SORGHUM YIELD RESPONSE TO DEFICIT IRRIGATION

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ABSTRACT. *Because dwindling water supplies are limiting crop production, a field study was conducted during 2005-2009 in southwest Kansas to determine the yield response of grain sorghum to irrigation and evapotranspiration (ET_c) and to measure plant growth parameters and soil water use. Sorghum was grown in a five-year rotation of corn-corn-wheat-sorghum-sunflower. Six irrigation treatments were imposed by applying 25 mm of irrigation every 6 to 26 days. Wheat stubble covered 59% to 68% of the soil surface soon after sorghum planting. Sorghum growth stages were not affected by irrigation treatments except maturity in the drier treatments. The soil retained nearly the same amount of dormant season precipitation across all irrigation treatments (34% to 41%), but the sorghum receiving the least irrigation was able to use 56 mm more stored soil water during the following growing season than in the fully irrigated treatment. Grain yield (GY) and total dry matter (DM) decreased significantly as irrigation decreased, but the GY and DM produced by the least irrigation were 91% and 89% of the full irrigation, respectively. Crop evapotranspiration (ET_c) decreased significantly (from 527 to 459 mm) as irrigation decreased. Because measured ET_c for the driest treatment was 87% of fully irrigated ET_c, a linear regression of GY data with respect to ET_c was not realistic until threshold values of ET_c (ET_c required to produce the first increment of grain) from prior field research were added to the data set. GY increased linearly with added irrigation, which was not expected because yield usually responds to irrigation in a diminishing-return fashion. In this case, sorghum, traditionally a dryland crop in the region, was able to utilize stored soil water following wheat to compensate for less irrigation. Small year-to-year variation in GY across irrigation treatments indicates that sorghum would be a good crop when water is very limited and would reduce potential income risk among years. Sorghum planted in part of an irrigated field would allow more water to be applied to a companion crop, such as corn, which needs more water but has more income potential.*

Keywords. *Deficit irrigation, Irrigation, Irrigation management, Limited irrigation, Sorghum.*

Water supplies for irrigation are decreasing in the U.S. Great Plains and in many other regions of the world. Water supplies can become limited when groundwater resources dwindle and cause reduced irrigation or when public water policy imposes constraints on the water resource. Irrigation management must respond to limited water supplies by producing the best long-term economic return per unit of water (English, 2002). Irrigators can respond to limited water supplies by (1) reducing water applications to the same crop and incurring water deficits during all or part of the growing season, (2) growing crops that match the water supply, (3) growing the same crop on a reduced area in combination with irrigated crops that have smaller water use requirements, or (4) reducing the irrigated area and substituting dryland crops or fallow periods (Martin et al., 1989; Klocke et al., 2006). Evaluating alternative cropping decisions starts with predictions of crop yields in response to irrigation amounts. Yields and commodity prices are then used to calculate gross income. Economic returns are calculated from gross income, production costs, and fixed costs.

Crop yield response to irrigation has been measured since the early years of agricultural research (Wagner, 1921). Field research on this topic has continued because irrigation systems, management techniques, and crop genetics have improved. As early as the late 1950s, field research was conducted across the U.S. Great Plains to develop production functions (yield versus irrigation and yield versus ET_c) for sorghum. Musick and Sletten (1966) measured sorghum yield response to irrigation applied through gated pipes and furrows near Garden City, Kansas, and Bushland, Texas (Garden City is 370 km north of Bushland). Four irrigation events were executed in both locations. Yields from one irrigation event were 80% of full yields in Garden City but 50% of full yields in Bushland. The researchers attributed the yield response differences to the differences in the soils, a clay loam in Bushland and a silt loam in Garden City. Growing season precipitation was nearly the same at the two locations, but the evaporative demand (reference ET) may have been quite different (data not reported). Stewart and Steiner (1990) reported on ten studies in Texas, California, Israel, and India conducted in the 1970s and 1980s. The combined data produced a linear sorghum

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yield response to crop evapotranspiration (ET_c): yield = $0.0015(ET_c) - 0.141$, with $R^2 = 0.71$, where yield is in units of kg m^{-2}, and ET_c is in units of mm. Between 1989 and 2002, four field studies were conducted in the northern High Plains of Texas, located 370 to 500 km south of Garden City, Kansas (Allen and Musick, 1993; Schneider and Howell, 1995; Bordovsky and Lyle, 1996; Colaizzi et al., 2004). A variety of irrigation and tillage management strategies were used, including sprinkler irrigation in clean tillage, in-canopy sprinkler irrigation with furrow dikes, every-row irrigation into small basins (low-energy precision application, or LEPA) with no residue coverage, and graded furrows with clean tillage. Average annual precipitation during the Texas studies was similar to Garden City's precipitation because precipitation increases from west to east rather than north to south across the Great Plains. The yield-ET_c relationship followed a linear model, but the yield response to irrigation was curvilinear, and year-to-year variability in yield increased as irrigation decreased.

Yield response to irrigation can be location-specific and can vary by year due to differences in precipitation amounts and timing, stored soil water, and evaporative demand. Garrity et al. (1982) conducted a field study in west-central Nebraska and found that sorghum had a nearly linear response to ET_c, but the timing of irrigation was important because sorghum yields varied due to water stress during different growth stages, and over-irrigation caused yield decreases.

Testing and validation of crop production models need data that include environmental, crop production, and soil water parameters (Klocke et al., 2010). Yield responses to irrigation are needed for management decisions, including crop selections and irrigation allocations to each crop (Klocke et al., 2006). In this study, grain sorghum was grown with no-tillage practices and non-limiting practices for weed and insect control. Six irrigation treatments from full to deficit irrigation were imposed. The objectives of this study were to: (1) measure reference (ET_r), precipitation, irrigation, plant population, grain and dry matter yield, crop growth stages, biweekly soil water, and crop residue from the previous crop; (2) derive ET_c, yield response to ET_c and irrigation, harvest index, soil water accumulation during the prior dormant season, stored soil water use during the growing season, fallow efficiency, and drainage; and (3) compare yield-ET_c and yield-irrigation results with those from the northern High Plains of Texas.

METHODS

LOCATION AND SOILS

This research was conducted at the Kansas State University Southwest Research-Extension Center near Garden City, Kansas. The soil type was a Ulysses silt loam (fine-silty, mixed, mesic Aridic Haplustoll) with pH of 8.3 and organic matter content of 1.5%. The soil had an available water capacity of 0.18 m m^{-1} between field capacity (volumetric water content of 33%) and permanent wilting (volumetric water content of 15%). The climate is semi-arid with long-term average annual precipitation of 477 mm, mean temperature of 12°C, open-pan evaporation (April to September) of 1810 mm, and a frost-free period of 170 days. During the study, average annual precipitation was 495 mm and reference ET (ET_r) was 1537 mm, calculated with a Penman combination equation (Kincaid and Heermann, 1974; Lamm et al., 1994).

CROPPING SYSTEM AND IRRIGATION PROTOCOL

Sorghum was grown in a five-year rotation of corn-corn-wheat-sorghum-sunflower during 2005-2009. All crops were planted in 2004, and the irrigation treatments were imposed that year. Therefore, all crops were in rotation in 2005, and the starting soil water content included the effects of the irrigation variable from the 2004 crop. Each crop was present every year in five cropping blocks, which were replicated over the five years. As each crop in the rotation moved from one crop block to the next, the irrigation treatments remained in the same physical location, so dry treatments followed dry treatments and wet treatments followed wet treatments. The prior year's irrigation treatment effects carried over to the same irrigation treatment in the following year.

A commercial four-span (44 m span width) linear-move sprinkler system (model 8000, Valmont Corp., Valley, Neb.) was modified to deliver water in any combination of irrigation treatments (Klocke et al., 2003). The irrigation plots were 13.7 m wide and 27.4 m long. Net application depth, i.e., the water reaching the soil surface, was 25 mm for every irrigation event on all treatments. The net application depth was confirmed with a catch-can test. High through low water treatments were replicated four times. Target application depths for the growing season across the six treatments were 100%, 80%, 70%, 50%, 40%, and 25% of full irrigation; however, the irrigation variable was achieved by increasing the number of days between irrigation events rather than applying a percentage of full irrigation during each irrigation event. With each pass of the irrigation system, an irrigation treatment was irrigated or not irrigated to achieve the irrigation variable, which was intended to simulate differences in irrigation system capacity to deliver water using a constant irrigation amount per event. A non-irrigated treatment was not included because continuous cropping from one season to the next would not be sustainable. Seasonal application depths for treatment 1, the wettest treatment, were scheduled for non-limited conditions when no more than 50% of the available soil water was depleted in the top 1.2 m of soil. Irrigation frequencies for treatments 2 through 6 increased or decreased from year to year, so all treatments received more water in years with low precipitation and less water in years with high precipitation. Thus, the irrigation amount varied from year to year due to differences in precipitation. If rainfall was sufficient to fill the soil profile in treatment 1 to field capacity, then water was not applied.

The irrigation treatment protocol was designed to include operational constraints of commercial center-pivot irrigation systems in the Great Plains region, where system pumping capacities limit the frequency of irrigation events. No more than two irrigation events per week were applied

Table 1. Dates of field operations for no-till management with non-limiting nutrient, weed, and insect management.

Field Operation	2005	2006	2007	2008	2009
Fertilize (starter, (10-34-0)[a]	20 May	22 May	23 May	19 May	-
Fertilize (side dress, 32-0-0)[a]	27 June	21 June	3 July	18 June	18 June
Pre-emergence herbicide	5 May	23 May	23 May	19 May	20 May
Planting date	20 May	22 May	23 May	19 May	20 May
Post-emergence herbicide	29 June	6 June	-	6 June	8 June
Foliar spray (iron chelate)	15 July	26 June	22 June	18 June	-
Harvest date	5 Oct.	16 Oct.	12 Oct.	28 Oct.	15 Oct.

[a] Percentage of nitrogen-phosphorous-potassium in fertilizer product.

to simulate pumping capacity limitations of common commercial systems (7.1 mm d^{-1}).

Cultural Practices

Cultural practices, hybrid selections, planting techniques, and fertilizer and herbicide applications were the same across irrigation treatments and followed the requirements of no-till management (table 1). Pre-emergence and post-emergence herbicides were applied as needed on a zero-tolerance weed threshold basis. Sorghum was seeded into wheat stubble with a no-till planter. The planter was equipped with a single smooth coulter preceding a double-disk furrow opener and two rubber-tired closing wheels mounted in a V configuration. Seeded plant population was 260,000 plants ha^{-1} across all irrigation treatments (Roozenboom and Fjell, 1998). Fertilizers were applied at uniform rates across all irrigation treatments for non-limited crop production. Because grain and dry matter production increased with the amount of irrigation (data shown later), nitrogen accumulated in the soil in the reduced irrigation treatments (data not collected). Liquid starter fertilizer was delivered directly to the seed furrow at a rate that did not affect emergence. Liquid fertilizer was also applied later in a stream directly behind the coulter just below the soil surface between every other pair of crop rows. Iron chelate was sprayed as needed on the foliage during vegetative growth to counteract the effects of chlorosis resulting from the soil pH of 8.3 at the study sites.

Crop Measurements

Crop residue coverage from the previous crop was measured shortly after planting using the line-transect method described by Dickey et al. (1986). Growth stages were recorded from field observations during the growing season. Vegetative growth stages were delineated by the number of fully extended leaves. Biomass was harvested from one 3 m long row during the growth stage when the forage normally would be harvested for silage. The driest irrigation treatment was harvested first, followed by the wetter treatments as each treatment reached 14.2% grain moisture, which typically spread harvest over one week. Grain yield (GY) was measured by hand-harvesting two adjacent 3 m rows that were protected from bird damage with a netted structure placed in the field before seed set.

Soil Water and Evapotranspiration

Volumetric soil water content was measured biweekly to a depth of 2.4 m in 0.3 m increments with neutron attenuation techniques (Evett and Steiner, 1995). Drainage was calculated with a Wilcox-type equation (Miller and Aarstad, 1972) that was locally calibrated:

$$dW/dT = 40.1(W/920)^{23.94} \quad (1)$$

where W is total soil water in the 2.4 m profile (mm), and dW/dT is drainage rate (mm d^{-1}).

The change in soil water from the start to the end of the sampling period, rainfall, net irrigation, and estimates of drainage were used in a water balance to calculate crop evapotranspiration (ET_c):

$$ET_c = NI + P - R - (SW2 - SW1) - D \quad (2)$$

where

NI = net irrigation (water infiltrated) during the sampling period

P = precipitation during the sampling period

R = runoff or runon during the sampling period (observed to be negligible)

D = drainage during the sampling period

$SW2$ = total soil water at the end of the sampling period

$SW1$ = total soil water at the beginning of the sampling period.

ET_c was calculated for the days between plant emergence and the first soil water measurement with a crop simulation model (Klocke et al., 2010). ET_r was calculated with an alfalfa-referenced modified Penman model (Kincaid and Heermann, 1974; Lamm et al., 1994) using weather factors including maximum and minimum air temperature, relative humidity, solar radiation, and wind run (wind speed × time) from an automated weather station near the study site.

Data from individual treatment replications were averaged over years and were subjected to an analysis of variance. Means were separated by Fisher's protected significant differences at 5% probability (SAS, 2006).

Results

Reference ET and Precipitation

Annual ET_r was lowest in 2009 (1362 mm) and highest in 2006 (1773 mm). The pattern of above- and below-average monthly ET_r varied from year to year (table 2 and fig. 1). Annual precipitation was lowest in 2008 (440 mm) and highest in 2006 (579 mm) (table 3). As with ET_r, monthly precipitation patterns also varied from year to year (fig. 2). However, 2006 was the only year when annual ET_r correlated with annual precipitation, when both were the highest of the five years; otherwise, ET_r and precipitation did not track with one another. Dormant season precipitation between harvest of the prior crop and planting (previous October through April) and growing season precipitation (May through September) were the components of

Table 2. Monthly reference ET (mm) for alfalfa for 2005-2009 (above-average amounts are underlined).

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
2004	53	64	142	137	251	222	209	167	178	84	37	44	1590
2005	32	42	103	144	196	235	269	187	191	115	82	44	1639
2006	76	83	140	211	222	281	255	172	142	91	61	39	1773
2007	15	29	91	106	175	178	215	216	164	136	79	24	1429
2008	42	53	109	143	182	213	233	160	138	90	65	56	1483
2009	74	85	121	116	157	178	192	185	110	62	51	32	1362
2005-2009 avg.	48	58	113	144	187	217	233	184	149	99	68	39	1537

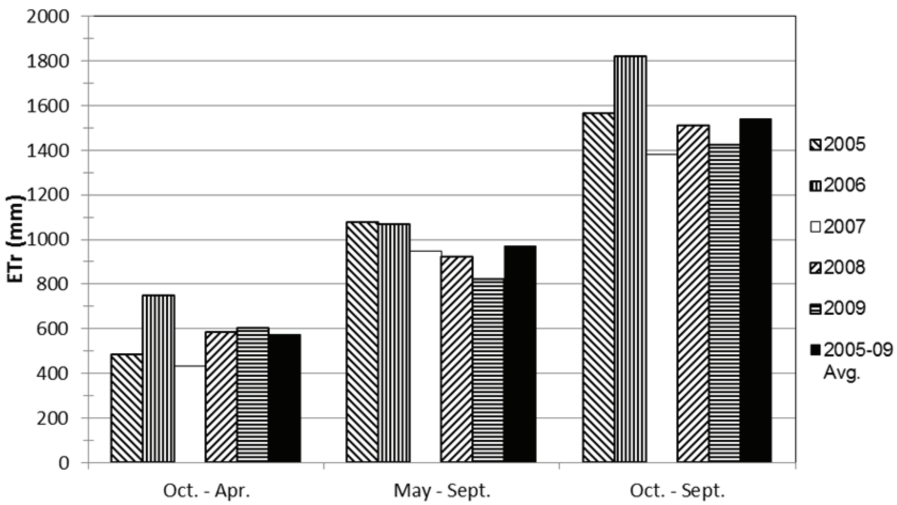

Figure 1. Prior non-growing season (Oct.-Apr.), growing-season (May-Sept.), and cropping-season (Oct.-Sept.) reference ET (ET_r).

Table 3. Monthly precipitation (mm) for 2005-2009 (above-average amounts are underlined).

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
2005	15	22	11	26	71	80	89	43	24	71	3	5	461
2006	7	0	37	19	64	59	119	65	23	58	2	126	579
2007	15	16	44	74	30	64	42	67	53	6	3	34	447
2008	8	14	7	42	49	79	31	64	18	119	9	1	440
2009	2	2	29	111	47	94	80	56	40	75	10	5	551
2005-2009 avg.	9	11	26	54	52	75	72	59	32	66	5	34	495
1971-2000 avg.	11	12	35	42	86	73	66	65	32	23	22	10	477

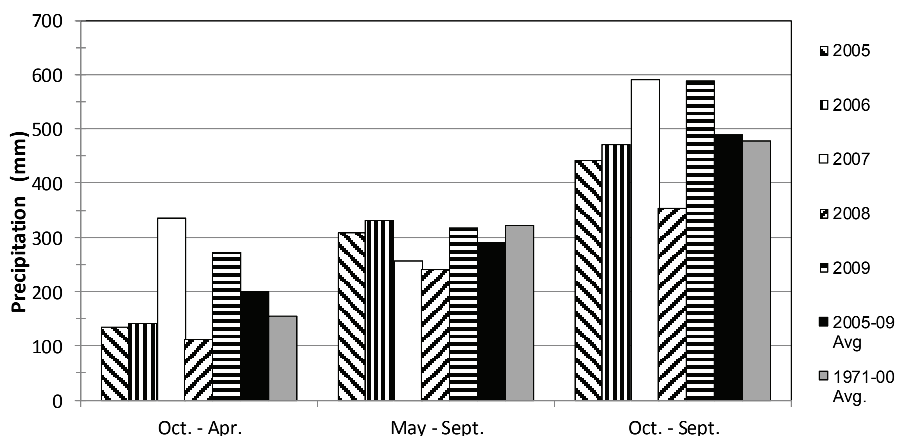

Figure 2. Non-growing season (Oct.-Apr.), growing-season (May-Sept.), and cropping-season (Oct.-Sept.) precipitation.

cropping season precipitation that contributed to crop water needs. Dormant season precipitation contributed to soil water storage for crop use during the following year, growing season precipitation contributed directly to crop water needs, and cropping season precipitation was the total amount potentially available to the crop. Year-to-year variations in growing season precipitation did not necessarily follow the same patterns as dormant season precipitation.

Irrigation and Growth Stages

Irrigation amounts varied from year to year due to fluctuations in precipitation because fully irrigated plots (treatment 1) received enough water to keep available soil water content less than 50% depleted (table 4). Deficit irrigation (treatments 2 through 6) also varied from year to year, but the goal was to maintain the same percentage of full irrigation across years by increasing or decreasing the time between irrigation events.

Growth stages were consistent across irrigation treatments for all years except irrigation treatments 4, 5, and 6, where the crop reached maturity seven days later than the other irrigation treatments in 2008, and treatments 5 and 6, where the crop reached maturity seven days earlier in 2009 (table 5). Seeded population was the same in all irrigation treatments (26 plants m^{-2}), but there were significant differences in final population, measured at grain harvest, although there was no clear trend across irrigation treatments (table 6). There was one head per plant across all irrigation treatments.

Grain and Dry Matter Yields

When averaged over the five years, winter wheat stubble dry matter production ranged from 0.83 kg m^{-2} in treatment 1 to 0.59 kg m^{-2} in treatment 6 during the year prior to sorghum (table 6). Wheat residue coverage measurements were taken after the sorghum was seeded with a no-till planter, which disturbed some residue. Wheat stubble coverage on the soil surface ranged from 59% to 68% across irrigation treatments, but no clear trend emerged from irrigation treatments 1 through 6. Even though wheat stubble production differed significantly, the differences were more muted in the remaining residue after sorghum was planted.

GY and DM production decreased significantly as irrigation decreased. There were significant differences between treatments 1 and treatments 5 and 6, but differences among the intermediate irrigation treatments overlapped. Relative GY and DM (irrigation treatment yield/fully irrigated yield) were nearly the same at each level of irrigation. Relative GY decreased 9% from treatment 1 to treatment 6, and relative DM decreased 12%. Harvest index (GY/DM) was the same among irrigation treatments, so the pattern of significant differences in GY and DM among irrigation treatments was the same.

Table 4. Growing season irrigation start and end dates, irrigation frequency, and total irrigation.

Irrigation Treatment	Start Date	End Date	Irrigation Frequency (days)	Total Irrigation (mm)	% of Full Irrigation
2005					
1	22 July	26 Aug.	4.4	200	100
2	22 July	26 Aug.	5.0	175	88
3	22 July	26 Aug.	5.8	150	75
4	22 July	12 Aug.	8.8	100	50
5	22 July	12 Aug.	11.7	75	38
6	22 July	22 July	-	25	13
2006					
1	20 July	29 Aug.	5.0	200	100
2	20 July	29 Aug.	5.7	175	88
3	20 July	29 Aug.	6.7	150	75
4	24 July	29 Aug.	8.0	125	63
5	24 July	29 Aug.	10.0	100	50
6	24 July	29 Aug.	13.3	75	38
2007					
1	23 July	20 Aug.	4.7	150	100
2	23 July	20 Aug.	5.6	125	83
3	26 July	20 Aug.	7.0	100	67
4	26 July	20 Aug.	9.3	75	50
5	30 July	20 Aug.	14.0	50	33
6	30 July	30 July	-	25	17
2008					
1	22 July	3 Sept.	5.3	200	100
2	22 July	3 Sept.	7.0	150	75
3	24 July	3 Sept.	8.4	127	64
4	24 July	3 Sept.	10.5	100	50
5	28 July	14 Aug.	14.0	75	38
6	28 July	14 Aug.	21.0	50	25
2009					
1	24 July	26 Aug.	8.3	100	100
2	24 July	26 Aug.	11.0	75	75
3	11 Aug.	14 Aug.	16.5	50	50
4	11 Aug.	26 Aug.	16.5	50	50
5	14 Aug.	14 Aug.	-	25	25
6	14 Aug.	14 Aug.	-	25	25

Yield Response to Evapotranspiration and Irrigation

Crop evapotranspiration (ET$_c$) decreased significantly, from 527 to 459 mm, as the amount of irrigation decreased (table 7). Likewise, the ratio of ET$_c$ and ET$_r$ decreased, from 0.66 to 0.58, with decreasing amounts of irrigation. Yield results from each irrigation treatment averaged over replications for each year (30 data points) were used for a regression of GY with respect to ET$_c$ (fig. 3). GY increased from 0.70 to 0.77 kg m^{-2} as ET$_c$ increased from 459 to 527 mm of ET$_c$. Because the data represented a narrow range of ET$_c$, threshold ET$_c$ values, i.e., the amount of ET$_c$ needed to produce the first increment of grain, were not available. Stone and Schlegel (2006) found an ET$_c$ threshold value of 150 mm for no-tillage and 100 mm for conventional tillage. By adding a threshold value of 150 mm to the data, a linear regression of GY with respect to ET$_c$ produced an R^2 value of 0.69. Data points within each year clustered with one another, which demonstrated that weather and distribution of precipitation events affected the crop differently from year to year. Data points for 2008 with the least annual precipitation fell below the regressed line, but the data points for 2005 with above-average ET$_r$ also fell below the line. It is difficult to explain the differences in yield responses to ET$_c$ among years, but differences in evaporative demand and rainfall patterns among years may have been in play.

Gomez and Gomez (1984) suggested that treatment means averaged over replications are more appropriate for regressions of independent and dependent variables. When GY data were averaged for each irrigation treatment replication and over all replicated years, six data points were generated. Adding the threshold value of 150 mm produced the same regression with an R^2 value of 0.99.

Relative GY was calculated for each irrigation treatment based on that year's yield from treatment 1, and relative irrigation was calculated in the same manner. Relative GY was regressed with relative irrigation using a linear model (fig. 4). Usually, yield responds to irrigation in a curvilinear

Table 5. Growth stage dates.

Year	Growth Stage	Irrigation Treatment 1	2	3	4	5	6
2005	Planted	20 May	20 May	20 May	20 May	20 May	20 May
	Emerged	6 June	6 June	6 June	6 June	6 June	6 June
	V 5	21 June	21 June	21 June	21 June	21 June	21 June
	Boot	5 Aug.	5 Aug.	5 Aug.	5 Aug.	5 Aug.	5 Aug.
	Headed	8 Aug.	8 Aug.	8 Aug.	8 Aug.	8 Aug.	8 Aug.
	Pollinating	15 Aug.	15 Aug.	15 Aug.	15 Aug.	15 Aug.	15 Aug.
	Mature	22 Sept.	22 Sept.	22 Sept.	22 Sept.	22 Sept.	22 Sept.
2006	Planted	22 May	22 May	22 May	22 May	22 May	22 May
	Emerged	31 May	31 May	31 May	31 May	31 May	31 May
	V 5	-	-	-	-	-	-
	Boot	24 July	24 July	24 July	24 July	24 July	24 July
	Headed	31 July	31 July	31 July	31 July	31 July	31 July
	Pollinating	3 Aug.	3 Aug.	3 Aug.	3 Aug.	3 Aug.	3 Aug.
	Mature	3 Oct.	3 Oct.	3 Oct.	3 Oct.	3 Oct.	3 Oct.
2007	Planted	23 May	23 May	23 May	23 May	23 May	23 May
	Emerged	4 June	4 June	4 June	4 June	4 June	4 June
	V 4	29 May	29 May	29 May	29 May	29 May	29 May
	Boot	-	-	-	-	-	-
	Headed	1 Aug.	1 Aug.	1 Aug.	1 Aug.	1 Aug.	1 Aug.
	Pollinating	3 Aug.	3 Aug.	3 Aug.	3 Aug.	3 Aug.	3 Aug.
	Mature	5 Oct.	5 Oct.	5 Oct.	5 Oct.	5 Oct.	5 Oct.
2008	Planted	19 May	19 May	19 May	19 May	19 May	19 May
	Emerged	9 June	9 June	9 June	9 June	9 June	9 June
	V 4	19 June	19 June	19 June	19 June	19 June	19 June
	Boot	-	-	-	-	-	-
	Headed	11 Aug.	11 Aug.	11 Aug.	11 Aug.	11 Aug.	11 Aug.
	Pollinating	19 Aug.	19 Aug.	19 Aug.	19 Aug.	19 Aug.	19 Aug.
	Mature	13 Oct.	13 Oct.	13 Oct.	20 Oct.	20 Oct.	20 Oct.
2009	Planted	20 May	20 May	20 May	20 May	20 May	20 May
	Emerged	5 June	5 June	5 June	5 June	5 June	5 June
	V 4	22 June	22 June	22 June	22 June	22 June	22 June
	Boot	24 July	24 July	24 July	24 July	24 July	24 July
	Headed	3 Aug.	3 Aug.	3 Aug.	3 Aug.	3 Aug.	3 Aug.
	Pollinating	13 Aug.	13 Aug.	13 Aug.	13 Aug.	13 Aug.	13 Aug.
	Mature	7 Oct.	7 Oct.	7 Oct.	7 Oct.	30 Sept.	30 Sept.
Average 2005-2009	Planted	21 May	21 May	21 May	21 May	21 May	21 May
	Emerged	5 June	5 June	5 June	5 June	5 June	5 June
	V 4	14 Sept.	14 Sept.	14 Sept.	14 Sept.	14 Sept.	14 Sept.
	Boot	28 Mar.	28 Mar.	28 Mar.	28 Mar.	28 Mar.	28 Mar.
	Headed	5 Aug.	5 Aug.	5 Aug.	5 Aug.	5 Aug.	5 Aug.
	Pollinating	11 Aug.	11 Aug.	11 Aug.	11 Aug.	11 Aug.	11 Aug.
	Mature	4 Oct.	4 Oct.	4 Oct.	5 Oct.	4 Oct.	4 Oct.

Table 6. Population, yields, harvest index, and crop residue from previous crop and by irrigation treatment.[a]

Irrigation Treatment	Residue Coverage (%)	Final Population (plants m^{-2})	Grain Yield (kg m^{-2})	Relative Grain Yield (%)	Total Dry Matter (kg m^{-2})	Relative Dry Matter (%)	Harvest Index
1	65	19.6 bc	0.77 a	100	1.56 a	100	0.50 a
2	68	20.3 ab	0.75 ab	97	1.51 ab	97	0.51 a
3	67	20.8 a	0.76 ab	99	1.54 ab	99	0.49 a
4	62	19.6 bc	0.72 bc	94	1.44 bc	92	0.50 a
5	59	19.1 c	0.70 c	91	1.39 c	89	0.51 a
6	61	18.9 c	0.70 c	91	1.37 c	88	0.51 a
$LSD_{0.05}$	5	1.1	0.04		0.1		

[a] Values in the same column followed by the same letter are not significantly different for p = 0.05.

fashion, which shows diminishing returns of yield as irrigation increases. There was some indication of year-to-year yield variability by the vertical scatter of the data points from the regression, which increased as irrigation decreased. However, this variation was much smaller than the results for corn in the same field study (Klocke et al., 2011).

Table 7. Evapotranspiration by irrigation treatment.[a]

Irrigation Treatment	ET_c (mm)	ET_r (mm)	ET_c/ET_r
1	527 a	794	0.66
2	504 b	794	0.63
3	501 b	794	0.63
4	484 c	794	0.61
5	468 d	794	0.59
6	459 d	794	0.58
$LSD_{0.05}$	11		

[a] Values in the same column followed by the same letter are not significantly different for p = 0.05.

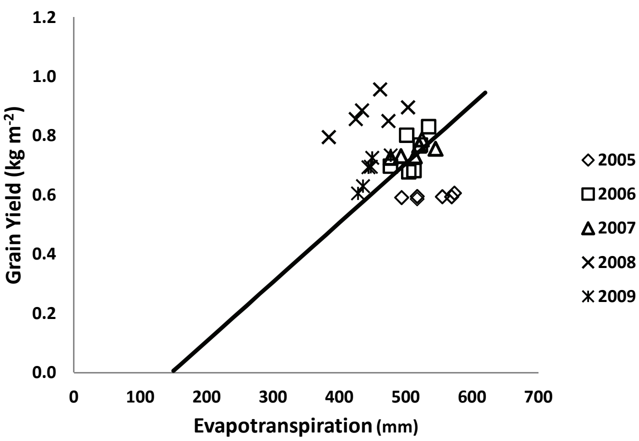

Figure 3. Sorghum grain yield vs. evapotranspiration for each irrigation treatment for all years at Garden City, Kansas (2005-2009) with threshold ET = 150 mm: GY – 0.0021(ET$_c$) – 0.29, with R^2 = 0.69.

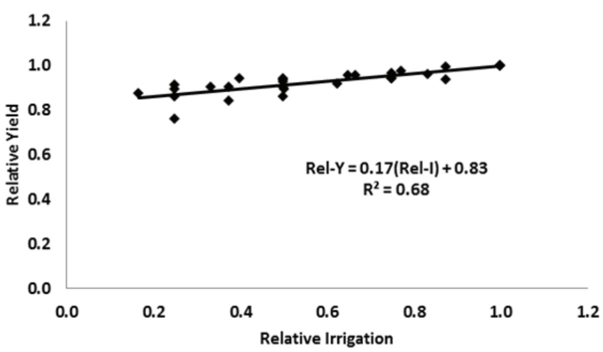

Figure 4. Relative grain yield vs. relative irrigation at Garden City, Kansas (2005-2009).

STORED SOIL WATER GAIN AND USE

Because the same irrigation treatment was applied in the same plot location for all years, soil water content at the end of the previous growing season influenced the next year's starting soil water content (table 8). Available soil water content (ASW) at the end of the previous growing season decreased significantly from 34.3% for treatment 1 to 29.6% for treatment 3, which was significantly different from treatments 4 through 6. Based on changes in soil water from the beginning to the ending of the growing season 2.4 m below the soil surface, the crop extracted more water from deeper in the profile in the drier treatments (data not shown). Soil water content increased during the dormant season (SW gain) for each irrigation treatment, but the gain in stored water was nearly the same, indicating that there were small or offsetting differences, if any, in soil water evaporation and drainage during that time period. ASW at the end of the current growing season decreased significantly from 52% for treatment 1 to 26% for treatment 6. The crop used significantly more water that accumulated during the dormant season, which contributed to ET$_c$ as irrigation decreased. The extra 56 mm of water use by treatment 6 translated into a GY difference of 0.07 kg m^{-2}, which contributed to narrowing the yield difference between those treatments. Fallow efficiency, derived as the ratio of soil water gain and precipitation during the dormant season, was the same across irrigation treatments because soil water gain was the same.

YIELD RESPONSE TO EVAPOTRANSPIRATION AND IRRIGATION IN TEXAS

During the period between 1989 and 2002, four field studies with 11 site-years of data were conducted in the northern and central High Plains of Texas located 370 to 500 km south of Garden City, Kansas (Allen and Musick, 1993; Schneider and Howell, 1995; Bordovsky and Lyle, 1996; Colaizzi et al., 2004). GY in response to ET$_c$ was recorded over the entire range of ET$_c$ values (fig. 5), whereas ET$_c$ data recorded at Garden City tended to be near maximum ET$_c$. Maximum yields were 0.2 kg m^{-2} more in Texas than at Garden City; likewise, ET$_c$ was 260 mm more in Texas than at Garden City. Of the 260 mm, 220 mm went to produce extra yield, leaving a net difference of 40 mm. The threshold ET$_c$ value was 106 mm, which corresponded to the value that Stone and Schlegel (2006) reported for conventional tillage. Stewart and Steiner (1990) summarized results from worldwide studies in the 1970s and 1980s and found that the slope of the yield-ET$_c$ function for sorghum grain was 1.5 kg m^{-3}. The slope was 1.7 kg m^{-3} from the studies conducted in Texas during the 1990s, while the Garden City study produced a slope of

Table 8. Available soil water content (ASW), soil water gain, fallow efficiency, soil water use, and drainage. Soil water measurements were taken to a depth of 2.4 m.[a]

Irrigation Treatment	Previous End ASW[b] (%)	Beginning ASW[c] (%)	Current End ASW[d] (%)	SW Gain[e] (mm)	Fallow Efficiency[f] (%)	SW Use[g] (mm)	Drainage[h] (mm)
1	34.3 a	81.3 a	52.1 a	203 a	38	127 d	4 a
2	32.9 ab	75.0 b	44.2 b	182 b	34	133 d	2.2 b
3	29.6 b	76.6 b	40.7 b	203 ab	38	155 c	1.6 bc
4	22.9 c	73.1 bc	35.4 c	217 a	41	163 bc	1.1 cd
5	22.0 c	69.4 cd	29.4 d	204 a	39	173 b	0.5 d
6	21.3 c	68.3 d	25.7 d	203 a	38	183 a	0.8 d
$LSD_{0.05}$	4.2	4.2	4.2	21	4	11	0.8

[a] Values in the same column followed by the same letter are not significantly different for p = 0.05.
[b] ASW at the end of the growing season of the previous crop.
[c] ASW at the beginning of the current growing season.
[d] ASW at the end of the current growing season.
[e] Soil water gain during the previous dormant season.
[f] Dormant season SW gain/dormant season precipitation.
[g] Soil water use during the current growing season.
[h] Drainage below 2.4 m during the current growing season.

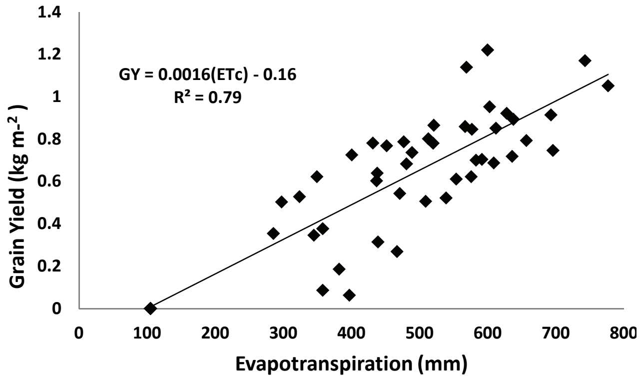

Figure 5. Grain sorghum yield vs. evapotranspiration at Texas locations (1989-2002).

2.1 kg m^{-3}. If an appropriate threshold ET_c value was chosen to define the yield-ET_c function in this study, it is not likely that the improvement in the slope of the yield-ET_c function came from better transpiration efficiency (Tanner and Sinclair, 1983). Rather, the current study had the benefit of wheat stubble residue to reduce soil water evaporation (Tolk et al., 1999; Klocke et al., 2009). An alternative scenario is that harvest index may have improved over 30 years and combined with soil water evaporation reduction to produce greater productivity.

Irrigation treatments in the Texas studies were percentages of the irrigation replacement amount for fully irrigated plots and included a non-irrigated treatment, a fully irrigated treatment, and one to three intermediate treatments (fig. 6). The vertical distances between the relative yield data points for each irrigation treatment show the year-to-year variability in GY. This variability increased as irrigation decreased. The year-to-variability in the non-irrigated relative yield was much more in the Texas results than in this study. Long-term average evaporative demand (Class A pan evaporation) is 2600 mm annually and 1500 mm from May through September in the Texas northern High Plains (Colaizzi et al., 2004). During the five-year field study in Garden City, annual evaporative demand was 1810 mm annually and 1140 mm from May through September. The climate in Texas led to more dependence on irrigation for sorghum and more year-to-year variability in yield response as irrigation decreased. This year-to-year variability in sorghum yields in Texas was similar to the

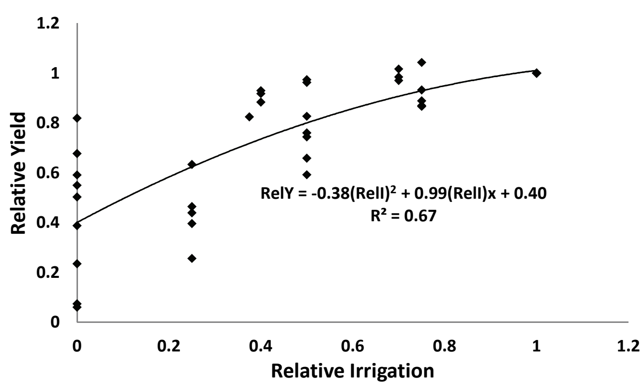

Figure 6. Relative grain yield vs. relative irrigation at Texas locations (1989-2002).

variability of corn yield response to irrigation in Garden City (Klocke et al., 2011). In 2008, the irrigated sorghum area was 41% of the total area harvested for sorghum in the Texas northern High Plains, while the irrigated area in southwest Kansas was 16% of the total area (NASS, 2011). More dryland sorghum can be grown in Kansas because the yield results are less variable from year to year, as shown in figure 4 in contrast with figure 6.

SUMMARY

A field study of fully irrigated to deficit-irrigated sorghum was conducted during 2005-2009 in southwest Kansas, where grain sorghum was grown in a five-year rotation of corn-corn-wheat-sorghum-sunflower. Over the five years, average annual precipitation was near the 30-year average, but there were significant year-to-year variations. Irrigation treatments were delineated by irrigation frequency from 6 to 26 days, with the constraint that the wettest irrigation treatment (scheduled on the basis of soil water depletion) could receive no more than two irrigation events per week, and each irrigation event delivered 25 mm of water to the soil surface. The progression of crop growth stages among irrigation treatments during the season was the same, except the maturity of the drier treatments was one week earlier one year and one week later another year. Surface residue coverage measured after planting sorghum from the previous year's wheat crop was 59% to 68% across irrigation treatments. Grain yield and total dry matter decreased significantly as irrigation decreased, but the least irrigation produced 91% of fully irrigated grain and 88% of fully irrigated dry matter. ET_c, calculated as the residual in a biweekly soil water balance, also decreased significantly as irrigation decreased, but the sorghum with the least irrigation used 13% less water than the full irrigation. Available soil water (ASW), measured at wheat harvest, after planting sorghum, and after sorghum harvest, decreased significantly as irrigation decreased. Soil water gain and fallow efficiency between wheat harvest and before sorghum planting was the same across irrigation treatments. Use of accumulated soil water by the crop increased significantly as irrigation decreased due to greater water extraction deeper into the soil profile.

Because measured ET_c for the driest treatment was 87% of fully irrigated ET_c, a linear regression of GY data with respect to ET_c was not realistic until a threshold value of ET_c (ET_c required to produce the first increment of grain) from prior field research with no-till practices was added to the data set. The resulting slope of the GY-ET_c regression was 2.1 kg m^{-3}, which was more than found in field studies conducted worldwide in the 1970s and 1980s (1.5 kg m^{-3}) and in field studies conducted in the Texas Panhandle during the 1990s (1.6 kg m^{-3}). Improvements in crop residue management to reduce soil water evaporation or improvements in harvest index may have contributed to the increase.

Grain yield increased linearly with added irrigation, which was not expected because yield usually responds to irrigation in a diminishing-return fashion. In this case, deficit-irrigated sorghum, traditionally a dryland crop in the region, was able to utilize stored soil water following wheat to compensate for less irrigation. Grain yields, measured during the 1990s in the Texas Panhandle, showed a curvilinear, diminishing-return response to irrigation, but the atmosphere's evaporative demand was significantly greater there than in this study in southwest Kansas.

Yield response to irrigation is the important first step in its application in economic studies of crop production and crop selections when water supplies are limited; furthermore, year-to-year variability in yields is necessary to evaluate income risk for irrigators. As demonstrated in this study, sorghum has less fluctuation in yields and uses less water than other crops, including corn. When water supplies are limited, sorghum could be paired with corn in the same field so that more water could be allocated to corn with the possibility of more economic return and less income risk than growing corn alone. Economic evaluation of these cropping strategies is needed to evaluate water policy alternatives for managing aquifers that are diminishing due to agricultural irrigation.

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