available at www.sciencedirect.com
ScienceDirect
journal homepage: www.elsevier.com/locate/agwat
ELSEVIER
Agricultural Water Management

Field water supply:yield relationships of grain sorghum grown in three USA Southern Great Plains soils

J.A. Tolk *, *T.A. Howell*

USDA Agricultural Research Service, P.O. Drawer 10, 2300 Experiment Station Road, Bushland, TX 79012, United States

ARTICLE INFO

Article history:
Received 15 January 2008
Accepted 29 May 2008

Keywords:
Water productivity
Irrigation water productivity
Water use efficiency
Irrigation water use efficiency
Evapotranspiration
Lysimeter
Deficit irrigation

ABSTRACT

Field water supply (FWS) combines the three sources of water used by a crop for evapotranspiration (ET), and consists of available soil water at planting (ASWP), rainfall, and irrigation. Examining the grain yield and FWS relationship (Y_g:FWS) may provide insight into the reported variability in crop water production functions such as water productivity (WP) and irrigation water productivity (IWP). Since water is most productive when entirely consumed in ET, diversion of FWS into non-ET losses such as drainage and excessive soil water evaporation results in declines in WP and IWP. The objective of this experiment was to examine the Y_g:FWS and Y_g:ET relationships of grain sorghum grown under a range of irrigation treatments (0, 25, 50, and 100% replacement of ET), beginning soil water contents, evaporative demands, in the Amarillo, Pullman, and Ulysses soils of the Great Plains. The purpose was to determine the amount of FWS beyond which declines in WP and IWP began to occur due to non-ET losses as indicated by a change in the slope and intercept of the Y_g:FWS and Y_g:ET relationships. Large amounts of non-ET irrigation application losses occurred in the finer-textured soils in the T-100 irrigation treatment. In both years, the T-100 irrigation application amounts and ASWP resulted in a FWS ranging from 750 to 870 mm which exceeded the maximum ET requirement of 530–630 mm and which reduced WP and IWP. Piecewise regression analysis of the Y_g:FWS and Y_g:ET relationships for the crops in the Pullman and Ulysses soils identified the knot point, or change in slope and intercept, in the FWS where both WP and IWP tended to be optimized. This was about 500 mm in both soils, and involved the utilization of about 250 mm in ASWP, irrigation applications averaging about 250 mm, and about 60–130 mm remaining in the soil at harvest. For the coarser-textured Amarillo soil, the yield response to increasing FWS was linear, because non-ET application losses such as drainage gradually increased with the irrigation application amount. The linear Y_g response in the sandy Amarillo soil and the piecewise Y_g responses in the clay and silt loams of the Pullman and Ulysses soils to FWS also reflected the difference in water-holding capacities of the soils that affected the amount of available water as irrigation increased. Irrigating without considering FWS resulted in non-ET irrigation application losses and declines in WP and IWP.

Published by Elsevier B.V.

1. Introduction

As world population increases and fresh water supplies per capita decline, the domination of irrigated agriculture over the world's fresh water supply is rapidly coming to an end, requiring agriculture to rethink its approach to irrigation (English et al., 2002; Fereres and Soriano, 2007; Hsiao et al., 2007). Deficit irrigation, defined as the deliberate under-

* *Corresponding author*. Tel.: +1 806 356 5736; fax: +1 806 356 5750.
E-mail address: Judy.Tolk@ars.usda.gov (J.A. Tolk).
0378-3774/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.agwat.2008.05.009

irrigation of a crop (English, 1990), aims at maximizing the net income per unit irrigation water used rather than per unit land used, and is practiced when water supplies are limited (Fereres and Soriano, 2007). After reviewing literature that reported yield versus water use experiments world-wide, Zwart and Bastiaanssen (2004) found that deficit irrigation improved crop water productivity sometimes by more than 200%. Crop water productivity (WP) is defined as

$$WP = \frac{Y}{ET} \quad (1)$$

where WP is in kg m^{-3}, Y is the marketable crop yield (kg ha^{-1}) and ET is evapotranspiration (m^3 ha^{-1}).

The strong linkage between yield and transpiration and later yield and ET has been studied by researchers since the beginning of the 20th century (Vaux and Pruitt, 1983; Howell et al., 1990). When examined over a range of irrigation treatments, the grain yield versus ET (Y_g:ET) relationship has typically been described as linear (Stewart et al., 1975, 1983; Hanks, 1983; Lamm et al., 1994; Howell et al., 1995; Al-Jamal et al., 2001), although curvilinear relationships have also been reported (Grimes et al., 1969; Zhang et al., 2004). According to Stewart and Hagan (1973), non-linear relationships are explicable only if the harvest index (ratio of grain biomass to total biomass) changes with increasing water deficit. Grimes et al. (1969), however, stated that a curvilinear Y:ET relationship for cotton was due to a probable decrease in efficiency of water utilization by the plants and drainage below the effective rooting depth at the highest irrigation levels. Musick and Dusek (1971), in reporting on a 3-year study on the effect of number, timing, and size of seasonal irrigation on grain sorghum yield, concluded that the lower-yielding treatments had a linear Y_g:ET relationship, while the higher-yielding treatments a curvilinear one.

By rearranging Eq. (1) and using a known WP value, it becomes tempting to predict yield based on available water supply. However, the range of Y:ET relationships summarized in Zwart and Bastiaanssen (2004) is large (e.g. for maize (*Zea mays* L.) a range from 1.1 to 2.7 kg m^{-3}) due to differences in climate, irrigation water management, and soil management, among others. Numerous proposals for the improvement of WP have been made, including reducing soil water evaporation (Wang et al., 2001), increasing transpiration efficiency (Wallace, 2000), and evaluating WP on a spatial or systems scale (Bouman, 2007; Hsiao et al., 2007).

Although useful in many analyses, WP as a function of water used does not clearly take into account the role of irrigation (Howell, 2001), which most likely is of greater interest than WP to producers. Bos (1980, 1985) developed an expression for irrigation water productivity (IWP) which related the increase in irrigated yield over dryland yield due to irrigation, given as

$$IWP = \frac{Y_i - Y_0}{IR} \quad (2)$$

where IWP is in kg m^{-3}, Y_i is irrigated yield in kg ha^{-1}, Y_0 is the dryland (unirrigated) yield in kg ha^{-1} and IR is irrigation in m^3 ha^{-1}.

Reported irrigation versus yield ($Y_i - Y_0$ or Y_i only) relationships for multiple irrigation levels have been both linear (Lamm et al., 1994) and curvilinear (Stewart et al., 1983; Bordovsky and Lyle, 1996; Tolk and Howell, 2003). Howell et al. (1995) showed a linear relationship for 1 year of a sprinkler irrigation study on maize and a quadratic relationship for the same study the following year.

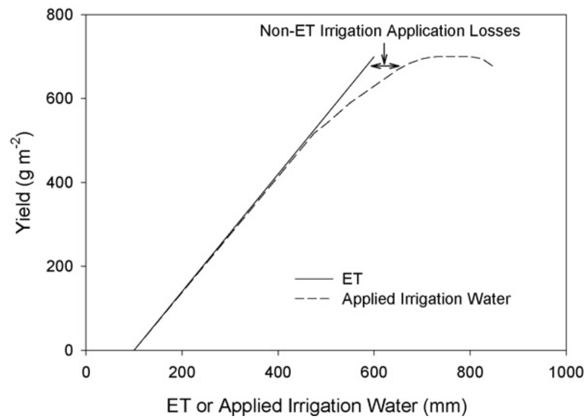

Fig. 1 – Generalized relationships between yield, evapotranspiration (ET) and applied irrigation water.

The generalized relationship between applied irrigation water, ET, and yield (Fig. 1) shows that, for a highly efficient irrigation system, low to moderate amounts of applied water are all initially consumed in ET producing a linear relationship with yield when there are no non-ET irrigation application losses. These losses include percolation, excessive soil water evaporation, and soil water storage in the profile. The largest irrigation water application efficiencies are achieved when the application amounts are entirely consumed in ET. At some point, irrigation application amounts exceed ET demand, the rate of yield increase due to irrigation slows, and the efficiency of irrigation begins to decline as the application losses increase. Finally, yield response to irrigation plateaus, even when irrigation continues to increase. When irrigation becomes excessive, the generalized relationship of Fig. 1 also shows that yield can decline.

Neither WP nor IWP adequately take into account all the water potentially available to the crop to be used in ET. In the case of deficit irrigation, which has also been defined as irrigation application amounts below the full ET requirements of a crop (Fereres and Soriano, 2007), the water needs of the crop may also be met by precipitation (PREC) and available soil water at planting (ASWP). Called field water supply (FWS) by Stewart and Hagan (1973), the totality of water that a crop can use in ET can be given as

$$FWS = IR + ASWP + PREC \quad (3)$$

How much water is used by the crop from each source can especially impact IWP. An example originally presented in Tolk and Howell (2003) showed the relationship between grain yield and ET, irrigation, and ASWP (Fig. 2). The solid line is the Y_g:ET relationship and the dashed line the Y_g:IR relationship, with the numbers advancing along each line representing the WP and IWP for the increasing irrigation levels. As can be seen by the difference between the slopes of the two relationships, "Non-ET" losses increased as irrigation amount increased. At

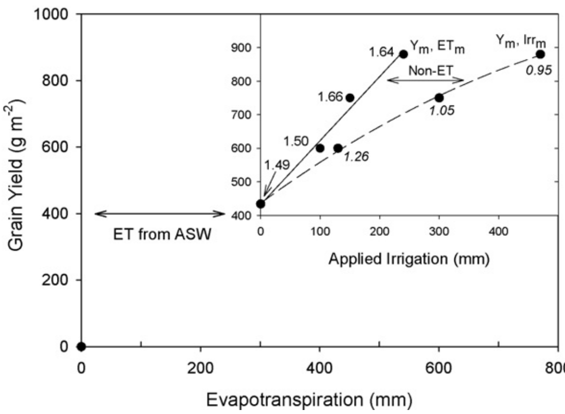

Fig. 2 – An example of the relationship between grain yield and evapotranspiration (ET), applied irrigation, and available soil water (ASW) for grain sorghum grown in a Pullman soil.

maximum yield (Y_m) only a portion of the maximum applied irrigation (Irr_m) had contributed to maximum ET (ET_m). The IWP declined from 1.26 to 0.95 kg m^{-3} while WUE remained above 1.6 kg m^{-3}. The figure also shows that irrigation was not the only contributor to ET and consequently grain yield. The ASWP alone used in ET produced about 50% of the maximum yield.

Although considered a non-ET loss, soil water storage can be important in preventing plant water stress. The amount of water that must be maintained in the soil to prevent severe water stress is a function of crop type, soil type, and evaporative demand. According to Kanemasu et al. (1976), Wright and Smith (1983), Rosenthal et al. (1987), and Robertson and Fukai (1994), water stress in grain sorghum did not begin until 60–70% of total available soil water (TASW) was used, but the level of allowable depletion is also a function of maximum ET (Doorenbos and Kassam, 1979; Robertson and Fukai, 1994). According to Doorenbos and Pruitt (1977), the maximum allowable depletion of TASW before stress occurs in grain sorghum ranges from 55% when maximum ET of a fully irrigated crop (ET_m) was 6 mm day^{-1} to 40% when ET_m was 10 mm day^{-1}. Knowing the amount of FWS allows an irrigator to maintain an adequate water supply that controls crop water stress sufficiently such that yields are maximized and irrigation application losses are minimized, or achieving both large WP and IWP. However, it is difficult to determine *a priori* what an adequate water supply is.

In a water-limited environment, the optimal depth of irrigation water must be determined which both capitalizes on ASWP and precipitation and achieves the greatest yields possible while reducing losses in water productivity. The objective of this research was to evaluate the Y_g:ET and Y_g:FWS relationships of grain sorghum grown under a range of irrigation treatments (0, 25, 50, and 100% replacement of ET), beginning soil water contents, evaporative demands, and different soil types in a rain shelter facility. The purpose was to determine the amount of FWS beyond which declines in WP and IWP began to occur due to non-ET losses.

2. Materials and methods

The experiment 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 mean sea level). The SPER facility is located in a 0.25-ha field with a rain shelter facility with 48 weighing or weighable lysimeters that contained soil of three different series. The lysimeters are 1.0 m × 0.75 m, and 2.4 m deep; containing monolithic cores to about a 2.3-m depth with a vacuum 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.

The rain shelter was a metal building 13 m × 18 m × 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).

The climate at Bushland is typical of the semiarid 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. Wind direction is predominately from the south-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.

2.1. *Agronomy*

The lysimeters were planted with grain sorghum ('Pioneer-8699'[1]) in 1998 and 1999 at a density of 16 plants m^{-2}. The plants were planted in a single row down the center of each lysimeter, which maintained a 0.75-m row spacing with the adjacent lysimeters and surrounding cropped area. In 1998, planting was on Day of Year (DOY) 181 (June 30), emergence on DOY 187 (July 6), mid-bloom (Vanderlip and Reeves, 1972) on DOY 229 (August 17), and harvest on DOY 272 (September 29). In 1999, planting was on DOY 188 (July 7), emergence on DOY 194 (July 13), mid-bloom on DOY 235 (August 23) and harvest on DOY 292 (October 19). 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 0.2 m. The lysimeters were hand harvested, and the grain mechanically threshed. Stover and grain were dried in an oven at 70 °C for 24-h, with grain yield reported at 0% moisture.

The seasonal ET was measured using deck scales (DS3040-10K, Weigh-Tronix, Fairmont, MN) or manually weighing the lysimeters periodically using a suspended load cell interfaced with a datalogger. The ET was calculated from the difference

[1] The mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Please cite this article in press as: Tolk, J.A., Howell, T.A., Field water supply:yield relationships of grain sorghum grown in three USA Southern Great Plains soils, Agric. Water Manage. (2008), doi:10.1016/j.agwat.2008.05.009

in lysimeter mass between weighing intervals, plus any applied water infiltration and minus any drainage water. The ET reported represents ET measured between emergence and harvest.

Irrigation treatments were 100% (T-100), 50% (T-50), 25% (T-25), and 0% (T-0) replacement of ET, with the T-50 and T-25 treatments simulating deficit irrigation. The lysimeters were irrigated prior to planting to try to achieve a uniform plant available water. Daily ET of at least two replicates of the fully irrigated treatments was measured using deck scales, and served as the basis for the calculation of irrigation treatment amounts. Irrigation applications were measured and applied weekly by hand. In 1998, there were nine irrigations beginning on DOY 197 (July 16) and ending on DOY 253 (September 10). In 1999, there were ten irrigations beginning on DOY 203 (July 22) and ending on DOY 267 (September 24).

2.2. 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. Each cropping season 36 lysimeters (12 of each soil series) were included in the irrigation experiment each cropping season, with three replicates of treatments. The remaining 12 lysimeters containing the Ulysses soil series were used in a separate 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 has 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 loess 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.

2.3. Soil water content measurement

Volumetric soil water contents were measured by neutron scattering (Model 503 DR, Campbell Pacific Nuclear, Martinez, CA) in a centrally located tube in each lysimeter. The measurements were taken at 0.2-m increments starting at 0.1 m and ending at 2.1 m for a total measurement depth of 2.2 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 root mean square error (RMSE) values 0.01 $m^3\,m^{-3}$. Based on the RMSE values, measurement error for 2.2 m does not exceed 22 mm.

The volumetric and mass water contents at permanent wilting point (PWP) and drained upper limit (DUL) used to estimate available soil water (ASW) for each soil are shown in Table 1. PWP was the water content of the soil at −1.5 MPa. Laboratory determination of PWP was made by the pressure plate technique using procedures described by Klute (1986). All samples used in the analysis came from larger bulk samples of each soil layer collected at each soil series collection site. Four sub-samples from each soil layer were sieved through a 0.002-m screen, placed in 0.05 m in diameter by 0.015-m long rings with lead weights on the top, saturated, and allowed to equilibrate at −1.5 MPa pressure for about 9 days. The sub-samples were oven dried at 105 °C for 24 h, and mass water content determined as the difference between the wet and dry sample masses. Mass water content was converted to volumetric water content by multiplying it by the bulk density of that layer. Mean bulk density was 1.69 (±0.03) Mg m^{-3} in the Amarillo soil, 1.45 (±0.07) Mg m^{-3} in the Pullman soil, and 1.42 (±0.04) Mg m^{-3} in the Ulysses soil.

To determine DUL, the soil profiles of six lysimeters of each soil type were thoroughly wetted, the soil surfaces covered to minimize evaporation, and then allowed to drain. When drainage was negligible, volumetric soil water contents were measured using neutron scattering. The data presented in Table 1 are comparable to data for soils similar in texture presented in Ratliff et al. (1983) and, for the Ulysses, to that presented in Stone et al. (2006).

2.4. Field water supply

FWS consists of the sum of ASWP, irrigation, and precipitation that occurs during the growing season. In this experiment, precipitation was virtually eliminated due to the presence of a rain shelter (the area caught on average 1–2 mm of precipitation before the shelter shut for each precipitation event). To determine ASWP, the lower limit of soil water available to the crop had to be established. This traditionally has been the water content of the soil held at −1.5 MPa. However, Cabelguenne and Debaeke (1998) showed that crops could extract soil water beyond PWP. Lehane and Staple (1960)

Table 1 – Soil water contents determining available soil water (ASW) for the three soils

	PWP ($m^3\,m^{-3}$)	DUL ($m^3\,m^{-3}$)	ASW ($m^3\,m^{-3}$)	PWP (mm)	DUL (mm)	ASW (mm)
Amarillo	0.13	0.25	0.12	286	550	264
Pullman	0.19	0.35	0.15	418	770	352
Ulysses	0.16	0.36	0.20	352	792	440

PWP, permanent wilting point; DUL, drained upper limit; volumetric soil water content ($m^3\,m^{-3}$); mass soil water content (mm).

Please cite this article in press as: Tolk, J.A., Howell, T.A., Field water supply:yield relationships of grain sorghum grown in three USA Southern Great Plains soils, Agric. Water Manage. (2008), doi:10.1016/j.agwat.2008.05.009

Table 2 – Soil water content at the beginning (SWC_b) and end (SWC_e) of the growing season for the Amarillo, Pullman, and Ulysses soils

Irr. Trt., ET (%)	Amarillo				Pullman				Ulysses			
	SWC_b		SWC_e		SWC_b		SWC_e		SWC_b		SWC_e	
	$m^3 m^{-3}$	mm	$m^3 m^{-3}$	mm	$m^3 m^{-3}$	mm	$m^3 m^{-3}$	mm	$m^3 m^{-3}$	mm	$m^3 m^{-3}$	mm
1998												
0	0.25	553	0.11	243	0.35	777	0.22	477	0.28	612	0.13	295
25	0.25	553	0.12	259	0.35	777	0.22	489	0.27	593	0.13	276
50	0.25	553	0.15	340	0.35	777	0.25	550	0.27	602	0.17	371
100	0.25	544	0.21	464	0.35	776	0.30	658	0.27	593	0.21	473
1999												
0	0.21	459	0.10	225	0.31	671	0.19	421	0.23	497	0.11	251
25	0.21	459	0.11	238	0.31	671	0.19	426	0.24	519	0.12	257
50	0.22	474	0.13	295	0.30	668	0.22	482	0.23	516	0.15	326
100	0.27	595	0.23	498	0.32	711	0.29	646	0.27	600	0.22	490

Irr. Trt., irrigation treatment, consisting of 0, 25, 50, and 100% replacement of evapotranspiration (ET); volumetric soil water content ($m^3 m^{-3}$); mass soil water content (mm).

reported field-measured soil water contents of cereals at harvest to be 14% lower than PWP.

In this experiment, the lowest soil water contents occurred in the T-0 treatment in 1999 (Table 2), and were used for the lower limit of ASW instead of the PWP reported in Table 1. The average volumetric soil water content to 2.2 m at the end of the season (SWC_e) for the Amarillo soil was 0.10 $m^3 m^{-3}$, with the average mass water content of 225 mm being 21% lower than the mass water content at PWP of 286 mm. The SWC_e of 0.19 $m^3 m^{-3}$ and mass water content of 421 mm for the Pullman soil were almost identical to the soil's PWP values in Table 1. The SWC_e for the Ulysses soil was 0.11 $m^3 m^{-3}$, with the mass water content of 251 mm being 29% lower than the PWP of 352 mm.

In addition to the calibration error, the error introduced in using SWC_e to determine the lower limit of plant available water was the drying of the water content of the surface layer below that which can be utilized by the plant. The difference between PWP and the neutron probe measurement of the water content in the top 0.2-m of the soil profile was 0.1 $m^3 m^{-3}$ or 20 mm for the Ulysses soil and 0.07 $m^3 m^{-3}$ or 14 mm for the Amarillo and Pullman soils.

2.5. *Statistical procedures*

Measurements were analyzed using the general linear model procedures of PROC GLM (SAS Institute, 1985). Soil types were randomly distributed within each pit, with three replications per soil type and irrigation treatment. The model included irrigation, soil type, and the interaction. 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 (Littell et al., 1996) as a split plot in time, with soil type and years as main effects and the random effect of soil nested with replicates. Covariance analysis of the relationship between ET, FWS, and grain yield was performed using procedures outlined by Freese (1964).

The Y_g:ET and Y_g:FWS data were evaluated using a two segment, piecewise linear regression (Sigmaplot for Windows, v. 10, Sysstat Software, Inc., San Jose, CA). Piecewise regression models have been described as ‘‘broken stick'' models, where two or more lines are joined together at unknown point(s) called knot points or breakpoints (Toms and Lesperance, 2003). The knot point represents the point at which the response of the dependent variable changes with respect to the independent variable, as represented by a change in slope and intercept. This analysis has been used in such diverse fields as the determination of the thresholds of ecological communities (Toms and Lesperance, 2003) and cracking characteristics of industrial materials (Lima et al., 2003).

As suggested by the relationships presented in Fig. 1, the yield versus FWS data could contain two distinct groups of data, each with a different slope and intercept. For the Y_g:FWS relationship, the hypothesis was that the knot point represented the FWS beyond which WP and IWP declined due to non-ET losses. A non-linear Y_g:ET relationship also suggests that there is a point where yield response to ET changes because, while the linear response of yield to transpiration remains the same, increases in non-yield producing evaporation have occurred.

Linear polynomial, quadratic polynomial, and piecewise models were evaluated. The criteria used to determine whether the proposed model was a good fit to the data were that the error term had a zero mean and constant variance, and the errors were normally distributed and uncorrelated (Montgomery et al., 2006). The model presented had the best fit in terms of largest R^2 and standard error of the estimate.

3. Results

3.1. *Crop development and climate*

The crop in 1998 was planted 7 days earlier compared with 1999, and crop development between years generally maintained this difference throughout the growing season until harvest. Reference ET (Allen et al., 1998) indicated hotter and drier conditions in July of 1998 compared with those in 1999 (Table 3) followed by more similar conditions in both years in

Table 3 – Average climatic parameters for each month of the cropping season in 1998 and 1999

	ET_o (mm day^{-1})	T_{max} (°C)	T_{min} (°C)	T_{dew} (°C)	U (m s^{-1})	R (MJ day^{-1})	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

ET_o, 0.12-m grass reference evapotranspiration; T_{max}, maximum temperature; T_{min}, minimum temperature; T_{dew}, dew point temperature; U, wind speed at 2-m height; R, solar radiation; VPD, vapor pressure deficit.

August. However, beginning in September, daily reference ET was larger in 1998 compared with that in 1999 (Fig. 3). For the equivalent period in each growing season (DOY 193 through DOY 270), reference ET totals were 476 mm in 1998 and 436 mm in 1999.

3.2. Yield, ET, and WP

Grain yields were similar in both years when averaged across soil type and irrigation treatment, with yields (including ±1 standard deviation) averaging 686.8 (±159.2) g m^{-2} in 1998 and 628.5 (±185.5) g m^{-2} in 1999. The average crop ET of 463.9 (±115) mm in 1998 was significantly larger than the 395.8 (±119.5) mm in 1999, also averaged across soil type and irrigation treatment. The WP of 1.60 kg m^{-3} in 1999 was significantly larger than the 1.49 kg m^{-3} in 1998, because comparable yields were produced with smaller cumulative ET.

Soil type had no significant effect on grain yield, ET, and WP averaged across irrigation treatments in 1998, or on grain yield and ET averaged across irrigation treatments in 1999. The WP of 1.47 kg m^{-3} of the crops in the Ulysses soil in 1999 was significantly lower than the 1.71 kg m^{-3} of the crops in the Amarillo soil and the 1.61 kg m^{-3} of those in the Pullman soil which were similar.

For the T-100 irrigation treatment, the grain yield was similar among soil types (Table 4) and between years, averaging 858 (±22.3) g m^{-2} across soil types and years. This is similar to the a maximum grain yield of 854 g m^{-2} reported by Farré and Faci (2006) for grain sorghum grown in a Mediterranean environment but 15% larger than the 731 g m^{-2} reported by Musick and Dusek (1971) for grain sorghum grown at Bushland, TX. Cumulative ET was significantly larger and WP significantly smaller in 1998 compared with 1999. In 1998, ET was 615 mm and WP was 1.41 kg m^{-3}, while in 1999 ET was 552 mm and WP was 1.53 kg m^{-3}. Maximum seasonal ET reported by Farré and Faci (2006) for grain sorghum was 588 mm with a WP of 1.46 kg m^{-3}. The T-100 irrigation treatment received 65 mm more irrigation water in 1998 than in 1999, which was comparable to the differences in ET between years (Table 4). While ET was significantly different between years, the similarity in yields suggests that maximum yield had been approached, and that most of the irrigation application increase in 1998 went into non-ET irrigation application losses (Fig. 1) such as soil water evaporation. Stewart and Hagan (1973) found that maximum yield was based on varietal characteristics alone, while maximum ET was dependent upon environment.

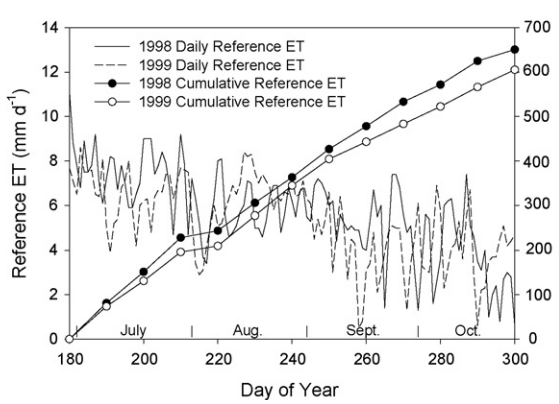

Fig. 3 – Daily and cumulative reference evapotranspiration (ET) for 1998 and 1999.

For the T-50 irrigation treatment, yields were also similar between years, averaging 754 (±45) g m^{-2} across soil types and years. The ET was significantly larger at 496 mm in 1998 compared with the ET of 441 mm in 1999, and the difference in irrigation was 30 mm. The WP tended to be lower at 1.56 kg m^{-3} in 1998 compared with the 1.66 kg m^{-3} in 1999.

For the T-25 irrigation treatment, yield and ET averaged across soil types were significantly larger in 1998 compared with 1999, with a yield of 612 g m^{-2} and ET of 433 mm produced in 1998 and a yield of 539 g m^{-2} and ET of 348 mm produced in 1999. The WP tended to be lower in 1998 at 1.42 kg m^{-3} compared with 1.55 kg m^{-3} in 1999.

For the T-0 irrigation treatment, the yield of 491 g m^{-2} and ET of 311 mm produced in 1998 were both significantly larger than the yield of 396 g m^{-2} and ET of 242 mm produced in 1999. The WP of 1.58 kg m^{-3} in 1998 was not significantly different from the WP of 1.65 kg m^{-3} in 1999. The minimum irrigation treatment of Farré and Faci (2006) produced a sorghum grain yield of 64 g m^{-2} with an ET of 274 mm resulting in a WP of 0.23 kg m^{-3}.

The WP of 1.56 kg m^{-3} produced by the T-50 irrigation treatment in 1998 was significantly larger than the WP of 1.42 kg m^{-3} for the T-25 irrigation treatment and the 1.41 kg m^{-3} for the T-100 irrigation treatment. While there were no significant differences in WP among irrigation

Please cite this article in press as: Tolk, J.A., Howell, T.A., Field water supply:yield relationships of grain sorghum grown in three USA Southern Great Plains soils, Agric. Water Manage. (2008), doi:10.1016/j.agwat.2008.05.009

Table 4 – Yield (Yld), evapotranspiration (ET), average irrigation application amounts (Irr.), and water production functions for the crops grown in 1998 and 1999 in the Amarillo, Pullman, and Ulysses soils with irrigation treatments of 0, 25, 50, and 100% replacement of ET

Trt., ET (%)	Irr. (mm)	Amarillo				Pullman				Ulysses			
		Yld (g m^{-2})	ET (mm)	WP (kg m^{-3})	IWP (kg m^{-3})	Yld (g m^{-2})	ET (mm)	WP (kg m^{-3})	IWP (kg m^{-3})	Yld (g m^{-2})	ET (mm)	WP (kg m^{-3})	IWP (kg m^{-3})
1998													
0	0	463c	283d	1.64a		504b	327d	1.54ab		506c	323d	1.49	
25	147	562c	395c	1.43b	0.67	582b	459c	1.27b	0.55	691b	445c	1.45	1.33a
50	260	716b	475b	1.51ab	0.90	826a	514b	1.61a	1.24	783ab	500b	1.50	1.07ab
100	515	876a	585a	1.50ab	0.74	865a	628a	1.38ab	0.70	868a	634a	1.31	0.70b
1999													
0	0	386c	206d	1.87a		434d	268d	1.62		369b	252d	1.47	
25	130	560b	317c	1.76ab	1.34	597c	374c	1.60	1.26	461b	353c	1.30	0.71b
50	230	705a	423b	1.66bc	1.06	750b	455b	1.65	1.05	743a	445b	1.67	1.63a
100	440	832a	535a	1.55c	0.95	879a	553a	1.59	0.95	828a	569a	1.45	1.06ab

WP, water productivity; IWP, irrigation water productivity. Mean values with the same letter do not differ significantly ($p < 0.05$) among irrigation treatments within each column and within each year.

treatments in 1999, the WP of 1.66 kg m^{-3} for the T-50 irrigation treatment was the largest, and the WP of 1.53 kg m^{-3} 3 for the T-100 irrigation treatment was the smallest.

3.3. *Irrigation water productivity*

Soil type did not result in significant differences in IWP in either year. The IWP was significantly different between years, however, with an IWP of 0.90 kg m^{-3} being produced in 1998 and 1.20 kg m^{-3} in 1999 when averaged across soil type and irrigation treatment. While IWP tended to increase with decreasing irrigation in each soil type (Table 4), the IWP of the T-50 irrigation treatment averaged across soil types was significantly larger than the other two irrigation treatments in both years, with an IWP of 1.10 kg m^{-3} being produced in 1998 and of 1.46 kg m^{-3} in 1999.

3.4. *ET versus yield*

The best fit for the Y_g:ET relationship for the crops in the Amarillo soil was a linear polynomial for each year. The slopes of the Y_g:ET relationship of 1.41 ET in 1998 and 1.38 ET in 1999 were almost identical in each year, but the intercepts were significantly different at 43 g m^{-2} in 1998 and 110 g m^{-2} in 1999 (Fig. 4). The significantly different intercepts may have resulted from the larger evaporative deficit in 1998 compared with 1999. The Y_g:ET relationship for grain sorghum also grown in a sandy loam soil (Farré and Faci, 2006) was also linear but with a larger slope at $Y_g = 2.55$ ET − 646.9 g m^{-2}.

The Y_g:ET relationships for the crops in the Pullman and Ulysses soils were analyzed using piecewise linear regression, which included data from both 1998 and 1999 due to a similarity in the Y_g:ET relationship in both years for each soil (Fig. 4). In using piecewise linear regression, a knot point at which the Y_g:ET relationship changed in both slope and intercept was identified.

For the crops in the Pullman soil, the predicted Y_g:ET relationship was $Y_g = 1.69$ ET − 31 g m^{-2} until the predicted Y_g:ET knot point at 852 g m^{-2} and 524 mm. At and beyond this point were the data for the Y_g:ET relationship of the T-100 irrigation treatment in both years, and where the predicted relationship flattened to $Y_g = 0.2$ ET + 745 g m^{-2}. The limited increase in yield beyond the knot point to the maximum yield of 879 g m^{-2} suggests that the maximum yield based on ET had been approached at the knot point, and that the additional ET at this level was primarily soil water evaporation with little

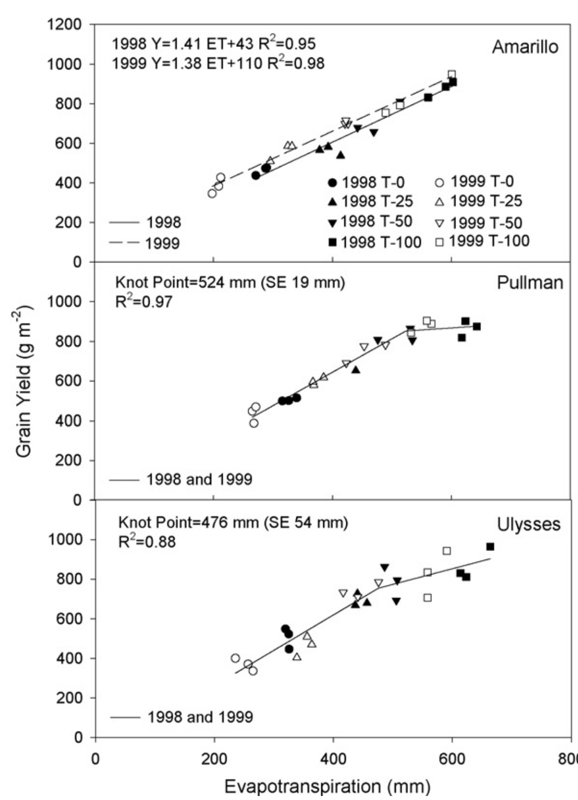

Fig. 4 – Evapotranspiration (ET) versus grain yield of grain sorghum for 1998 and 1999 for the three soil types for the four irrigation treatments of 0 (T-0), 25 (T-25), 50 (T-50), and 100% (T-100) replacement of ET. Standard errors (S.E.s) are given for the FWS knot points.

Please cite this article in press as: Tolk, J.A., Howell, T.A., Field water supply:yield relationships of grain sorghum grown in three USA Southern Great Plains soils, Agric. Water Manage. (2008), doi:10.1016/j.agwat.2008.05.009

increase in yield due to transpiration. A curvilinear relationship could not be fit to these data.

The change in Y_g:ET relationship for the crops in the Ulysses soil occurred at an predicted Y_g:ET knot point of 755 g m^{-2} and 476 mm, which was about 100 g m^{-2} and 50 mm smaller than that in the Pullman soil. At that point, the predicted relationship changed from Y_g = 1.78 ET − 95 g m^{-2} to Y_g = 0.8 ET + 379 g m^{-2}. The second line segment included the Y_g:ET relationships of the T-100 irrigation treatments and the 1998 T-50 irrigation treatment. Unlike the second line segment for the Pullman soil, the second line segment for the Ulysses soil indicated that grain yield continued to increase as ET increased by more than 100 g m^{-2} to a maximum of 868 g m^{-2}. However, the reduction in slope in the second line segment compared with that of the first line segment meant that soil water evaporation had most likely increased.

3.5. *Field water supply versus yield*

The beginning volumetric soil water contents (SWC_b) in 1998 (Table 2) were at DUL (Table 1) for the irrigation treatments in the Amarillo and Pullman soils, and about 76% of DUL for the treatments in the Ulysses soil. Using the ending soil water content (SWC_e in mm) of the T-0 treatment in 1999 (Table 2) as the lower limit of water use, the initial ASW to 2.2 m in 1998 averaged 325 mm for the crops in the Amarillo soil and 350 mm for the crops in the other two soils.

The volumetric water contents to 2.2 m in 1999 for the T-0, T-25, and T-50 irrigation treatments were about 0.04 m^3 m^{-3}, or 88 mm, smaller compared with those in 1998, providing about 239 mm of available soil water in the Amarillo soil, 249 mm in the Pullman soil, and 260 mm in the Ulysses soil. The T-100 irrigation treatment for the Amarillo soil in 1999 had an initial volumetric water content exceeding DUL, which later drained 27 mm from one replicate. The final soil water content measurement on DOY 273 showed that the lysimeters in the Amarillo T-100 irrigation treatment had water contents exceeding DUL at depths greater than 1.8 m. This excess did not drain due to a faulty drainage system which was later discovered. The initial soil water content for the T-100 irrigation treatment in the Pullman soil was only slightly larger than the other three irrigation treatments in 1999. While the T-100 irrigation treatment in the Ulysses soil in 1999 at 0.27 m^3 m^{-3} was 0.04 m^3 m^{-3} larger than the other three treatments, it was still smaller than the DUL of 0.36 m^3 m^{-3}.

Average irrigation application amounts for the T-25, T-50, and T-100 irrigation treatments were 147, 260, and 515 mm in 1998, and 130, 230, and 440 mm in 1999, respectively (Table 4). Averaged across soil type and including ASWP, this created a range in FWS from the T-0 irrigation treatment to the T-100 irrigation treatment of 348–854 mm in 1998, and 250–785 mm in 1999 (Table 5). The total FWS (FWS_t) in 1998 was 95 mm larger than that in 1999, when averaged across soil type and irrigation treatment.

For the crops in the Amarillo soil, the Y_g:FWS relationship could be analyzed using the data for both years (Fig. 5), unlike the Y_g:ET relationship which had significantly different intercepts for each year. But, like the Y_g:ET relationship, predicted yield increased linearly with FWS as Y_g = 0.77 FWS + 239 g m^{-2}.

The Y_g:FWS relationships for the crops in the Pullman and Ulysses soils were again analyzed using piecewise linear regression and included data for both years (Fig. 5). For the crops in the Pullman and Ulysses soil, the first line segment reflected the rapid yield increase between yields produced by ASWP only (T-0 irrigation treatment with ASWP ranging from 250 to 400 mm) and yields produced with the addition of the smallest irrigation applications (T-25 irrigation treatment of 147 mm in 1998 and 130 mm in 1999). Beyond the knot points, the second line segment defined the change from nearly complete to partial utilization of FWS as irrigation water supply increased FWS beyond that needed to meet ET demand (see ET in Table 4, FWS_e in Table 5 and Fig. 2). The slope of the second line segment represents the efficiency of additional irrigation for increasing yield beyond the knot point.

For the crops in the Pullman soil, the increase in yield with the relationship of Y_g = 1.43 FWS + 42 g m^{-2} in the first line segment was followed by a drop to Y_g = 0.39 FWS + 557 g m^{-2} in the second line segment. Beyond the predicted Y_g:FWS knot point of 748 g m^{-2} and 494 mm, the predicted yield increase for the crops in the Pullman soil by 20% to a maximum of 895 g m^{-2} would require almost 77% (380 mm) more in FWS.

Table 5 – Field water supply for the total growing season (FWS_t) and at the end of season (FWS_e) for the Amarillo, Pullman, and Ulysses soils

Trt., ET (%)	Amarillo		Pullman		Ulysses		All Soils	
	FWS_t (mm)	FWS_e (mm)	FWS_t (mm)	FWS_e (mm)	FWS_t (mm)	FWS_e (mm)	FWS_t (mm)	FWS_e (mm)
1998								
0	328 (±0)	18 (±18)	356 (±0)	56 (±22)	361 (±0.0)	44 (±49)	348 (±22)	39 (±33)
25	468 (±0)	34 (±19)	496 (±0)	68 (±38)	482 (±0.0)	25 (±5)	482 (±12)	43 (±29)
50	585 (±2)	115 (±50)	615 (±1)	129 (±12)	611 (±15)	120 (±43)	603 (±16)	122 (±34)
100	833 (±15)	239 (±4)	870 (±3)	237 (±19)	858 (±21)	222 (±33)	854 (±18)	233 (±21)
1999								
0	241 (±0)	0 (±5)	257 (±0)	−1 (±5)	253 (±0)	0 (±5)	250 (±7)	0 (±4)
25	371 (±0)	13 (±15)	387 (±0)	5 (±23)	383 (±0)	8 (±6)	380 (±7)	9 (±15)
50	488 (±34)	70 (±38)	482 (±5)	61 (±26)	502 (±24)	74 (±21)	491 (±23)	69 (±26)
100	814 (±54)	273 (±41)	751 (±19)	225 (±17)	791 (±36)	239 (±63)	785 (±44)	246 (±44)

Trt., irrigation treatment, consisting of 0, 25, 50, and 100% replacement of evapotranspiration (ET). Numbers in parentheses represent ±1 standard deviation.

Please cite this article in press as: Tolk, J.A., Howell, T.A., Field water supply:yield relationships of grain sorghum grown in three USA Southern Great Plains soils, Agric. Water Manage. (2008), doi:10.1016/j.agwat.2008.05.009

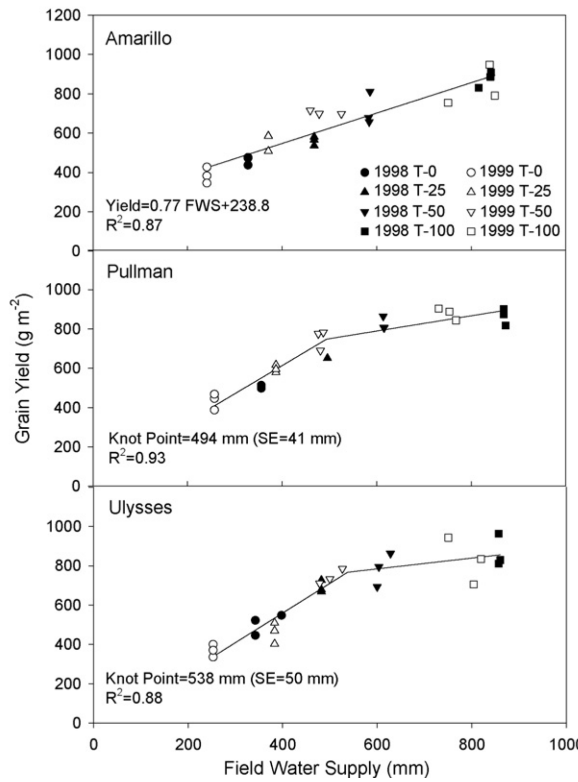

Fig. 5 – Grain yield as a function of field water supply (FWS) for each soil type for the four irrigation treatments of 0 (T-0), 25 (T-25), 50 (T-50), and 100% (T-100) replacement of ET. Standard errors (S.E.s) are given for the FWS knot points.

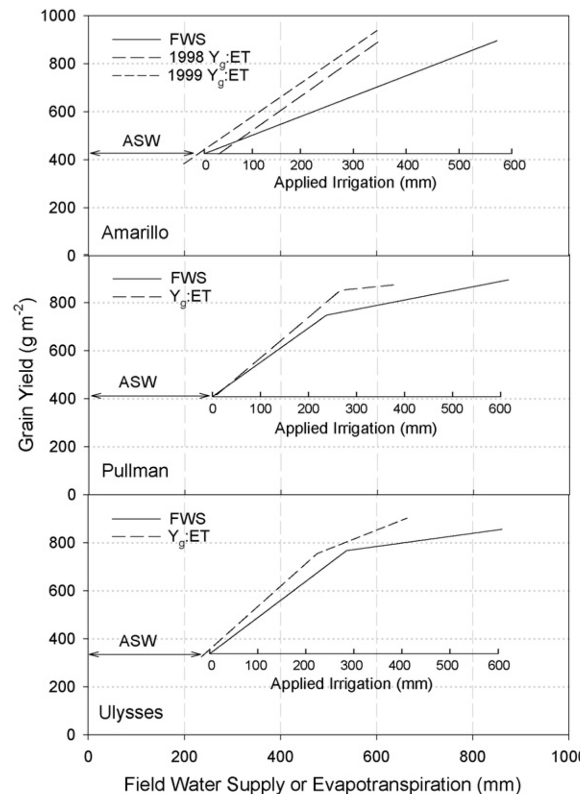

Fig. 6 – The relationships among available soil water (ASW), field water supply (FWS), evapotranspiration (ET), applied irrigation, and grain yield (Y) for each soil type.

For the crops in the Ulysses soil, the change in relationship from $Y_g = 1.51$ FWS – 43 g m^{-2} for the first line segment to $Y_g = 0.27$ FWS + 620 g m^{-2} for the second line segment beyond the predicted Y_g:FWS knot point of 767 g m^{-2} and 538 mm was similar to the response of the crops in the Pullman soil. Beyond the knot point, the predicted yield increase by 16% (126 g m^{-2}) to the maximum level of 895 g m^{-2} would require 62% (335 mm) more in FWS.

4. Discussion

Combining the predicted Y_g:ET and Y_g:FWS relationships with applied irrigation showed that, for the Amarillo soil, a progressively larger amount of FWS was not being used in ET throughout the entire range of irrigation (Fig. 6). In 1999, estimated ET for a 600 g m^{-2} in yield was 355 mm and estimated FWS was 468 mm, for a ET:FWS ratio of 0.76. An increase to 800 g m^{-2} in yield reduced the ratio to 0.69, with the estimated requirements being about 500 mm in ET and 727 mm of FWS. In general, both WP and IWP declined as irrigation increased.

Up to the Y_g:FWS knot points in the Pullman and Ulysses soils, the combined Y_g:ET and Y_g:FWS relationships predicted that most of the FWS was being used in ET. For example, the yield in the Pullman soil at the FWS knot point of 494 mm was 748 g m^{-2} and ET was 462 mm for a ET:FWS ratio of 0.94. Beyond the knot point in the Pullman soil, an increase to a near maximum grain yield of 850 g m^{-2} required an estimated 758 mm of FWS and 515 mm in ET, for a ET:FWS ratio of 0.68. The crops in the Ulysses soil had a similar response.

The data points for the Y_g:FWS and Y_g:ET ratios of the T-50 irrigation treatment tended to cluster about the knot points of those relationships in the Pullman and Ulysses soils (Fig. 6). In this experiment, the 1999 T-50 irrigation treatment in the Ulysses soil had both a large WP and IWP (Table 4). Of the 500 mm of FWS in this treatment (Table 5), irrigation contributed 230 mm, ASWP contributed about 200 mm, and about 70 mm remained in the soil at harvest. The large WP resulted from most of the FWS being used in ET, while a certain amount of ASW remained in the soil to prevent plant water stress (Stegman, 1983). The large IWP resulted from all of the irrigation application also being used in ET. For both soils, the FWS knot point, which was 494 mm in the Pullman soil and 538 mm in the Ulysses soil, was the point at which about 250 mm in ASWP had been utilized, irrigation applications averaged about 250 mm, and about 60–130 mm remained in the soil at harvest.

The Y_g:ET and Y_g:FWS data points for the T-100 irrigation treatment occurred beyond the knot points of those relationships in both years. The T-100 irrigation treatment was the full replacement of ET. In both years, the combination of the T-100 irrigation application amounts and ASWP which ranged from about 750 to 870 mm exceeded the maximum ET requirement of about 530–630 mm. Due to the ASWP, much of the T-100 irrigation application went into non-ET losses.

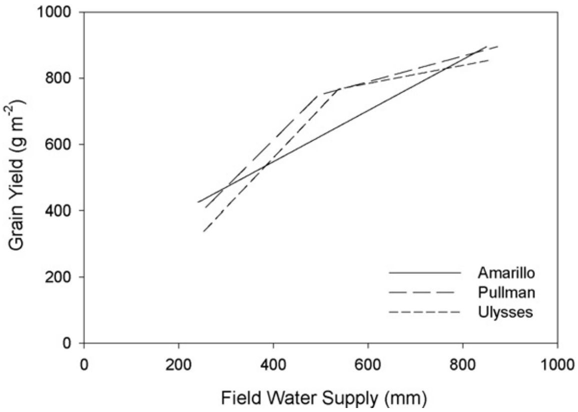

Fig. 7 – A comparison among soil types of the field water supply and grain yield relationship.

The piecewise Y_g:FWS relationships for the crops in the Pullman and Ulysses soils and the linear Y_g:FWS relationship for the crop in the Amarillo soil most likely was due to the differences among the soils' hydraulic characteristics. Grain yield tended to be similar among soil types at both the smallest and largest FWS (Fig. 7). However, Y_g of the crops in the Ulysses and Pullman soils tended to be larger compared with the Y_g of the crops in the Amarillo soil in the mid-range of FWS where the knot points of the Pullman and Ulysses soils occurred. The mid-range increases in Y_g of these two soils may be due to the differences in water-holding capacity between the finer-textured silts and clays of the Ulysses and Pullman soils compared with the sandy loam of the Amarillo soil. In the mid-range of FWS, the smaller pore spaces of the Ulysses and Pullman soils were better able to hold water and make it available for ET and yield production. The larger pore spaces of the Amarillo soil were unable to hold as much water for crop use. This soil hydraulic characteristic was less important at the largest irrigation application amounts, resulting in a similarity in yield among soil types.

5. Conclusions

Irrigating without regard to FWS resulted in large amounts of non-ET irrigation application losses in the finer-textured soils in the fully irrigated treatment, which was a weekly application of a 100% replacement of ET. In both years, the T-100 irrigation application amounts and ASWP resulted in a FWS ranging from about 750 to 870 mm which exceeded the maximum ET requirement of about 530–630 mm and reduced WP and IWP. Piecewise regression analysis of the Y_g:FWS and Y_g:ET relationships for the crops in the Pullman and Ulysses soils identified the point in the FWS where both WP and IWP tended to be optimized. This FWS knot point, which was 494 mm in the Pullman soil and 538 mm in the Ulysses soil, involved the utilization of about 250 mm in ASWP, irrigation applications averaging about 250 mm, and about 60–130 mm remaining in the soil at harvest. Beyond this point, a 60% or more increase in FWS due to the T-100 irrigation treatment in the Pullman and Ulysses soils increased yield only by about 20% or less. For the coarser-textured Amarillo soil, the yield response to increasing FWS was linear throughout the range of FWS, but non-ET application losses such as drainage gradually increased as the irrigation application amount increased. The linear Y_g response to FWS in the sandy Amarillo soil and the piecewise Y_g responses to FWS in the clay and silt loams of the Pullman and Ulysses soils also reflected the difference in water-holding capacities of the soils that would make water available to the crops as irrigation increased.

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. FAO Irrig. Drain Paper No. 56. 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.

Bos, M.G., 1985. Summary of ICID definitions of irrigation efficiency. ICID Bull. 34, 28–31.

Bouman, B.A.M., 2007. A conceptual framework for the improvement of crop water productivity at different spatial scales. Agric. Syst. 93, 43–60.

Cabelguenne, M., Debaeke, P., 1998. Experimental determination and modelling of the soil water extraction capacities of crops of maize, sunflower, soya bean, sorghum and wheat. Plant Soil 202, 175–192.

Doorenbos, J., Kassam, A.H., 1979. Yield response to water. FAO Irrigation and Drain., Paper 33. Rome, Italy, 193 pp.

Doorenbos, J., Pruitt, W.H., 1977. Crop water requirements. FAO Irrigation and Drain., Paper 24. Rome, Italy, 144 pp.

English, M.J., 1990. Deficit irrigation. I. Analytical framework. J. Irrig. Drain. Eng. 116 (3), 399–412.

English, M.J., Solomon, K.H., Hoffman, G.J., 2002. A paradigm shift in irrigation management. J. Irrig. Drain. Eng. 128 (5), 267–277.

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.

Farré, I., Faci, J.M., 2006. Comparative response of maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench) to deficit irrigation in a Mediterranean environment. Agric. Water Manage. 83, 135–143.

Fereres, E., Soriano, M.A., 2007. Deficit irrigation for reducing agricultural water use. J. Exp. Bot. 58 (2), 147–159.

Freese, F., 1964. Linear regression methods for forest research. USDA-FS Res. Pap. FPL 17. USDA-FS, U.S. Forest Products Lab., Madison, WI.

Grimes, D.W., Yamada, H., Dickens, W.L., 1969. Functions for cotton (*Gossypium hirsutum* L.) production from irrigation and nitrogen fertilization variables: 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.

Please cite this article in press as: Tolk, J.A., Howell, T.A., Field water supply:yield relationships of grain sorghum grown in three USA Southern Great Plains soils, Agric. Water Manage. (2008), doi:10.1016/j.agwat.2008.05.009

(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.
Hsiao, T.C., Steduto, P., Fereres, E., 2007. A systematic and quantitative approach to improve water use efficiency in agriculture. Irrig. Sci. 25, 209–231.
Kanemasu, E.T., Stone, L.R., Powers, W.L., 1976. Evapotranspiration model tested for soybean and sorghum. Agron. J. 68, 569–572.
Klute, A., 1986. Water retention: laboratory methods. In: Klute, A. (Ed.), Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods, 2nd ed. Agron. Monogr. 9, ASA and SSSA, Madison, WI, pp. 635–661.
Lamm, F.R., Rogers, D.H., Manges, H.L., 1994. Irrigation scheduling with planned soil water depletion. Trans. ASAE 37 (5), 1491–1497.
Lehane, J.J., Staple, W.J., 1960. Relationship of the permanent wilting percentage and the soil moisture content at harvest to the 15-atmosphere percentage. Can. J. Soil Sci. 40, 264–269.
Lima, M.M., Godoy, C., Avelar-Batista, J.C., Modenesi, P.J., 2003. Toughness evaluation of HVOF WC-Co coatings using non-linear regression analysis. Mater. Sci. Eng. 357 (1–2), 337–345.
Littell, R.C., Milliken, G.A., Stroup, W.W., Wolfinger, R.D., 1996. SAS System for Mixed Models. SAS Institute, Inc., Cary, NC.
Montgomery, D.C., Peck, E.A., Vining, G.G., 2006. Introduction to Linear Regression Analysis, 4th ed. Wiley and Sons, NY.
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 (3), 401–404 410.
Ratliff, L.F., Ritchie, J.T., Dassel, D.K., 1983. A survey of field-measured limits of soil water availability and related laboratory-measured properties. Soil Sci. Soc. Am. J. 47, 770–775.
Robertson, M.J., Fukai, S., 1994. Comparison of water extraction models for grain sorghum under continuous soil drying. Field Crops Res. 36, 145–160.
Rosenthal, W.D., Arkin, G.F., Shouse, P.J., Jordan, W.R., 1987. Water deficit effects on transpiration and leaf growth. Agron. J. 79, 1019–1026.
SAS Institute, Inc., 1985. SAS User's Guide: Statistics, 5th ed. SAS Institute, Inc., Cary, NC.
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. Irrig. 2, 1–30.
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.
Stewart, J.I., Hagan, R.M., 1973. Functions to predict effect of crop water deficits. J. Irrig. 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.
Stone, L.R., Schlegel, A.J., Khan, A.H., Klocke, N.L., Aiken, R.M., 2006. Water supply:yield relationships developed for study of water management. J. Nat. Resour. Life Sci. Educ. 35, 161–173.
Tolk, J.A., Howell, T.A., 2003. Water use efficiencies of grain sorghum grown in three USA Southern Great Plains soils. Agric. Water Manage. 59, 97–111.
Toms, J.D., Lesperance, M.L., 2003. Piecewise regression: a tool for identifying ecological thresholds. Ecology 84 (8), 2034–2041.
Vanderlip, R.L., Reeves, H.E., 1972. Growth stages of sorghum [*Sorghum bicolor*, (L.) Moench.] Agron. J. 64, 13–16.
Vaux Jr., H.J., Pruitt, W.O., 1983. Crop–water production functions. In: Hillel, D. (Ed.), Advances in Irrigation, vol. 2. Academic Press, NY, pp. 61–97.
Wallace, J.S., 2000. Increasing agricultural water use efficiency to meet future food production. Agric. Ecosyst., Environ. 82, 105–119.
Wang, H., Zhang, L., Dawes, W.R., Liu, C., 2001. Improving water use efficiency of irrigated crops in the North China Plain—measurements and modeling. Agric. Water Manage. 48, 151–167.
Wright, G.C., Smith, R.C.G., 1983. Differences between two grain sorghum genotypes in adaptation to drought stress II. Root water uptake and water use. Aust. J. Agric. Res. 34, 627–636.
Zhang, Y., Kendy, E., Qiang, Y., Changming, L., Yanjun, S., Hongyong, S., 2004. Effect of soil water deficit on evapotranspiration, crop yield, and water use efficiency in the North China Plain. Agric. Water Manage. 64, 107–122.
Zwart, S.J., Bastiaanssen, W.G.M., 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton, and maize. Agric. Water Manage. 69, 115–133.

Please cite this article in press as: Tolk, J.A., Howell, T.A., Field water supply:yield relationships of grain sorghum grown in three USA Southern Great Plains soils, Agric. Water Manage. (2008), doi:10.1016/j.agwat.2008.05.009