ELSEVIER

Agricultural Water Management 59 (2003) 97–111

Agricultural
water management

www.elsevier.com/locate/agwat

Water use efficiencies of grain sorghum grown in three USA southern Great Plains soils

Judy A. Tolk*, Terry A. Howell

USDA-ARS, Conservation and Production Research Laboratory, PO Drawer 10, Bushland, TX 79012, USA

Accepted 21 August 2002

Abstract

The ratios of economic yield:evapotranspiration (*Y*:ET), or water use efficiency (WUE), and economic yield:irrigation water application, or irrigation WUE (IWUE), help evaluate the productivity of irrigation in agricultural systems. Water stress at critical growth stages, excessive soil water evaporation, soil water storage, runoff, and drainage are among the many factors which result in declines in either or both of these ratios. The objective of this research was to evaluate the effect of soil type, soil water use characteristics, and seasonal climatic differences on the WUE and IWUE of grain sorghum grown in the semi-arid climate of the southern Great Plains of the USA. In 1998 and 1999, grain sorghum (*Sorghum bicolor* (L.) Moench 'PIO-8699') was grown in 0.75-m rows with 16 plants/m^2 at Bushland, TX in lysimeters containing monolithic soil cores of either the Amarillo, Pullman, or Ulysses soil series. Irrigation treatments in both years were 100, 50, 25, and 0% based on replacement of ET, simulating deficit irrigation that results from limited water availability such as reduced well capacities. The WUE was significantly higher and ET lower in the milder climatic conditions of 1999 compared with 1998, which had a higher evaporative demand. Once normalized for climatic differences, yield response to ET was similar for both years. Crops grown in the Amarillo soil had significantly higher WUE compared with crops in the other soils, primarily due to reduced ET rather than increased yield. Grain sorghum grown in the Ulysses soil was able to produce higher yields at lower plant available water (PAW) compared with the other two soils, but the crops in all soils reduced yield when experiencing water stress at a critical growth stage of pollination. At comparable final soil water contents, grain yields of the crop in the Pullman soil were higher in 1999 (lower evaporative demand) compared with yields produced in 1998 (higher evaporative demand), while the crops in the other two soils produced similar yields in both environments. The relationship between irrigation application and yield was more curvilinear in 1998 possibly due to increased soil water evaporation at the higher irrigation applications, while the relationship was more linear in 1999. In general, IWUE declined with increasing irrigation

* Corresponding author. Tel.: +1-806-356-5736; fax: +1-806-356-5750.
E-mail address: jtolk@cprl.ars.usda.gov (J.A. Tolk).

0378-3774/02/$ – see front matter. Published by Elsevier Science B.V.
PII: S0378-3774(02)00157-9

application within each year, but was variable in some irrigation treatments, due to water stress at critical growth stages. No differences among soil types occurred in IWUE in either year, primarily due to variability among replicates.
Published by Elsevier Science B.V.

Keywords: Water use efficiency; Irrigation water use efficiency; Evapotranspiration; Lysimeter; Plant available water; Soil water depletion; Water stress

1. Introduction

Water use efficiency (WUE) and irrigation water use efficiency (IWUE) are two terms used to promote the efficient use of irrigation water at the crop production level (Bos, 1980). Water use efficiency can be defined as the ratio of economic yield (Y) to evapotranspiration (ET), given as $\text{WUE} = Y\text{ET}^{-1}$. Irrigation water use efficiency relates yield to the volume of irrigation water applied, with one definition showing the increase in irrigated yield (Y_i) over dryland yield (Y_0) due to irrigation (IR), or $(Y_i - Y_0)\text{IR}^{-1}$ (Bos, 1980). Management-related declines in WUE can result from such factors as inadequate fertility and pest control, less than optimum planting date, and reduced transpiration relative to other water balance components (Howell, 2001). Declines in IWUE can also occur due to soil water storage, deep percolation, excessive soil water evaporation, and runoff (Howell et al., 1990).

Most reported Y:ET relationships are linear (Stewart et al., 1975, 1983; Hanks, 1983; Lamm et al., 1994; Howell et al., 1995; Al-Jamal et al., 2001). According to Stewart and Hagan (1973), non-linear relationships such as those reported by Grimes et al. (1969) and Musick and Sletten (1966) are explicable only if the harvest index (ratio of grain biomass to total biomass) changes with increasing water deficits. Reported Y:IR relationships have been both linear (Lamm et al., 1994) and curvilinear (Musick et al., 1964; Stewart et al., 1983; Bordovsky and Lyle, 1996). Howell et al. (1995) showed a linear relationship for 1 year of a low energy precision application (LEPA) irrigation study on corn (*Zea mays* L.), and a quadratic relationship for the same study repeated the following year. They concluded that the differences between the 2 years were due to the variation in seasonal rainfall amounts and distribution, with little water remaining stored in the soil at harvest in the year with the linear relationship.

When discussing the effect of irrigation on crop yield, Howell et al. (1990) pointed out that while maximum WUE tends to occur at maximum ET (ET_m), maximum IWUE usually occurs at an ET generally less than ET_m. This suggests that irrigating to achieve the maximum yield (Y_m) and consequently ET_m would not be the most efficient use of irrigation water. The relationship between WUE and IWUE may also vary from year to year due to climate. Howell et al. (1995), in comparing 2 years of LEPA-irrigated corn data, showed that both maximum WUE and IWUE occurred at or near ET_m in a growing season that had high rainfall and that was somewhat cooler than normal. But, in the following year when the climate was more typical of the region, both maximum WUE and IWUE occurred at a seasonal ET considerably less than ET_m. Musick and Dusek (1971) found that the highest IWUE occurred when irrigation was applied during dry periods or at intervals creating only a moderate water stress. Vaux and Pruitt (1983) pointed out that not only irrigation but also available soil water and rainfall contributed to ET.

The most efficient use of applied irrigation water would be for all of it to be used in ET. Martin et al. (1984) developed a procedure to evaluate irrigation effectiveness based on the relationships between ET, yield, and irrigation, and the assumption that at small irrigation levels all the water applied as irrigation goes toward ET. Based on the derivative of the IR:ET curve ($\delta ET\ \delta IR^{-1}$), it can be used to determine the fraction of the irrigation used in ET which results in a yield increase. Howell et al. (1990) used the procedure to evaluate the efficiencies of impact sprinkler, level-basin, and graded furrow irrigation, and found similar efficiencies for impact sprinkler and level basin. The graded furrow efficiency was considerably lower compared with the other two methods, and approached zero at the maximum irrigation application due to runoff losses. Martin et al. (1984) pointed out that different irrigation strategies, soils, and systems would require different amounts of irrigation to produce maximum ET and yield.

Reported water use efficiencies of grain sorghum vary due to many factors, including the crop water use characteristics as influenced by the interaction between the region's soil hydraulic characteristics and climate. Few studies have been performed that examine crop yield response to soil hydraulic characteristics under a uniform environment. The objective of this research was to evaluate the effect of soil type, soil water use characteristics, and seasonal climatic differences on the WUE and IWUE of grain sorghum grown in the semi-arid climate of the southern Great Plains of the USA.

2. Materials and methods

2.1. Facilities

The study was conducted at the Soil–Plant–Environment Research (SPER) facility, USDA-Agricultural Research Service, Bushland, TX, USA (35°11′N, 102°06′W, 1170 m elevation above MSL). The SPER facility is located in a 0.25-ha field with a rain shelter facility with 48 weighable lysimeters that contained soil of three different series. The lysimeters were 1.0 by 0.75 m, and 2.4 m deep; contained monolithic cores to about a 2.3-m depth; and had a suction drainage system in the bottom. The lysimeters were arranged in two pits, with each pit containing two side-by-side rows of 12 lysimeters each. Soil series were randomly located within each pit.

Wind direction was predominately from the south to southwest. The lysimeter area was surrounded by similarly cropped grain sorghum for about 30–35 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.

The rain shelter was a metal building 13 by 18 by 3.7 m high, with a control system that automatically initiated building movement over the lysimeters when about 1 mm of rain was detected. The facility and monolithic core collection techniques were described in more detail by Schneider et al. (1993).

2.2. Agronomy

The lysimeters were planted with grain sorghum (*Sorghum bicolor* (L.) Moench, 'PIO-8699'[1]) in 1998 and 1999 at a density of 16 plants/m^2. The lysimeters were fertilized according to recommendations based on soil analyses prior to planting for each soil. Tillage was done by hand to a depth of about 20 cm. Daily ET of at least two replicates of the fully irrigated treatments was measured using deck scales (DS3040-10 K, Weigh-Tronix, Fairmont, MN), and served as the basis for the calculation of irrigation treatment amounts. Irrigation treatments were 100 (T-100), 50 (T-50), 25 (T-25), and 0% (T-0) based on replacement of ET, simulating deficit irrigation (does not meet crop water requirements) that results from limited water availability such as reduced well capacities. Irrigation applications were measured and applied weekly by hand. The seasonal ET of the remaining irrigation treatments was measured either by deck scales or manually weighing the lysimeters periodically using a suspended load cell interfaced with a datalogger. The ET was calculated from the difference in lysimeter mass between weighing intervals, plus any applied water infiltration and minus any drainage water. The rain shelter permitted management of water applications so that simulated limited irrigation and dryland studies could be evaluated.

2.3. Soils

Soil types were Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) from Bushland, TX; Ulysses clay loam (fine-silty, mixed, mesic Aridic Haplustoll) from Garden City, KS; and Amarillo sandy loam (fine-loamy, mixed, thermic Aridic Paleustalf) from Big Spring, TX. There were 12 lysimeters containing the Pullman soil series, 12 containing the Amarillo soil series, and 24 containing the Ulysses soil series. Thirty-six lysimeters (12 of each soil series) were included in the main experiment each cropping season, with three replicates of treatments. The remaining 12 lysimeters containing the Ulysses soil series were in an auxiliary experiment.

The Pullman is a deep, well drained, very slowly permeable soil that formed in calcareous clayey materials. It has a moderate to high water-holding capacity depending on the depth to the calcic horizons which begin at about 1–1.5 m, and a dense Bt layer at about 0.8 m. The Ulysses is a very deep, well drained, moderately permeable upland soil that formed in calcareous loss and has a high water-holding capacity. The Ulysses typically is classified as a silt loam, but slightly lower silt contents of our soil in its surface layers resulted in its designation as a clay loam. This is within the allowable variation of the series. The Amarillo is a deep, well drained, moderately permeable soil that formed in calcareous loamy materials that has a moderate water-holding capacity, calcic horizons beginning at about 1 m and relatively high bulk densities.

2.4. Soil water content

Volumetric soil water contents were measured by neutron thermalization (Model 503 DR, Campbell Pacific Nuclear, Martinez, CA) in a centrally located tube in each lysimeter.

[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

The measurements were taken at 0.2-m increments starting at 0.1 m and ending at 2.1 m. The gauge was calibrated in situ at the Garden City, KS; Big Spring, TX; and Bushland, TX monolith collection sites using techniques described by Evett and Steiner (1995). Separate calibration equations were developed for each major soil horizon with r^2 values >0.9 and RMSE values 0.01 m^3/m^3.

The lysimeters typically had about 300 mm of plant available water (PAW) to 2.2 m at planting in 1998 and about 200–250 mm PAW in 1999. Plant available water was defined as the amount of water held in a soil between field capacity and the lower limit of water availability. Field capacity was determined at the SPER facility following field techniques described by Cassel and Nielsen (1986). The lower limit of water availability was determined from soil water contents of the simulated dryland and limited irrigation treatments measured at harvest in these and prior studies on grain sorghum. The data selected for use followed techniques described by Viehmeyer and Hendrickson (1949). The PAW, determined for the depth of 0.2–2.2 m, was 288 mm for the Pullman soil, 450 mm for the Ulysses soil, and 331 mm for the Amarillo soil. The 0–0.2 m values were eliminated due to soil water evaporation from the surface layer below the minimum soil water content that can be used by the crop.

2.5. Climate

The climate at Bushland is typical of the semi-arid high plains, which has a high evaporative demand (about 2600 mm based on Class A pan evaporation) and low precipitation (about 470 mm). About 70% (350 mm) of the rainfall occurs from May to September, when evaporative potential averages about 1520 mm.

2.6. Statistical procedures and curve fitting

Measurements were analyzed using the general linear model procedures of SAS (PROC GLM, SAS Institute, 1985). Soil types were randomly distributed within each pit, with three replications per soil type and irrigation treatment. To minimize irrigation treatment-related differences in microclimate and plant growth from confounding the results, the T-100 and T-50 treatments were assigned to one pit and the T-50 and T-25 to the other. The model included irrigation, soil type, and the interaction. Irrigation treatment was separately tested using the irrigation treatment within replicates error term. Mean separations were computed using the Ryan–Einot–Gabriel–Welsch multiple-range test which controls type 1 experimental error. The data comparing between years was analyzed using a mixed linear model (PROC MIXED, SAS Institute, Cary, NC) as a split plot in time, with soil type and years as main effects and the random effect of soil nested within replicates.

The relationship between IR and Y was described using a quadratic equation, or

$$Y = Y_0 + a(\mathrm{IR}) + b(\mathrm{IR}^2) \quad (1)$$

where Y_0 is the intercept on the yield axis. The relationship between percent PAW remaining at harvest (%PAW) and Y was fit using a rectangular hyperbola (Landsberg, 1977) following relationships described by Musick et al. (1963) and Stegman (1983).

Table 1
Average climatic parameters of 0.12-m grass reference evapotranspiration (ET_0), maximum temperature (T_{max}), minimum temperature (T_{min}), dew point temperature (T_{dew}), 2-m wind speed (U), solar radiation (R), and vapor pressure deficit (VPD) for each month of the cropping season in 1998 and 1999

	ET_0 (mm per day)	T_{max} (°C)	T_{min} (°C)	T_{dew} (°C)	U (m/s)	R (MJ per day)	VPD (kPa)
1998							
July	7.5	33.5	18.9	15.2	3.6	25.9	2.2
August	5.9	30.5	16.8	14.9	3.2	23.1	1.4
September	5.5	30.2	15.5	12.6	3.4	19.9	1.5
1999							
July	6.6	30.8	18.0	17.0	3.8	27.0	1.2
August	6.3	31.5	17.7	16.0	3.3	24.6	1.3
September	4.1	24.8	12.5	11.2	3.3	17.6	0.9
October	4.1	22.1	6.0	3.4	4.0	16.4	0.9

In this analysis, the equation takes the form of

$$Y = \frac{\%\text{PAW} \times Y_m}{b + \%\text{PAW}}. \tag{2}$$

3. Results

The climatic conditions during the 1998 growing season tended to produce higher reference evapotranspiration (Allen et al., 1998), vapor pressure deficits, and maximum temperatures compared with those in 1999 (Table 1). The grain sorghum variety used in the studies was a medium to short maturing variety with maturity predicted at 105 days after emergence. In 1998, the grain sorghum was harvested 91 days after seeding and, in 1999, 104 days after seeding.

Table 2
Grain yield, evapotranspiration (ET), water use efficiency (WUE), irrigation water use efficiency (IWUE), harvest index (HI), weight per seed, and number of seeds/m^2 averaged across irrigation treatments for the crops grown in Amarillo, Pullman, and Ulysses soils

	Yield[a] (g/m^2)		ET (mm)		WUE (kg/m^3)		IWUE (kg/m^3)		HI (g/g)		Seed weight (mg per seed)		Seed number ($1000/m^2$)	
	1998	1999	1998	1999	1998	1999	1998	1999	1998	1999	1998	1999	1998	1999.
Amarillo	654	620 ab	457 b	373 b	1.44	1.68 a	0.77	1.12	0.52	0.53 a	20.3 ab	21.3 a	31.9 b	28.9
Pullman	694	665 a	512 a	419 a	1.37	1.57 b	0.78	1.08	0.51	0.52 a	21.7 a	22.5 a	31.7 b	29.0
Ulysses	712	600 b	500 a	408 a	1.44	1.45 c	0.97	0.98	0.51	0.48 b	19.8 b	19.1 b	36.0 a	30.8
Mean	687	629	490	400	1.42	1.57	0.84	1.06	0.51	0.51	20.6	21.0	33.2	29.6

Mean separations (represented by letters 'a' and 'b') compare differences among soil type within a column (excluding the mean).

[a] Reported at 0% moisture.

Table 3
Grain yield, evapotranspiration (ET), water use efficiency (WUE), irrigation water use efficiency (IWUE), harvest index (HI), weight per seed, and number of seeds/m^2 compared between years, among soil types, and the interaction between year and soil type

	Yield	ET	WUE	IWUE	HI	Seed weight	Seed number
Year	n.s.[a]	**	**	**	n.s.	n.s.	*
Soil	n.s.	n.s.	*	n.s.	**	**	n.s.
Year × soil	n.s.	n.s.	*	n.s.	*	n.s.	n.s.

[a] n.s. = not significantly different.
* Significant at the $P < 0.05$ level.
** Significant at the $P < 0.01$ level.

The effect of soil type (averaged across irrigation treatments for each year) was not significantly different for grain yield, WUE, and harvest index (HI) in 1998 but was in 1999, when the crop in the Ulysses soil produced the lowest HI and WUE compared with the crops in the other soils (Table 2). Stone et al. (1996) reported a mean WUE of 1.47 kg/m^3 for grain sorghum grown in a 14-year study in Ulysses soil in Kansas, based on grain yields ranging from 557 to 769 g and seasonal water use from 259 to 663 mm. Schneider and Howell (1995) reported a mean WUE of 1.51 kg/m^3 for a 2-year sprinkler irrigation study on grain sorghum in Pullman clay loam soil, based on grain yields ranging from 377 to 952 g and seasonal water use of 375 to 618 mm. The smaller seed size among soil types of the crop in the Ulysses soil, significantly so in 1999, suggests that the crop experienced more water stress at heading or afterwards (Eck and Musick, 1979) than the crops in the other soils. In 1999, the significantly lower ET of the grain sorghum in the Amarillo soil,

Table 4
Evapotranspiration (ET), grain yield, water use efficiency (WUE), and irrigation water use efficiency (IWUE) for the crops grown in the Amarillo, Pullman, and Ulysses soils; irrigation application amounts (Irr.); and irrigation treatments of 0, 25, 50, and 100% based on replacement of ET

Treatment	Irr. (mm)	Amarillo				Pullman				Ulysses			
		Yield[a] (g/m^2)	ET (mm)	WUE (kg/m^3)	IWUE (kg/m^3)	Yield (g/m^2)	ET (mm)	WUE (kg/m^3)	IWUE (kg/m^3)	Yield (g/m^2)	ET (mm)	WUE (kg/m^3)	IWUE (kg/m^3)
ET (%) in 1998													
0	0	463 c	297 d	1.56 a	–	504 b	348 c	1.45 a	–	506 c	339 d	1.49	–
25	147	562 c	423 c	1.33 b	0.67	582 b	494 b	1.18 b	0.53	691 b	475 c	1.45	1.26 a
50	280	716 b	497 b	1.44 ab	0.90	826 a	542 b	1.53 a	1.15	783 ab	523 b	1.50	0.99 ab
100	555	876 a	612 a	1.43 ab	0.74	865 a	662 a	1.31 ab	0.65	868 a	663 a	1.31	0.65 b
ET (%) in 1999													
0	0	386 c	223 d	1.72	–	434 d	292 d	1.49	–	369 b	266 d	1.39 ab	–
25	130	560 b	334 c	1.67	1.34	597 c	398 c	1.50	1.26	461 b	367 c	1.25 b	0.71
50	300	705 a	409 b	1.72	1.06	750 b	452 b	1.66	1.05	743 a	444 b	1.67 a	1.25
100	470	832 a	524 a	1.58	0.95	879 a	536 a	1.64	0.95	829 a	554 a	1.49 ab	0.98

Mean separations (represnted by letters 'a' and 'b') compare differences ($P < 0.05$) among irrigation treatments within each column and within each year.
[a] Reported at 0% moisture.

coupled with the grain yield that was intermediate between the other two soils, was coincident with a significantly higher WUE.

When comparing between years by averaging across soil types, the climatic differences did not result in significant differences in mean grain yield or HI between 1998 and 1999 (Table 3). Both WUE and IWUE were significantly higher in 1999, while ET was significantly higher in 1998 (Table 2), most likely due to increased soil water evaporation. Seed number of 33,228 seeds/m^2 in 1998 was significantly higher than the 29,592 seeds/m^2 in 1999. When comparing among soil types by averaging both years, the crops in the Amarillo soil produced significantly higher WUE of 1.56 kg/m^3 while the WUE of the crops in the Pullman and Ulysses soils was comparable at about 1.46 kg/m^3. The HI of the crop in the Ulysses soil was significantly lower by at 0.50 g/g than the 0.52 g/g of the crops in the other two soils.

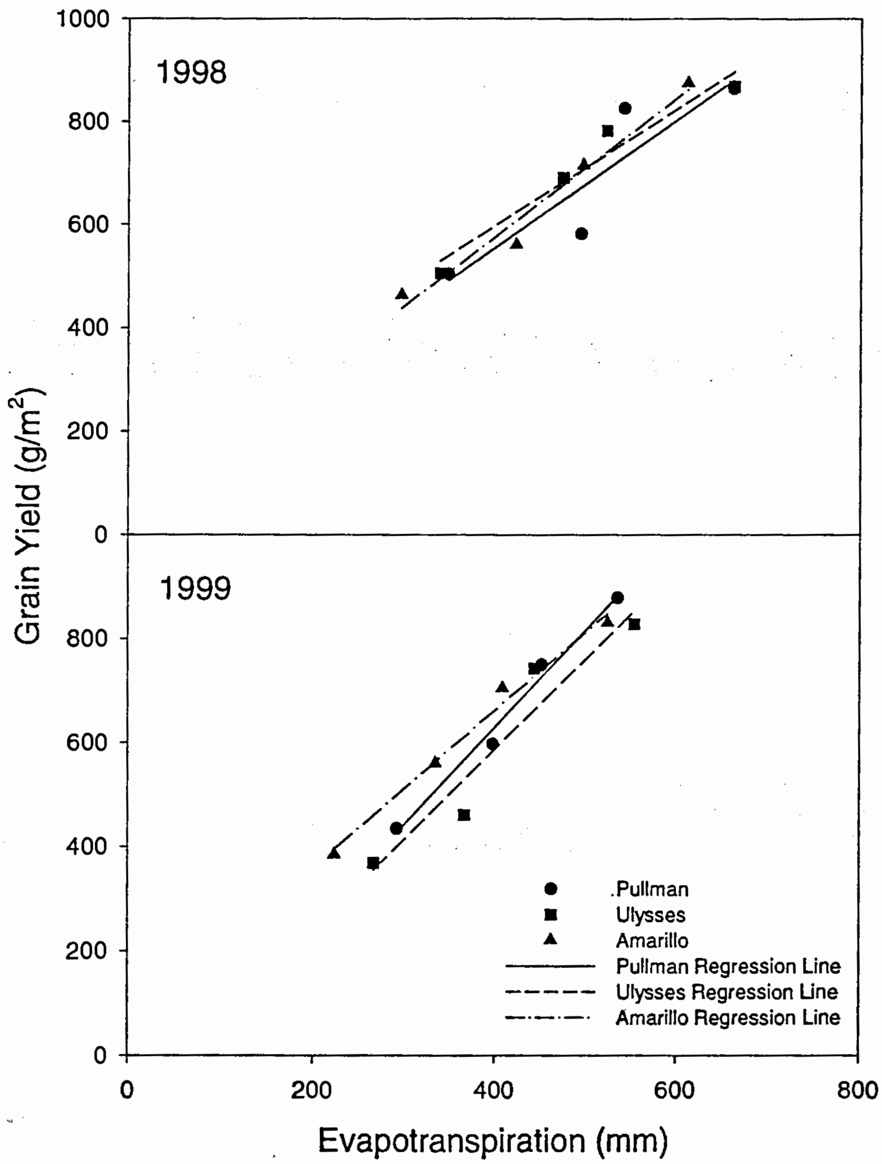

Fig. 1. Evapotranspiration vs. grain yield of grain sorghum for 1998 and 1999.

The T-100 irrigation treatment required 85 mm more irrigation in 1998 compared with 1999, which is almost identical to the amount of increase in ET between the 2 years for that treatment (Table 4). Significant differences occurred in WUE among irrigation treatments in 1998 but not 1999 in crops in the Amarillo and Pullman soils, while no differences occurred in 1998 but did in 1999 for the crop in the Ulysses soil. Yields increased with increasing ET and irrigation application amounts and, although IWUE tended to decline with increasing irrigation, the response to the T-25 treatment varied.

4. Discussion

The maximum yields were similar in 1998 and 1999, but the maximum seasonal ETs were not (Fig. 1). Stewart and Hagan (1973) found that maximum yield was based on varietal characteristics alone, while maximum ET was dependent upon environment. Due to the hot, dry conditions in 1998, greater amounts of seasonal ET were required in 1998 compared with 1999 to achieve a similar amount of yield increase. When 'normalized' by being put in terms of the ratio to maximum values for each year of yield (Y/Y_m) to ET (ET/ET_m) to account for differences in response to climate (Stegman, 1983), the Y:ET relationships were similar between years (Fig. 2). These data support the idea that an array of yields can be associated with a given seasonal ET and, more importantly, that for any given ET_m there exists an approximate Y_m (Stegman, 1983).

The significantly higher WUE of the crop in the Amarillo soil in 1999 was due to the tendency of that crop to produce yields similar to those in the other soils but with a lower seasonal ET, especially in the limited irrigation treatments (T-0 and T-25) (Table 4). The

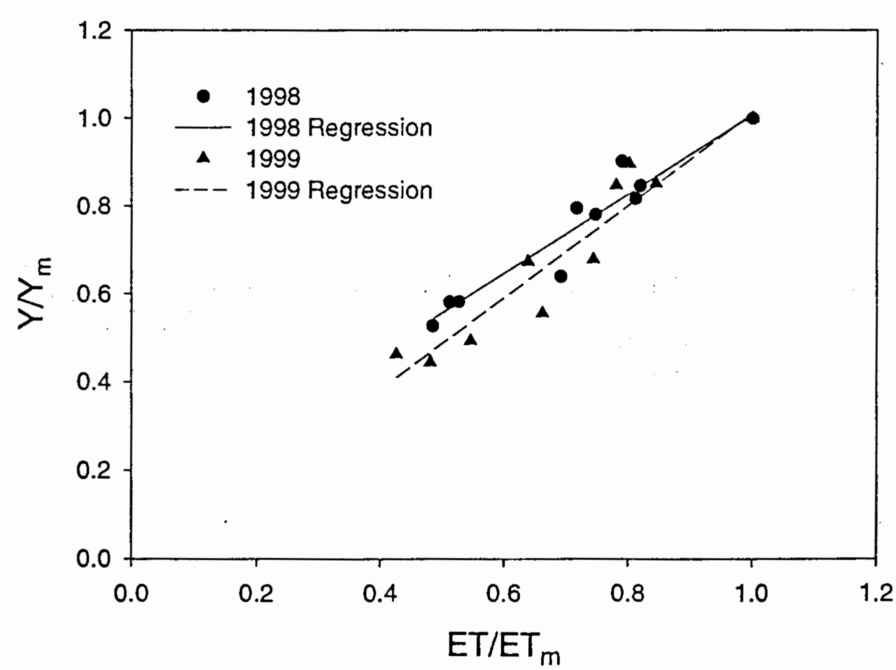

Fig. 2. The ratios of treatment evapotranspiration (ET) to maximum ET (ET/ET_m) and grain yield to maximum grain yield (Y/Y_m) of each cropping season.

reduced ET may be due to the soil's coarse texture, which may have limited rooting (Gerard et al., 1982), and/or reduced soil water evaporation (Campbell and Norman, 1998). The fairly stable WUE for the crop in the Ulysses soil in 1998 and in the Amarillo and Pullman soils in 1999 across irrigation treatments indicates that yield and ET declined similarly in response to increasing irrigation deficits (Musick and Grimes, 1961). However, severe moisture stress may have reduced yields more than ET in the T-25 irrigation treatment in 1998 in the Amarillo and Pullman soils, resulting in the declines in WUE (Musick et al., 1963).

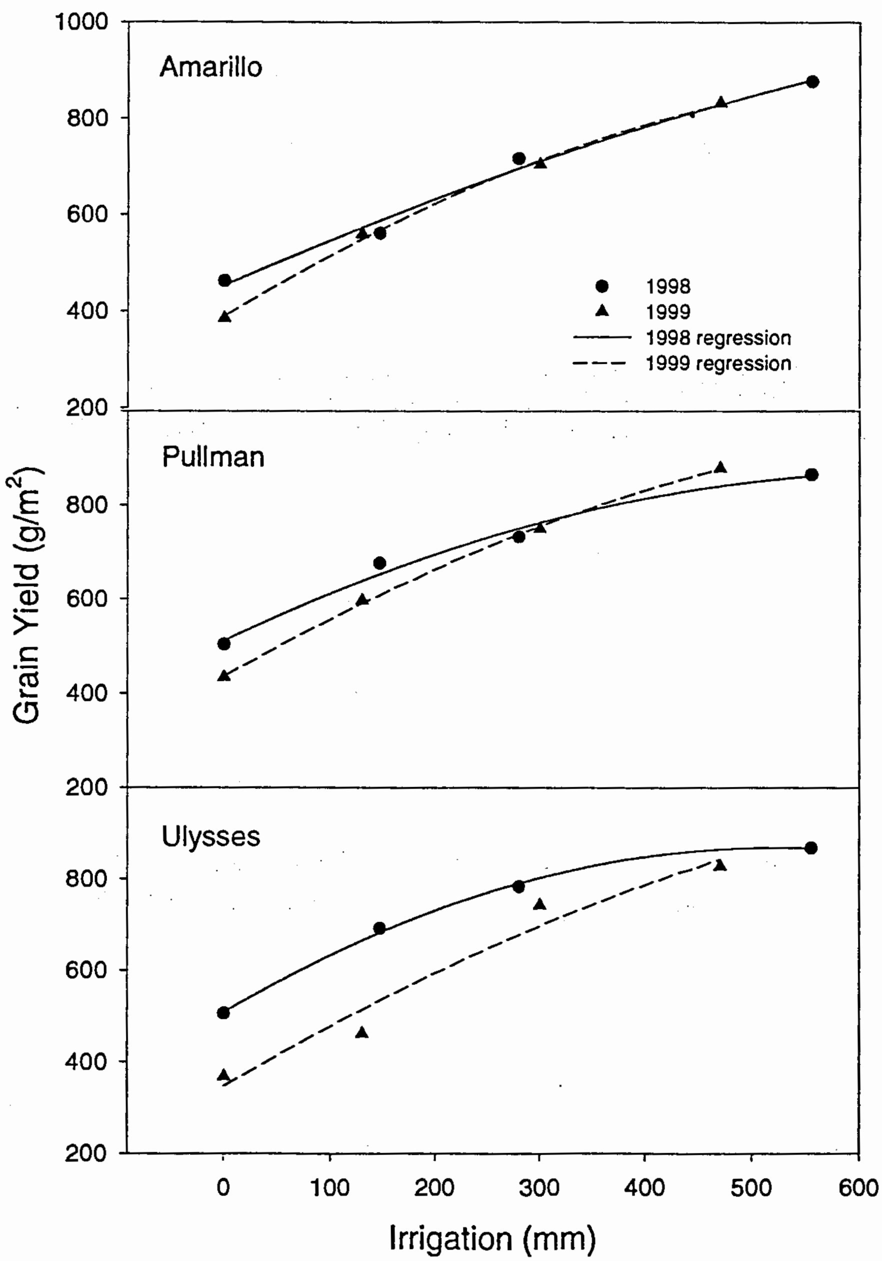

Fig. 3. Irrigation vs. grain yield response for 1998 and 1999 in the three soil types.

Grain yield response to irrigation tended to be more curvilinear in 1998 than in 1999 (Fig. 3) especially for the Ulysses and Pullman soils. Irrigation applications were based on replacement of ET in both years. With the higher evaporative demands in 1998 compared with 1999, the more curvilinear relationship in 1998 suggests that the irrigation applications exceeded the maximum crop water use and the excess was being used in soil water evaporation. Crop yield response to irrigation was almost identical in both years in the Amarillo soil, somewhat similar in the Pullman soil, but different in the Ulysses soil (Fig. 3). The crop in the Ulysses soil produced 37% more grain yield in the T-0 treatment and 50% more in the T-25 treatment in 1998 compared with that in 1999.

Irrigation water use efficiencies in general were not significantly different between irrigation treatments, but IWUE did tend to decline with increasing irrigation application amounts (Table 4). Fig. 4 shows the relationships between irrigation and yield, and ET and yield for the crop in the Pullman soil in 1999. The numbers associated with the data points on the solid line represent the WUE values for the *Y*:ET relationships, and the numbers on the dashed line the IWUE values. As can be seen, a considerable amount of irrigation is not being consumed by ET. Evaluation of the data by yield response to irrigation procedures outlined by Martin et al. (1984) shows that, at the maximum irrigation applications, very little of the applied water resulted in yield increases (Fig. 5). This was especially true for the crop in the Pullman soil in 1999.

In semi-arid climates, the percent of plant available water remaining in the soil at harvest (%PAW) is a potential indicator of the level of soil water stress experienced by the crop

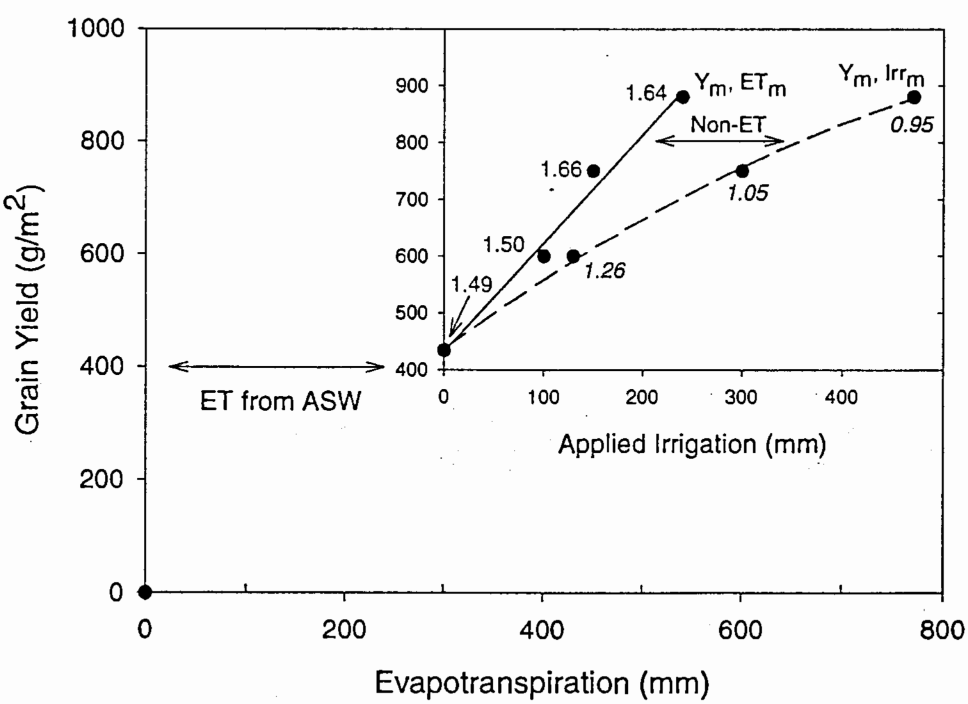

Fig. 4. The relationship between grain yield and evapotranspiration (ET) and irrigation application used for the determination of water use efficiency (WUE, solid line) and irrigation water use efficiency (IWUE, dashed line) of grain sorghum grown in the Pullman soil in 1999 (Table 4). Values accompanying the points along the lines are the WUE and IWUE (italic) for the four irrigation applications (0, 25, 50, and 100%) based on replacement of ET. Also noted is the contribution of available soil water (ASW) to ET.

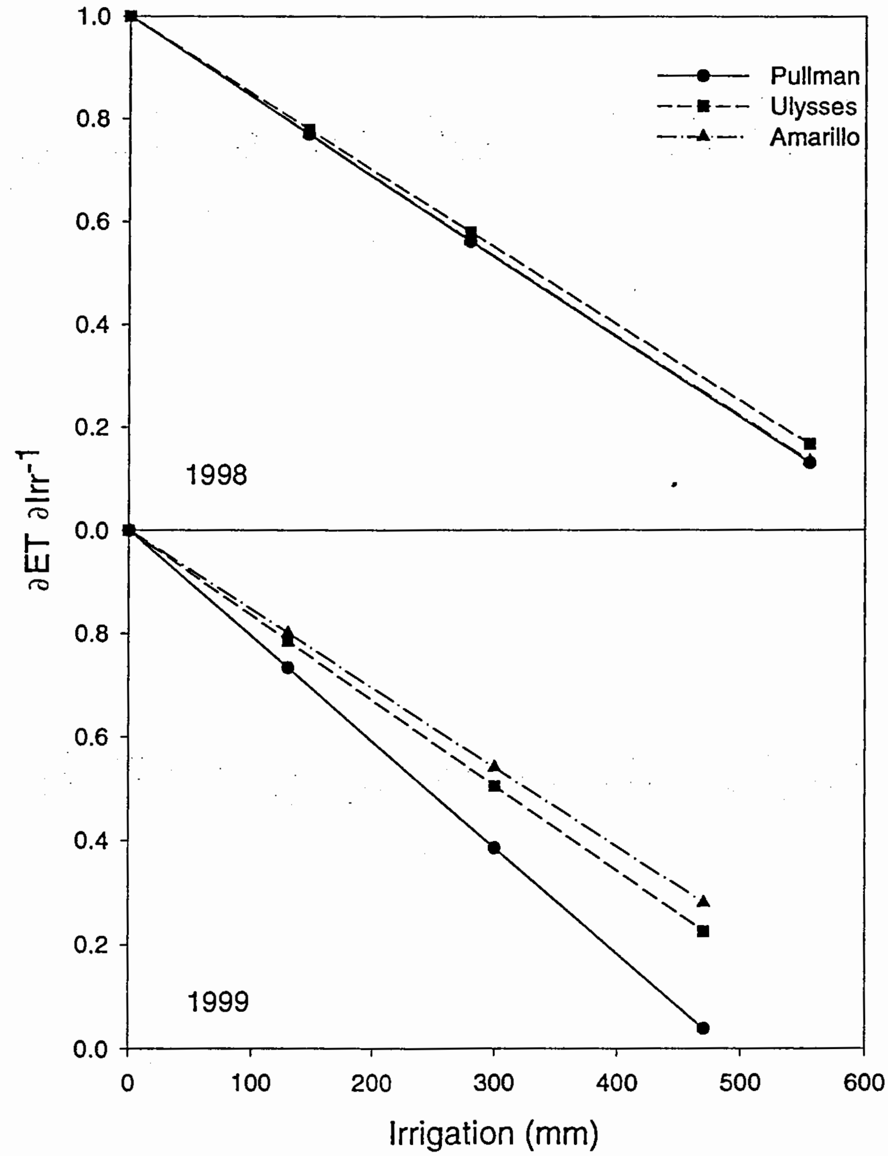

Fig. 5. An analysis of irrigation effectiveness, with the derivative of the evapotranspiration (ET) and irrigation application (Irr.), or δET δIR.$^{-1}$, indicating the ratio of the amount of applied irrigation being consumed in ET.

during the growing season and the resulting impact on yield. Factors which determine the severity of the yield reduction due to water stress include the amount of depletion below some threshold soil water content value that initiates stress, e.g. 50%, and its timing associated with growth stage sensitivity; evaporative demand; root density; and soil texture (Stegman, 1983; Howell, 2001). Despite climatic differences, the yield and soil water depletion relationship was comparable for 1998 and 1999 in both the Amarillo and Ulysses soils, although the shape of the relationship tended to differ between the two soil types (Fig. 6). Yields remained within 10% of T-100 treatment yields in the Ulysses soil until %PAW was about 20% when yields declined rapidly. While in the Amarillo soil, yield declines tended to be more curvilinear, with smaller yield reductions beginning at higher %PAW. The relationship did differ between the 2 years for the crops in the Pullman soil,

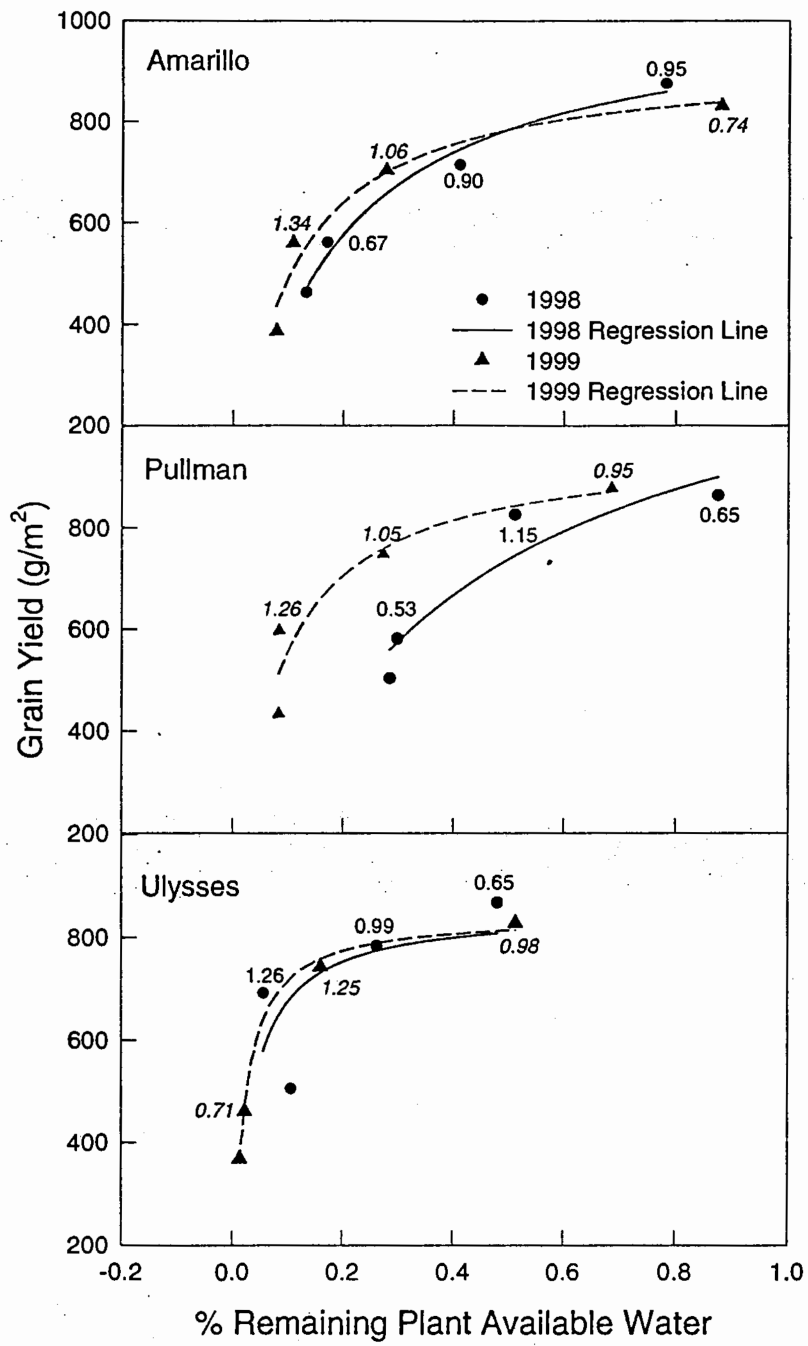

Fig. 6. The relationship between the amount of plant available water remaining in the soil profile at harvest and grain yield for each soil type in the two cropping seasons. Also given are the irrigation water use efficiency values for the irrigation treatments (Table 4).

with the yields at similar water contents being lower in 1998 compared with 1999. This was possibly due to the higher evaporative demand of 1998 affecting the rate of water transport through the soil needed to meet crop water demands (Campbell and Norman, 1998).

Declines in IWUE with increasing irrigation are associated with soil water storage, drainage, excessive soil water evaporation, and runoff (Howell et al., 1990) or if water deficit occurs at a critical growth stage. For the T-100 treatment, which tended to have low IWUE, the %PAW at harvest remained above 50% for both years (Fig. 6). Musick and Dusek (1971) noted that the highest IWUE occurred when irrigation was applied to sorghum during dry periods or intervals creating only moderate water stress. In 1998, the low IWUE of the T-25 irrigation treatment in the Amarillo and Pullman soils suggests that the limited irrigation amount did not help relieve some of the severe water stress, even at higher soil water contents, compared with 1999. Water used from stored soil water also contributes to ET (Fig. 5). Available soil water at planting was lower in 1999 compared with 1998 (see Section 2). By heading, the %PAW of the T-25 irrigation treatment in the Ulysses soil had declined to about 20% compared with 38% for the Pullman soil and 45% for the Amarillo soil, resulting in a sharp decline in grain yield in the Ulysses soil.

5. Conclusions

The difference in climatic conditions between 1998 and 1999 affected WUE, IWUE, and ET of grain sorghum, with WUE and IWUE significantly higher and ET lower in 1999 due to milder climatic conditions compared with 1998. Once normalized, yield response to ET was similar for the crops in all soils for both years. Crops grown in the Amarillo soil had significantly higher WUE compared with crops in the other soils, primarily due to reduced ET rather than increased yield. Grain sorghum grown in the Ulysses soil was able to produce higher yields at lower plant available water compared with the other two soils, but the crops in all soils reduced yield when experiencing water stress at a critical growth stage such as pollination. Although the final soil water contents were similar, grain yields of the crop in the Pullman soil were lower in 1998 (higher evaporative demand) compared with yields in 1999 (milder climate), while yields were similar in both years for the crops in the other soils. The relationship between irrigation application and yield was more curvilinear in 1998, possibly due to increased soil water evaporation at higher irrigation applications, while the relationship was more linear in 1999. In general, IWUE declined with increasing irrigation application within each year, but was variable in some irrigation treatments, due to water stress at critical growth stages. No differences among soil types occurred in IWUE in either year.

References

Al-Jamal, M.S., Ball, S., Sammis, T.W., 2001. Comparison of sprinkler, trickle and furrow irrigation efficiencies for onion production. Agric. Water Manage. 46, 253–266.

Allen, R.G., Periera, 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.

Bordovsky, J.P., Lyle, W.M., 1996. LEPA irrigation of grain sorghum with varying water supplies. Trans. ASAE 39, 2033–2038.

Bos, M.G., 1980. Irrigation efficiencies at crop production level. ICID Bull. 29 (2), 18–25, 60.

Campbell, G.S., Norman, J.M., 1998. An Introduction to Environmental Biophysics, 2nd ed. Springer, NY.

Cassel, D.K., Nielsen, D.R., 1986. Field capacity and available water capacity. In: Klute, A. (Ed.), Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods, Agronomy Monograph no. 9, 2nd ed. SSSA, Madison, WI.

Eck, H.V., Musick, J.T., 1979. Plant water stress effects on irrigated grain sorghum. Part I. Effects on yield. Crop Sci. 19, 589–592.

Evett, S.R., Steiner, J.L., 1995. Precision of neutron scattering and capacitance type soil water content gauges from field calibration. Soil Sci. Soc. Am. J. 59, 961–968.

Gerard, C.J., Sexon, P., Shaw, G., 1982. Physical factors influencing soil strength and root growth. Agron. J. 74, 875–879.

Grimes, D.W., Yamada, H., Dickens, W.L., 1969. Functions for cotton (*Gossypium hirsutum* L.) production from irrigation and nitrogen fertilization variables. Part I. Yield and evapotranspiration. Agron. J. 61 (5), 769–773.

Hanks, R.J., 1983. Yield and water use relationships: an overview. In: Taylor, H.M., Jordan, W.R., Sinclair, T.R. (Eds.), Limitations to Efficient Water Use in Crop Production. ASA-CSSA-SSSA, Madison, WI, pp. 393–411.

Howell, T.A., 2001. Enhancing water use efficiency in irrigated agriculture. Agron. J. 93, 281–289.

Howell, T.A., Cuenca, R.H., Solomon, K.H., 1990. Crop yield response. In: Hoffman, G.J., Howell, T.A., Solomon, K.H. (Eds.), Management of Farm Irrigation Systems. ASAE, St. Joseph, MI, pp. 93–122.

Howell, T.A., Yazar, A., Schneider, A.D., Dusek, D.A., Copeland, K.S., 1995. Yield and water use efficiency of corn in response to LEPA irrigation. Trans. ASAE 38 (6), 1737–1747.

Lamm, F.R., Rogers, D.H., Manges, H.L., 1994. Irrigation scheduling with planned soil water depletion. Trans. ASAE 37 (5), 1491–1497.

Landsberg, J.J., 1977. Some useful equations for biological studies. Exp. Agric. 13, 273–286.

Martin, D.L., Watt, D.G., Gilley, J.R., 1984. Model and production function for irrigation management. J. Irrigat. Drain. Eng. 110 (2), 149–164.

Musick, J.T., Dusek, D.A., 1971. Grain sorghum response to number, timing, and size of irrigations in the southern High Plains. Trans. ASAE 14, 401–404, 410.

Musick, J.T., Grimes, D.W., 1961. Water management and consumptive use by irrigated grain sorghum in western Kansas. Kansas Agric. Exp. Stn. Technol. Bull., 113.

Musick, J.T., Sletten, W.H., 1966. Grain sorghum irrigation-water management on Richfield and Pullman soils. Trans. ASAE, 9:369–371, 373.

Musick, J.T., Grimes, W.H., Herron, G.M., 1963. Irrigation water management and nitrogen fertilization of grain sorghums. Agron. J. 55, 295–298.

Musick, J.T., Sletten, W.H., Dusek, D.A., 1964. Irrigating Grain Sorghum for Efficient Use of Limited Water, Paper No. 64-208. American Society of Agricultural Engineering, St. Joseph, MI.

SAS Institute, 1985. SAS User's Guide: Statistics, 5th ed. SAS Institute, Cary, NC.

Schneider, A.D., Howell, T.A., 1995. Grain sorghum response to sprinkler application methods and system capacity. Trans. ASAE 38, 1693–1697.

Schneider, A.D., Howell, T.A., Steiner, J.L., 1993. An evapotranspiration research facility using monolithic lysimeters from three soils. Appl. Eng. Agric. 9, 227–235.

Stegman, E.C., 1983. Irrigation scheduling: applied timing criteria. Adv. Irrigat. 2, 1–30.

Stewart, J.I., Hagan, R.M., 1973. Functions to predict effect of crop water deficits. J. Irrigat. Drain. Div., Proc. ASCE 99 (IR4), 421–439.

Stewart, J.I., Misra, R.D., Pruitt, W.O., Hagan, R.M., 1975. Irrigating corn and grain sorghum with a deficient water supply. Trans. ASAE 18 (2), 270–280.

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. Agron. J. 75 (4), 629–634.

Stone, L.R., Schlegel, A.J., Gwin Jr, R.E., Khan, A.H., 1996. Response of corn, grain sorghum, and sunflower to irrigation in the high plains of Kansas. Agric. Water Manage. 30, 251–259.

Vaux Jr, H.J., Pruitt, W.O., 1983. Crop-water production functions. Adv. Irrigat. 2, 61–97.

Viehmeyer, F.J., Hendrickson, A.H., 1949. Methods of measuring field capacity and the permanent wilting point of soils. Soil Sci. 68, 75–94.