2008), our growth-stage-specific K_C values are larger than the K_{cb} of 0.1 at initial stage and smaller than the peak K_{cb} of 1.0.

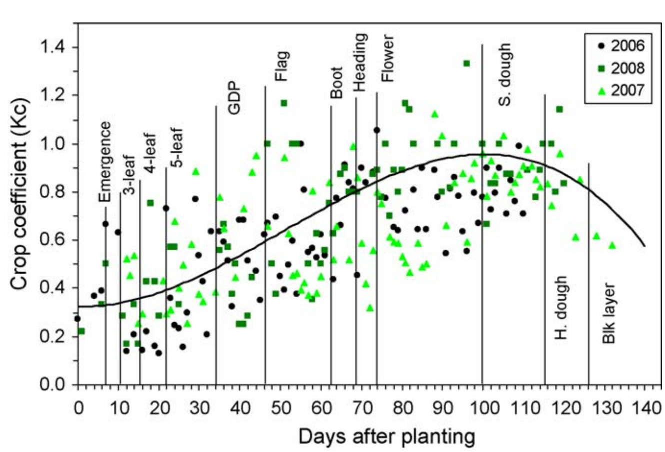

Fig. 9. Growth-stage-specific crop coefficients (K_C) of sorghum determined as a function of the days after planting in 2006 and 2007 at Uvalde, TX. Vertical lines represent 3-year-average growth stages. A third polynomial equation for the Lys K_C is as follows: Lys $K_C = 0.32 + 3.28 \times 10^{-3}\text{DAP} + 5.49 \times 10^{-5}\text{DAP}^2 - 4.10 \times 10^{-7}\text{DAP}^3$.

Table 3
Sorghum crop coefficients (K_C) determined at Uvalde, TX (A) in comparison to those from FAO-56 (Allen et al., 1998) (B).

Growth stage	DAP†	K_C
(A)		
Emergence	7	0.40
3-Leaf	8–13	0.40
4-Leaf	14–17	0.45
5-Leaf	18–25	0.50
GDP‡	26–40	0.70
Flag leaf	41–50	0.70
Boot	60–65	0.75
Heading	67–73	0.80
Flowering	72–76	0.85
Soft dough	95–104	0.80
Hard dough	105–120	0.80
Black layer	121–129	0.75
(B)		
K_C ini	0–20	0.30
K_C mid	55–95	1.00–1.10
K_C end	95–130	0.55

† DAP, days after planting.
‡ GDP, grain development period.

4. Summary and conclusion

This research was aimed for determination of exact plant water usage or crop evapotranspiration (ET_C) and crop coefficients (K_C) for maize and sorghum grown in the Wintergarden region of TX, USA. Irrigation scheduling can then be improved for private consultants and growers to avoid water over use and to more precisely meet the crop water demand to produce greater yields, crop quality, and enhanced water use efficiency. Accumulated ET_C estimates for each crop growing season ranged from 441 to 641 mm for maize and from 491 to 533 mm for sorghum. Growth-stage-specific K_C values were determined based on the K_C curves that represent the distribution of K_C over time throughout the season (Wright, 1982). The seasonal K_C values varied from 0.2 to 1.2 for maize and 0.2 to 1.0 for sorghum. Our results presented that K_C values can be different from one region to the other. It is assumed that the different environmental conditions between regions allow variation in variety selection and crop developmental stage which affect K_C (Allen et al., 1998). The need for regionalized K_C is demonstrated by the comparison between the K_C developed at Uvalde, TX and those obtained at Bushland, TX as well as elsewhere in the USA. For example, maize and sorghum crop coefficients determined at Uvalde were significantly different from those determined at Bushland. These differences are assumed due to elevated air temperatures and water vapor pressure deficit over the growing season that caused temporal and transient leaf stomata closure (Baker et al., 2007; Bruce, 1997; Cornic and Massassi, 1996), impeding plants to transpire at its full potential. In the Wintergarden region, the use of K_C developed in other regions will result in either over- or less-watering and consequently increased production costs or reduced profits. In conclusion the development of regionally based K_C helps tremendously in irrigation management and furthermore provides precise water applications in those areas where high irrigation efficiencies are achieved by center pivot with LEPA (low energy precision application) systems or subsurface drip irrigation.

Acknowledgement

This study is a partial outcome of the Precision Irrigators Network (PIN) project, funded by Texas Water Development Board (TWDB: Project no. 0603580596), and Rio Grande Basin Initiative (RGBI: grant no. 2005-34461-15661). The authors would like to express their appreciation to Texas Water Resources Institute (TWRI) for administrative project assistance. We also thank Dr. Clothier and the anonymous reviewers for their valuable comments.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. In: Proceedings of the Irrigation and Drainage Paper No. 56, Food and Agricultural Organization, United Nations, Rome, Italy.

ASCE-EWRI, 2005. The ASCE Standardized Reference Evapotranspiration Equation. Environment and Water Resources Institute (EWRI) of ASCE, Standardization of Reference Evapotranspiration Task Committee Final Rep. <http://www.kimberly.uidaho.edu/water/asceewri/ascestzdetmain2005.pdf>.

Ayars, J.E., Hutmacher, R.B., 1994. Crop coefficients for irrigating cotton in the presence of groundwater. Irrigation Science 15, 45–52.

Baker, J.T., Gitz, D.C., Payton, P., Wanjura, D.F., Upchurch, D.R., 2007. Using leaf gas exchange to quantify drought in cotton irrigated based on canopy temperature measurements. Agronomy Journal 99, 637–644.

Barrett, M.E., 1999. Complying with the Edwards Aquifer rules: Technical Guidance on Best Management Practices/Prepared for the Texas Natural Resources Conservation Commission by the Center for Research in Water Resources, Bureau of Engineering Research, University of Texas, Austin, TX. Texas Natural Resource Conservation Commission Report No., RG-348.

Brock, F.V., Crawford, K.C., Elliott, R.L., Cuperus, G.W., Sadler, S.J., Johnson, H.L., Eilts, M.D., 1995. The Oklahoma mesomet: a technical overview. Journal of Atmospheric Oceanic Technology 12, 5–19.

Bruce, J.A., 1997. Does transpiration control stomatal responses to water vapour pressure deficit? Plant Cell and Environment 20, 136–141.

Burman, R.D., Wright, J.L., Nixon, P.R., Hill, R.W., 1980a. Irrigation management–water requirements and water balance. In: Irrigation, Challenges of the 80's, Proceedings of the Second National Irrigation Symposium, American Society of Agricultural Engineers, St. Joseph, MI, pp. 141–153.

Burman, R.D., Nixon, P.R., Wright, J.L., Pruitt, W.O., 1980b. Water requirements. In: Jensen, M.E. (Ed.), Design of Farm Irrigation Systems, ASAE Mono., American Society of Agricultural Engineers, St. Joseph, MI, pp. 189–232.

Cornic, G., Massassi, A., 1996. Leaf photosynthesis under drought stress. In: Baker, N.R. (Ed.), Photosynthesis and the Environment. Kluwer Academic Publishers, The Netherlands.

Doorenbos, J., Pruitt, W.O., 1975. Guidelines for predicting crop water requirements. Irrig. and Drain. Paper No. 24, Food and Agric. Org., United Nations, Rome, Italy, 168 pp.

Doorenbos, J., Pruitt, W.O., 1977. Guidelines for predicting crop water requirements. Irrig. and Drain. Paper No. 24, 2nd ed., Food and Agric. Org., United Nations, Rome, Italy, 144 pp.

Dusek, D.A., Howell, T.A., Schneider, A.D., Copeland, K.S., 1987. Bushland weighing lysimeter data acquisition systems for evapotranspiration research. ASAE Paper No. 87-2506, American Society of Agricultural Engineers, St. Joseph, MI.

Guerra, L.C., Hoogenboom, G., Hook, J.E., Thomas, D.L., Boken, V.K., Harrisonc, K.A., 2005. Evaluation of on-farm irrigation application using the simulation model EPIC. Irrigation Science 23, 171–181.

Guerra, L.C., Garcia y Garcia, A., Hook, J.E., Harrisonc, K.A., Thomas, D.L., Stooksbury, D.E., Hoogenboom, G., 2007. Irrigation water use estimates based on crop simulation models and kriging. Agricultural Water Management 89, 199–207.

Hargreaves, G.H., Samani, Z.A., 1985. Reference crop evapotranspiration from temperature. Applied Engineering in Agriculture 1, 96–99.

Howell, T.A., 1998. Using the PET network to improve irrigation water management. In: Triplett, L.L. (Ed.), The Great Plains Symposium 1998: The Ogallala Aquifer, Determining the Value of Water Proceedings of the 1988 Great Plains Symposium, March 10–12, 1998, Lubbock, TX, the Great Plains Foundation, Overland Park, KS, pp. 38–45.

Howell, T.A., Schneider, A.D., Dusek, D.A., Marek, T.H., Steiner, J.L., 1995. Calibration and scale performance of Bushland weighing lysimeters. Transaction of the ASAE 38 (4), 1019–1024.

Howell, T.A., Steiner, J.L., Schneider, A.D., Evett, S.R., Tolk, J.A., 1997. Seasonal and maximum daily evapotranspiration of irrigated winter wheat, sorghum, and corn: Southern High Plains. Transaction of the ASAE 40, 623–634.

Howell, T.A., Tolk, J.A., Schneider, A.D., Evett, S.R., 1998. Evapotranspiration, yield, and water use efficiency of corn hybrids differing in maturity. Agronomy Journal 90 (1), 3–9.

Howell, T.A., Evett, S.R., Tolk, J.A., Schneider, A.D., 2004. Evapotranspiration of full-, deficit-irrigated, and dryland cotton on the Northern Texas High Plains. Journal of Irrigation and Drainage Engineering 130, 277–285.

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: Proceedings of the World Water and Environmental Resources Congress. Examining the Confluence of Environmental and Water Concerns, May 21–25, 2006. Omaha, Nebraska CDROM.

Howell, T.A., Tolk, J.A., Evett, S.R., Copeland, K.S., Dusek, D.A., 2007. Evapotranspiration of deficit irrigated sorghum. In: Proceedings of the World Water and Environmental Resources Congress, May 15–19, 2007. Tampa, FL CDROM.

Howell, T.A., Evett, S.R., Tolk, J.A., Copeland, K.S., Colaizzi, P.D., Gowda, P., 2008. Evapotranspiration of corn and forage sorghum for silage. In: Proceedings of the Environmental and Water Resources Institute World Congress, May 12–16, 2008. Honolulu, Hawaii CDROM.

Jensen, M.E., 1968. Water consumption by agricultural plants. In: Kozlowski, T.T. (Ed.), Water Deficits and Plant Growth, vol. II. Academic Press, Inc., New York, NY, pp. 1–22.

Jensen, M. E., Sletten, W. H., 1965. Evapotranspiration and soil moisture-fertilizer interrelations with irrigated grain sorghum in the Southern High Plains. U.S. Dept. Agric., Res. Serv., Conserv. Res. Rep. 5. Washington, DC.

Jensen, M.E., Burman, R.D., Allen, R.G., 1990. Evaporation and irrigation water requirements. ASCE Manuals and Reports on Eng. Practices No. 70. New York, NY, American Society of Civil Engineering, 360 pp.

Marek, T., Howell, T., New, L., Bean, B., Dusek, D., Michels Jr., G.J., 1996. Texas northplains PET network. In: Camp, C.R., Sadler, E.J., Yoder, R.E. (Eds.), Evapotranspiration and Irrigation Scheduling, Proceedings of the International Conference, American Society of Agricultural Engineers, St. Joseph, MI, pp. 710–715.

Marek, T., Piccinni, G., Schneider, A., Howell, T., Jett, M., Dusek, D., 2006. Weighing lysimeters for the determination of crop water requirements and crop coefficients. Applied Engineering in Agriculture 22 (6), 851–856.

Musick, J.T., Dusek, D.A., 1980b. Irrigated corn yield response to water. Transaction of the ASAE 23 (92-98), 103.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models: Part I. A discussion of principles. Journal of Hydrology 10 (3), 282–290.

Pruitt, W.O., Doorenbos, J., 1977. Background and development of methods to predict reference crop evapotranspiration (ET_O). In Irrigation and Drainage paper No. 24, 2nd ed., Food and Agricultural Organization of the United Nations, Rome, Italy, pp. 108–119.

Sammis, T.W., Wu, I.P., 1985. Effect of drip irrigation design and management on crop yield. Transaction of the ASAE 28, 832–838.

Santos, A.M., Cabelguenne, M., Santos, F.L., Oliveira, M.R., Serralheiro, R.P., Bica, M.A., 2000. EPIC-PHASE: a model to explore irrigation strategies. Journal of Agricultural Engineering Research 75, 409–416.

Schneider, A.D., Howell, T.A., Moustafa, A.T.A., Evett, S.R., Abou-Zied, W., 1998. A simplified weighing lysimeter for monolithic or repacked soils. Applied Engineering in Agriculture 14 (3), 267–273.

Seymour, R.M., Lyle, W.M., Lascano, R.J., Smith, J.G., 1994. Potential evapotranspiration information for irrigation management in the Texas Southern High Plains. In: Harrison, D.G., Zazueata, F.S., Harrison, T.V. (Eds.), Computers in Agriculture, American Society of Agricultural Engineers, St. Joseph, MI, pp. 653–656.

Snyder, R.L., 1983. Managing irrigation by computers. In: Proceedings of California Plant and Soil Conference. pp. 28–30.

Stegman, E.C., 1988. Corn crop curve comparisons for the central and northern great plains of the U.S. Transaction of the ASAE 4, 226–233.

Stewart, B.A., Musick, J.T., Dusek, D.A., 1983. Yield and water use efficiency of grain sorghum in a limited irrigation-dryland farming system. Agronomy Journal 75, 629–634.

Texas Water Development Board, 2001. Surveys of irrigation in Texas 1958, 1964, 1969, 1974, 1979, 1984, 1989, 1994, and 2000. Report 347, Austin, TX.

Thornthwate, C.W., 1948. An approach towards a rational classification of climate. Geographical Review 38, 55–94.

Tolk, J.A., Howell, T.A., Evett, S.R., 1998. Evapotranspiration and yield of corn grown on three high plains soils. Agronomy Journal 90, 447–454.

Watson, I., Burnett, A.D., 1995. Hydrology: An Environmental Approach. CRC Press, Boca Raton, FL.

Wright, J.L., 1982. New evapotranspiration crop coefficients. Journal of Irrigation and Drainage Engineering 108 (1), 57–74.