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CORN 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 corn to irrigation and evapotranspiration (ETc), and to document plant growth parameters and soil water use. Corn was grown in a five-year rotation of corn-corn-wheat-grain sorghum-sunflower. Results from the corn after sunflower and corn after corn are presented here. Six irrigation treatments were produced by applying 25 mm of irrigation every 5 to 17 days. Year-to-year grain yields averaged over irrigation and crop sequence appeared to be correlated with leaf area index, which possibly reflected the severity of hail events that occurred in four of the five years of the study. However, dry matter accumulation per plant did not vary across irrigation treatments. Surface residue coverage from the previous year's crop was 38% for sunflower and 61% for corn. ETc and productivity, also known as water use efficiency (WUE), decreased significantly as irrigation decreased. The deficit irrigation treatments used more of the previous non-growing season precipitation than the fully irrigated treatment due to greater soil water storage capacity in the drier soil profile. Furthermore, these treatments extracted more soil water during the growing season as irrigation decreased. Linear models of ETc predicted grain and dry matter yields with R^2 values of 0.67 and 0.59, respectively. The relationship of relative grain yield and ETc was also linear and more pronounced, with an R^2 value of 0.82. In contrast, the relationship of relative yield and irrigation followed a curvilinear model. During the five-year study, variability in yields increased as irrigation decreased, illustrating a greater income risk with less irrigation. Yield response to irrigation, especially over multiple years, is essential information to build economic studies of cropping alternatives, deficit irrigation management, and income risk. These relationships need to be developed regionally to characterize the effects of environmental factors, especially precipitation.*

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

Water supplies for irrigation are decreasing in the U.S. Great Plains, particularly from the Ogallala Aquifer, and in many regions of the world. Water supplies can become limited when groundwater resources dwindle and cause reduced water delivery by pumps or when public water policy imposes constraints on the water resource. Irrigation management must respond to limited water supplies by producing the best 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.

The 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. Because corn is an important irrigated crop, field research during the past 20 years has been conducted across the U.S. Great Plains to develop production functions (yield versus irrigation) for corn. Furthermore, irrigated corn production during this period has contributed to the depletion of groundwater resources. Field research from the Great Plains research indicates that as irrigation applications to corn decrease, yields do not decrease at the same rate. Four field studies during 1987-1995 in the central panhandle of Texas showed that applications of 60% to 70% of full irrigation produced 82% of full yield; moreover, 50% to 60% of full irrigation produced 55% of full yield (Howell et al., 1989; Lyle and Bordovsky, 1995; Howell et al., 1995; Schneider and Howell, 1998). Klocke et al. (2007) measured yield and irrigation for corn during 1986-1998 in west central Nebraska and found that grain yields were 90% of full irrigation yields when applying only 47% of full irrigation. In this study, the first irrigation event of the deficit-irrigated treatment was delayed until the beginning of the reproductive growth stage. When attempting to replicate these results on a commercial scale on three fields in west central Nebraska during 1996-2001, 77% of full irrigation was needed to produce 92% of the fully irrigated yield (Klocke et al., 2004). In the research setting, irrigation could be applied when the crop's water needs were most critical (reproductive and grain fill). In the commercial

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field setting, irrigation timing was constrained by the system's ability to reach the point in the field where crop water needs were most critical.

The CERES-Maize crop model, based on 28 years of corn production data, showed that applications of 50% of the non-yield limiting rate of irrigation only reduced yield 13% (Howell et al., 1989). However, this reduced rate of irrigation increased the year-to-year yield variance four-fold. Tolk et al. (1999) applied 60% or 100% of growing season rainfall to corn in weighing lysimeters with bare or mulched surfaces. They found significant increases in water use efficiency (WUE) with mulched surfaces compared with bare surfaces because the corn used more water for crop growth and yield rather than evaporation of soil water. Klocke et al. (2009) found that corn and wheat stubble that almost completely covered the soil surface under a corn crop canopy reduced soil water evaporation by half when compared with a bare soil surface.

Yield response to irrigation can be location specific and can vary by year due to differences in precipitation amounts and timing and stored soil water. Economic studies can use average yield responses over years to find overall trends, but year-to-year variations in yields are needed for risk analysis. Testing and validation of crop production models need robust data sets that may include reference evapotranspiration (ETr), soil water measurements, crop grain yields, dry matter accumulation, harvest index, growth stage dates, maximum leaf area index, plant population, and crop residue coverage on the soil surface. These parameters were measured in this study to find the response of corn to a range of irrigation application amounts. The corn was grown in a no-till environment with non-limiting practices for weed and insect control and fertility management. Crop productivity (yield/ETc), soil water accumulation during the non-growing season, and soil water use during the growing season were also derived from field data. Therefore, the objectives of this study were to: (1) build a robust data set of parameters for testing crop models over a range of irrigation, (2) find the relationships of grain and dry matter yields to ETc and irrigation, and (3) carry out the study over multiple years to find year-to-year variability in yield responses.

METHODS

LOCATION AND SOILS

The cropping systems project was located 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 8.1 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 of content of 33%) and permanent wilting (volumetric water content of 15%). Long-term average climatic data for Garden City are 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.

CROPPING SYSTEM AND IRRIGATION PROTOCOL

Corn was grown in a five-year rotation of corn-corn-wheat-sorghum-sunflower during 2005-2009. Two consecutive years of corn (relative maturity of 118 days) were planted, the first year after sunflower and the next year after corn. Results from the two years of corn production are reported here. All crops were planted in 2004 and the irrigation treatments were imposed, so all crops were in rotation in 2005 and the starting soil water content included the effects of the irrigation variable from the previous 2004 crop. Each crop was present every year in five cropping blocks, which were replicated over years.

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). Six irrigation treatments were placed in a random pattern within each irrigation system span, which created four replications in a randomized complete block design. 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 maintained on the same individual plots during all years. Target application depths across the six treatments were 100%, 80%, 70%, 50%, 40%, and 25% of full irrigation; however, the irrigation variable was achieved by decreasing the irrigation frequency across treatments 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-irrigation treatment was not included because continuous cropping of corn is not feasible in the region and crop failure is expected for most years. Seasonal application depths for treatment 1, the wettest treatment, varied from year to year because irrigation amounts 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 depths for treatments 2 through 6 were scaled from treatment 1 so that all treatments received more water in years with low precipitation. If rainfall was sufficient to fill the soil profile in treatment 1 to field capacity, then water was not applied. Growing season irrigation amounts decreased as the time between irrigation events increased. No more than two irrigation events (50 mm) per week were applied on treatment 1 to simulate pumping capacity limitations of common commercial systems (7.1 mm d^{-1}). 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.

CULTURAL PRACTICES

Cultural practices, including hybrids, no-till planting techniques, fertilizer applications, and weed control, were the same across irrigation treatments (table 1). Cultural practices followed the requirements of no-till management. Pre-emergence and post-emergence herbicides were applied as needed on a zero-tolerance threshold basis. Fertilizers were applied at uniform rates across all irrigation treatments for non-limited crop production. Presumably, nitrogen accumulated in reduced irrigation treatments (data not taken). Liquid starter fertilizer with all prescribed micro- and macronutrients was delivered directly to the seed furrow at a rate that did not affect emergence. Liquid fertilizer was applied as a side-

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

Field Operation	2005	2006	2007	2008	2009
Fertilize, starter (10-34-0)[a]	4 May	4 May	30 April	1 May	14 May
Fertilize, side-dress (32-0-0)	22 June	15 June	18 June	18 June	17 June
Pre-emerge herbicide	5 May	4 May	30 April	1 May	4 May
Planting	4 May	4 May	30 April	1 May	14 May
Post-emerge herbicide	3 June	9 June	13 June	5 June	10 June
Harvest	3 October	4 October	24 September	24 September	17 October

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

dress treatment in a stream directly behind the coulter just below the soil surface between every other pair of crop rows. Crops were planted into the previous crop's residue with no-till techniques. The no-till 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 populations increased across the six irrigation treatments with increasing levels of irrigation (48,200; 54,400; 60,500; 66,700; 72,900; and 79,100 plants ha^{-1}) based on recommendations from local agronomists (C. Thompson, personal communication, 5 March 2004). Plant populations were intended to match each irrigation treatment's yield potential. Higher populations were chosen so they would not limit production in treatments receiving more irrigation, and lower populations were chosen so lower irrigation treatments were not penalized if less irrigation would not support yield expectations.

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, for example V6 occurred when six leaves were fully extended. Leaf area was measured shortly after all leaves had fully extended by removing five plants from the field and passing the leaves through an optical scanner (portable leaf area meter, Li-Cor, Lincoln, Neb.). 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 content, which typically spread harvest over one week. Grain yield was measured by hand-harvesting two adjacent 3 m rows.

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:

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

where

W = total soil water in 2.4 m profile (mm)
dW/dT = 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 (ETc):

$$ETc = NI + P - R - (SW2 - SW1) - D \qquad (2)$$

where

NI = net irrigation (water infiltrated) during the sampling period
P = precipitation during the sampling period
R = runoff or run-on 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.

ETc was calculated for the days between plant emergence and the first soil water measurement with the Kansas Water Budget (KSWB) (Klocke et al., 2010). Reference ET (ETr) was calculated with an alfalfa-referenced Modified Penman model (Kincaid and Heermann, 1984; 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.

RESULTS

REFERENCE EVAPOTRANSPIRATION AND PRECIPITATION

Annual ETr was lowest in 2009 (1362 mm) and highest in 2006 (1773 mm). The pattern of above- and below-average monthly ETr varied from year to year (table 2). Annual precipitation was lowest in 2008 (440 mm) and highest in 2006 (579 mm) (table 3). As with ETr, monthly precipitation patterns varied from year to year. However, 2006 was the only year when annual ETr correlated with annual precipitation when both were the highest of the five years; otherwise, ETr and precipitation did not track with one another. The effects of precipitation on the crops were better described with non-growing season (previous October through April), growing season (May through September), and cropping season (previous October through September) data (figs. 1 and 2). Non-growing season precipitation contributed to potential soil water storage, growing season precipitation contributed 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 non-growing precipitation. These fluctuations in ETr and precipitation were important factors influencing crop production responses.

IRRIGATION AND GROWTH STAGES

The first irrigation event occurred on treatment 1 when 50% of the available soil water was depleted in the top 1.2 m of soil, usually during the vegetative growth stage when eight

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

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
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

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

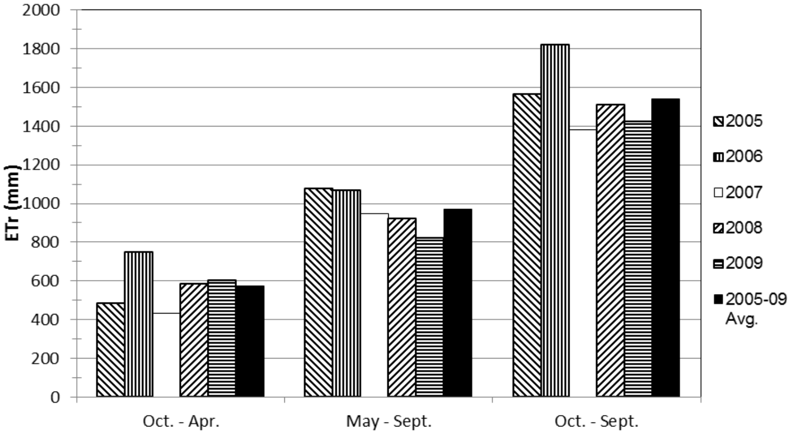

Figure 1. Prior non-growing season (Oct.-Apr.), growing-season (May-Sept.), and cropping-season (Oct.-Sept.) reference ET (ETr).

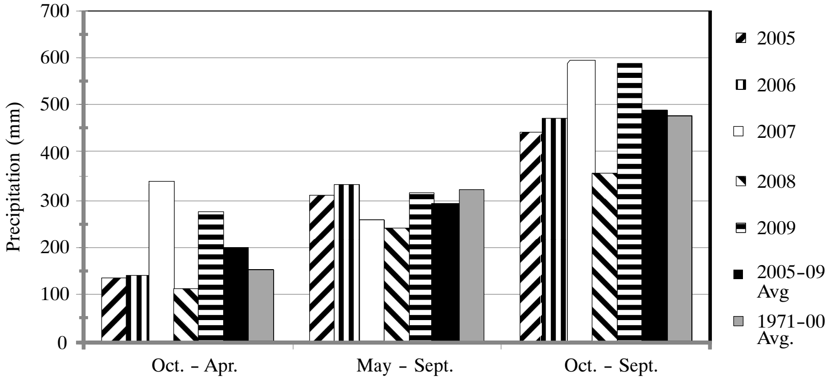

Figure 2. Non-growing season (Oct.-Apr.), growing-season (May-Sept.), and cropping-season (Oct.-Sept.) precipitation.

to ten leaves were fully extended (V8 to V10) (table 4). The accumulation of soil water during the previous non-growing season and early growing season precipitation influenced the first irrigation date. Since the irrigation treatment variable was achieved with irrigation event frequency, dates of irrigation events on treatments 2 through 6 were somewhat different from year to year because precipitation patterns influenced the timing of the actual irrigation events. Although total irrigation varied among years due to precipitation differences, the target irrigation amounts across irrigation treatments on a percentage basis were consistent, especially when averaged over years. Corn after sunflower received more total water than corn after corn because sunflower removed more stored soil water than corn during

Table 4. Growing season irrigation beginning and ending dates, irrigation frequency, and total irrigation.

		Corn after Sunflower					Corn after Corn				
Year	Irrigation Treatment	Beginning Irrig.	Ending Irrig.	Irrig. Freq. (d)	Total Irrig. (mm)	% of Full Irrig.	Beginning Irrig.	Ending Irrig.	Irrig. Freq. (d)	Total Irrig. (mm)	% of Full Irrig.
2005	1	28 June	26 Aug.	4.9	325	100	27 June	22 Aug.	5.6	275	100
	2	28 June	26 Aug.	6.6	250	77	27 June	11 Aug.	5.6	225	82
	3	28 June	26 Aug.	7.4	225	69	27 June	11 Aug.	6.4	200	73
	4	1 July	12 Aug.	8.4	150	46	30 June	22 Aug.	10.6	150	55
	5	1 July	19 Aug.	9.8	150	46	30 June	11 Aug.	10.5	125	45
	6	18 July	9 Aug.	11.0	75	23	21 July	11 Aug.	10.5	75	27
2006	1	10 June	7 Sept.	5.9	400	100	12 June	31 Aug.	5.3	400	100
	2	10 June	7 Sept.	7.4	325	81	12 June	31 Aug.	6.7	325	81
	3	10 June	7 Sept.	8.1	300	75	12 June	31 Aug.	7.3	300	75
	4	10 June	29 Aug.	10.0	225	56	12 June	28 Aug.	9.6	225	56
	5	10 June	7 Sept.	17.8	150	38	12 June	31 Aug.	16.0	150	38
	6	29 June	18 Aug.	16.7	100	25	29 June	17 Aug.	16.3	100	25
2007	1	5 July	23 Aug.	4.1	325	100	5 July	22 Aug.	4.8	275	100
	2	5 July	23 Aug.	4.9	275	85	5 July	22 Aug.	6.0	225	82
	3	9 July	23 Aug.	5.6	225	69	10 July	16 Aug.	6.2	175	64
	4	9 July	23 Aug.	7.5	175	54	10 July	9 Aug.	7.5	127	46
	5	12 July	20 Aug.	9.8	125	38	16 July	9 Aug.	8.0	100	36
	6	12 July	9 Aug.	14.0	75	23	16 July	9 Aug.	12.0	75	27
2008	1	1 July	27 Aug.	4.4	350	100	1 July	19 Aug.	4.5	300	100
	2	1 July	27 Aug.	5.7	275	79	1 July	19 Aug.	6.1	225	75
	3	3 July	27 Aug.	6.9	225	64	9 July	19 Aug.	5.9	200	67
	4	3 July	27 Aug.	9.2	175	50	9 July	19 Aug.	8.2	150	50
	5	9 July	20 Aug.	10.5	125	36	11 July	5 Aug.	8.3	100	33
	6	9 July	5 Aug.	13.5	75	21	11 July	8 Aug.	14.0	75	25
2009	1	9 July	25 Aug.	4.7	275	100	10 July	26 Aug.	6.7	200	100
	2	9 July	25 Aug.	6.7	200	73	10 July	26 Aug.	9.4	150	75
	3	13 July	25 Aug.	7.2	175	64	14 July	26 Aug.	10.8	125	63
	4	13 July	17 Aug.	8.8	125	45	14 July	26 Aug.	14.3	100	50
	5	16 July	17 Aug.	10.7	100	36	17 July	19 Aug.	16.5	75	38
	6	16 July	25 Aug.	20.0	75	27	17 July	19 Aug.	33.0	50	25
Avg.	1	28 June	27 Aug.	4.8	335	100	29 June	24 Aug.	5.4	290	100
	2	28 June	27 Aug.	6.3	265	79	29 June	21 Aug.	6.8	230	79
	3	30 June	27 Aug.	7.0	230	69	2 July	20 Aug.	7.3	200	69
	4	1 July	21 Aug.	8.8	170	51	3 July	20 Aug.	10.1	150	52
	5	3 July	22 Aug.	11.7	130	39	5 July	15 Aug.	11.9	110	38
	6	10 July	13 Aug.	15.0	80	24	12 July	12 Aug.	17.2	75	26

the previous growing season, leaving a drier soil profile at the beginning of the next growing season (as reported in the following section). Additional irrigation for corn after sunflower was consistent with the criterion of no more than 50% depletion of available soil water in the fully irrigated treatment. Growth stage dates were similar across irrigation treatments, except for late dent in 2008 and maturity in 2006, 2008, and 2009, which occurred earlier in drier treatments (table 5).

CROP PRODUCTION FACTORS

Crop residue coverage on the soil surface from the previous year's crop was nearly the same for irrigation treatments 1 through 5 (53% to 49%), but treatment 6 had significantly less residue cover than the other treatments (table 6). Apparently, the crop population of the previous crop, which decreased as irrigation amounts decreased, did not have a large impact on residue coverage the following year. Sunflower preceding the corn crop left significantly less surface residue than corn stubble (table 6).

Year-to-year differences in peak leaf area index were caused by hail events that occurred every year of the study, except in 2007 (table 6). Significant leaf stripping was caused by hail events that occurred on 4 July 2005, 11 July 2006, 20 June 2008, and 18 July 2009, when all events occurred prior to tassel emergence. Leaf area index was a good indicator of the hail's impact on the crop (Currie and Klocke, 2008). There was a hail event on 19 June 2007, but it was very minor and caused little to no leaf damage, as indicated by leaf area measurements. Grain yield, total dry matter, and dry matter per plant among years correlated with the severity of the hail events.

Grain yield and total dry matter averaged over irrigation treatments and crop sequence showed the year-to-year trends in crop production (table 6). The yearly differences in grain yield and dry matter followed the pattern of the previous non-growing season precipitation rather than the growing season precipitation (fig. 2). More year-to-year variation in non-growing season precipitation than growing season precipitation expressed itself in yield response. The amount of irrigation averaged over crop sequence and years was

Table 5. Growth stage dates averaged over corn after sunflower and corn after corn by irrigation treatments.

Year and Growth Stage	Irrigation Treatment 1	2	3	4	5	6
2005						
Planted	4 May	4 May	4 May	4 May	4 May	4 May
Emerged	20 May	20 May	20 May	20 May	20 May	20 May
V6[a]	23 June	23 June	23 June	23 June	23 June	23 June
Tasseled	18 July	18 July	18 July	18 July	18 July	18 July
Silk brown	--	--	--	--	--	--
Late dent	--	--	--	--	--	--
Mature	21 Sept.	21 Sept.	21 Sept.	21 Sept.	21 Sept.	21 Sept.
2006						
Planted	4 May	4 May	4 May	4 May	4 May	4 May
Emerged	22 May	22 May	22 May	22 May	22 May	22 May
V6	13 June	13 June	13 June	13 June	13 June	13 June
Tasseled	20 July	20 July	20 July	20 July	20 July	20 July
Silk brown	28 July	28 July	28 July	28 July	28 July	28 July
Late dent	--	--	--	--	--	--
Mature	2 Oct.	2 Oct.	10/2 Oct.	25 Sept.	25 Sept.	25 Sept.
2007						
Planted	30 Apr.	30 Apr.	30 Apr.	30 Apr.	30 Apr.	30 Apr.
Emerged	15 May	15 May	15 May	15 May	15 May	15 May
V6	19 June	19 June	19 June	19 June	19 June	19 June
Tasseled	16 July	16 July	16 July	16 July	16 July	16 July
Silk brown	--	--	--	--	--	--
Late dent	27 Aug.	27 Aug.	27 Aug.	27 Aug.	27 Aug.	27 Aug.
Mature	17 Sept.	17 Sept.	17 Sept.	17 Sept.	17 Sept.	17 Sept.
2008						
Planted	1 May	1 May	1 May	1 May	1 May	1 May
Emerged	21 May	21 May	21 May	21 May	21 May	21 May
V6	16 June	16 June	16 June	16 June	16 June	16 June
Tasseled	24 July	24 July	24 July	24 July	24 July	24 July
Silk brown	28 July	28 July	28 July	28 July	28 July	28 July
Late dent	3 Sept.	3 Sept.	3 Sept.	3 Sept.	29 Aug.	29 Aug.
Mature	22 Sept.	22 Sept.	22 Sept.	22 Sept.	15 Sept.	15 Sept.
2009						
Planted	14 May	14 May	14 May	14 May	14 May	14 May
Emerged	26 May	26 May	26 May	26 May	26 May	26 May
V6	22 June	22 June	22 June	22 June	22 June	22 June
Tasseled	20 July	20 July	20 July	20 July	20 July	20 July
Silk brown	3 Aug.	3 Aug.	3 Aug.	3 Aug.	3 Aug.	3 Aug.
Late dent	31 Aug.	31 Aug.	31 Aug.	31 Aug.	31 Aug.	31 Aug.
Mature	2 Oct.	2 Oct.	2 Oct.	2 Oct.	28 Sept.	28 Sept.

[a] V6 = six fully emerged leaves.

positively correlated with grain yield, total dry matter, and relative grain yield. Relative grain yield was calculated as the ratio of yield of each irrigation treatment and the yield of treatment 1 for that year so differences in hail damage and other environmental stressors from year to year could be minimized. Even though corn after sunflower yielded somewhat more grain than corn after corn, the relative yields of the two crop sequences were the same.

The driest irrigation treatment (treatment 6) had the lowest harvest index (the ratio of grain and plant dry matter) yet the highest test weight. Final plant population decreased significantly across irrigation treatment due to the planted population variable, but the dry matter per plant was the same. Apparently, better grain test weight from the driest treatment compensated for the lowest harvest index to produce the total dry matter per plant. The harvest index, test weight, and dry matter per plant parameters, taken together, indicate that plant populations across irrigation treatments were appropriate.

CROP EVAPOTRANSPIRATION AND PRODUCTIVITY

Crop evapotranspiration (ETc) when averaged over irrigation treatments and crop sequence (table 7) followed the same year-to-year pattern as growing season ETr, where ETr and ETc decreased by year from 2005 through 2009 (fig. 1). ETc consistently decreased, from 630 to 454 mm, as the amount of irrigation decreased (table 7). Likewise, the ratio of ETc and ETr consistently decreased, from 0.76 to 0.54, with decreasing amounts of irrigation. The differences in ETc were strongly correlated with grain yield, relative grain yield, and final dry matter. Productivity was not significantly different among irrigation treatments 1 through 3 but decreased significantly among irrigation treatments 4 through 6. ETc from corn after sunflower was significantly more than corn after corn, which translated into more grain yield for corn after sunflower (table 6).

Several field research studies have been conducted in the Great Plains to measure yields as a function of ETc and irrigation. Productivity was derived from the ratio of yield and ETc over a range of irrigation amounts (Howell et al., 1989; Lyle and Bordovsky, 1995; Howell et al., 1995; Schneider and Howell, 1998; Klocke et al., 2007) (table 8). The Lyle, Howell, and Schneider studies were conducted in the Texas panhandle; the current study was conducted in western Kansas; and the Klocke study was conducted in west central Nebraska. The Nebraska field site was 375 km directly north of the Kansas site, and the Texas site was 290 km south of the Kansas site and 110 km west of the other two sites. The results of the Texas studies were combined to cover the same time period as the Nebraska study. Growing season precipitation was 303 to 328 mm for all of the studies. Irrigation treatments were based on irrigation as a percentage of full irrigation. Crop yields were similar for each irrigation treatment among locations; however, more irrigation was required to achieve the same yields as the study locations moved from north to south. Relative yields for the 50% irrigation treatment decreased from north to south (92% to 62%). Productivity values decreased as irrigation decreased in the Texas and Kansas studies, but the productivity was nearly the same for the 100% and 50% irrigation treatments in Nebraska. The Texas study was conducted with clean-tilled soil surfaces, whereas the Nebraska and Kansas studies were conducted with no-till techniques. As suggested by Tolk et al. (1999), some of the water that evaporated from bare soil might have been used for transpiration rather than evaporation for the residue-covered soil. The differences in soil water evaporation between bare and residue-covered soils would diminish as irrigation decreased (Klocke et al., 2009), which was illustrated in similar productivity from the 25% irrigation treatments in Texas and Kansas.

YIELD RESPONSE TO EVAPOTRANSPIRATION AND IRRIGATION

When the individual irrigation treatments by year results were regressed, linear relationships between ETc and grain yield and dry matter were defined by R^2 values greater than 0.59 (fig. 3). The relationship of dry matter yields to ETc was more variable than grain yields, perhaps due in part to variation in the hail damage over the years. The linear

Table 6. Crop yields and plant characteristics.[a]

	Grain Yield ($kg\ m^{-2}$)	Relative Grain Yield	Total Dry Matter ($kg\ m^{-2}$)	Harvest Index	Test Weight ($kg\ m^{-3}$)	Final Population ($plants\ m^{-2}$)	Dry Matter Per Plant (kg)	Leaf Area Index	Residue Coverage (%)
(a) Year as an independent variable over irrigation treatments and crop sequence									
2005	0.89 c	0.87 a	1.40 c	1.75	764 a	6.2 a	0.23 c	N/A	46.9 c
2006	0.86 c	0.76 b	1.54 cb	1.26	754 b	5.4 c	0.28 b	3.22 b	52.6 a
2007	1.27 a	0.84 a	2.09 a	1.55	745 c	5.8 b	0.38 a	4.08 a	49.0 bc
2008	0.60 d	0.65 c	0.98 d	1.59	737 d	5.0 d	0.19 d	2.47 c	48.0 bc
2009	1.04 b	0.81 ab	1.62 b	1.79	756 b	5.7 b	0.28 b	3.26 b	50.6 ab
$LSD_{0.05}$	0.063	0.062	0.148		4.2	0.22	0.034	0.285	3.2
(b) Irrigation treatment as an independent variable over year and crop sequence									
1	1.19 a	1.00 a	1.94 a	1.59	747 c	6.9 a	0.29 a	4.11 a	51.3 ab
2	1.12 a	0.94 ab	1.62 bc	2.24	750 bc	6.2 b	0.26 a	N/A	52.6 a
3	1.05 b	0.88 b	1.69 b	1.64	750 bc	6.0 b	0.28 a	N/A	51.2 ab
4	0.87 c	0.73 c	1.47 c	1.45	750 bc	5.4 c	0.26 a	3.17 b	49.8 ab
5	0.75 d	0.63 d	1.24 d	1.53	754 ab	4.9 d	0.28 a	N/A	48.5 b
6	0.61 e	0.50 e	1.19 d	1.05	755 a	4.2 e	0.29 a	2.49 c	43.2 c
$LSD_{0.05}$	0.07	0.07	0.161		4.6	0.24	0.037	--	3.6
(c) Crop sequence as an independent variable over year and irrigation treatment									
Sunf.-corn	0.96 a	0.78 a	N/A	N/A	751 a	5.5 b	N/A	N/A	38.1 b
Corn-corn	0.91 b	0.79 a	1.53	1.59	751 a	5.7 a	0.28	3.26	60.8 a
$LSD_{0.05}$	0.04 b	0.039	--		2.7	0.14	--	--	2.1

[a] Within each section (a), (b), or (c), values followed by the same letter in the same column are not significantly different at $p < 0.05$.

Table 7. Evapotranspiration, productivity, and grain yield/irrigation.[a]

	ETc (mm)	ETr (mm)	ETc/ETr	Productivity[b] ($kg\ m^{-3}$)
(a) Year as an independent variable over irrigation treatments and crop sequence				
2005	591 a	938	0.63 c	1.64 c
2006	558 bc	930	0.60 d	1.52 c
2007	562 bc	951	0.66 b	2.29 a
2008	444 d	765	0.58 e	1.34 d
2009	551 c	715	0.77 a	1.92 b
$LSD_{0.05}$	9.93		0.012	0.13
(b) Irrigation treatment as an independent variable over year and crop sequence				
1	630 a	828	0.76 a	1.95 a
2	585 b	823	0.71 b	1.97 a
3	570 c	838	0.68 c	1.89 a
4	518 d	835	0.62 d	1.72 b
5	490 e	830	0.59 e	1.57 c
6	454 f	840	0.54 f	1.35 d
$LSD_{0.05}$	10.88		0.013	0.14
(c) Crop sequence as an independent variable over year and irrigation treatment				
Sunf.-corn	551 a	835	0.66 a	1.76 a
Corn-corn	532 b	831	0.64 b	1.73 a
$LSD_{0.05}$	6.28		0.007	0.08

[a] Within each section (a), (b), or (c), values followed by the same letter in the same column are not significantly different at $p < 0.05$.

[b] Productivity = grain yield/ETc.

regression of relative grain yield and ETc was much was less variable, with an R^2 of 0.82 (fig. 4). The yearly data can be distinguished, but the linear relationship included all years. Gomez and Gomez (1984) suggested that treatment means averaged over replications are more appropriate for regressions of independent and dependent variables. When grain yield data were averaged for each irrigation treatment over replicated years, the relationship was very well defined by the following equation:

$$GY = 0.0042ETc - 1.4 \ (R^2 = 0.94) \qquad (3)$$

where GY is grain yield ($kg\ m^{-2}$), and ETc is crop evapotranspiration (mm).

A quadratic regression was used for the relationship of grain yield and irrigation (fig. 5). Yield responses to irrigation among years can be distinguished from one another, but all data points were used to form the quadratic relationship. A particular year's data fell above or below the regression equation to reflect year-to-year differences in the environment, particularly differences in precipitation. As irrigation decreased, the year-to-year variation increased. This supports the work of Howell et al., (1989), which also showed increases in yield variation with decreases in irrigation level with simulations of 28 years of data. When grain yield data were averaged for each irrigation treatment over replicated years, the relationship was well defined by the following equation:

$$GY = -6E\text{-}06(NI)^2 + 0.005NI + 0.23 \ (R^2 = 0.99) \qquad (4)$$

where NI is net irrigation (water infiltrated, mm).

STORED SOIL WATER GAIN AND USE

Since the same irrigation treatment was 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. Soil water content measured at the end of the previous growing season was the same for 2007, 2008, and 2009 but significantly greater in 2005 and significantly less in 2006 (table 9). Soil water gain during the non-growing season preceding all years followed the pattern of precipitation amounts during October through April (fig. 2). Soil water content at the end of the previous growing season decreased 101 mm as irrigation decreased. The crop extracted more water from deeper in the profile as irrigation decreased (data not shown) because the deep silt loam soil allowed roots to extend to depths of 1.8 to 2 m in the driest treatment. In contrast, soil water extraction was limited to

Table 8. Grain yield, relative yield, crop ET, and productivity responses to irrigation in central and southern Great Plains field studies.

Years	Rainfall (mm)	Irrigation mm	Irrigation % of full	Yield ($kg\ m^{-2}$)	Rel. Yield (%)	ETc (mm)	Productivity ($kg\ m^{-3}$)	Location	Source
1987-1998	303	480	100	1.3	100	814	1.6	Texas	Howell et al., 1989;
		219	50	0.8	62	585	1.4	panhandle	Lyle and Bordovsky, 1995;
		131	25	0.6	46	482	1.2		Howell et al., 1995;
									Schneider and Howell, 1998
2005-2009	314	292	100	1.2	100	630	1.9	Western	Current study
		133	50	0.9	75	504	1.8	Kansas	
		76	25	0.6	50	454	1.3		
1986-1998	328	250	100	1.2	100	660	1.8	West central	Klocke et al., 2007
		107	50	1.1	92	581	1.9	Nebraska	
		--	25	--	--	--	--		

Table 9. Soil water content at the end of the previous growing season and at the beginning and end of the current growing season, soil water gain during the previous non-growing season, fallow efficiency during the previous growing season, soil water use during the current growing season, and drainage during the current growing season. Soil water measurements were taken to a depth of 2.4 m.[a]

	Previous[b] End SW (mm)	Beginning[b] SW (mm)	Ending[b] SW (mm)	SW Gain (mm)	Fallow Efficiency[c]	SW Use (mm)	Growing Season Drainage (mm)
(a) Year as an independent variable over irrigation treatments and crop sequence							
2005	540 a	642 a	483 bc	102 c	0.39 b	159 a	0.61 bc
2006	455 c	505 d	486 b	50 d	0.29 c	19 d	0.08 c
2007	480 b	658 a	527 a	178 a	0.55 a	131 b	1.71 a
2008	485 b	521 c	469 c	36 d	0.21 d	52 c	0.16 c
2009	486 b	616 b	482 bc	130 b	0.51 a	134 b	0.98 b
$LSD_{0.05}$	14.3	16.1	14.9	15	0.065	10	0.56
(b) Irrigation treatment as an independent variable over year and crop sequence							
1	549 a	629 a	564 a	80 b	0.3 b	65 d	2.1 a
2	513 b	614 ab	531 b	101 a	0.41 a	83 c	0.8 b
3	500 b	605 b	505 c	105 a	0.41 a	100 b	0.67 bc
4	468 c	577 c	473 d	109 a	0.43 a	104 b	0.34 bc
5	458 cd	557 d	440 e	99 a	0.39 a	117 a	0.12 c
6	448 d	548 d	425 e	100 a	0.39 a	123 a	0.22 bc
$LSD_{0.05}$	15.6	17.7	16.3	16	0.07	11	0.61
(c) Crop sequence as an independent variable over year and irrigation treatment							
Sunf.-corn	484 b	576 b	481 b	92 b	0.39 a	95 b	0.43 b
Corn-corn	494 a	601 a	497 a	107 a	0.39 a	103 a	0.98 a
$LSD_{0.05}$	9	10.2	9.4	9	0.04	6.3	0.35

[a] Within each section (a), (b), or (c), values followed by the same letter in the same column are not significantly different at $p < 0.05$.

[b] Total soil water in 2.4 m soil profile.

[c] Fallow efficiency = soil water gain/non-growing season precipitation.

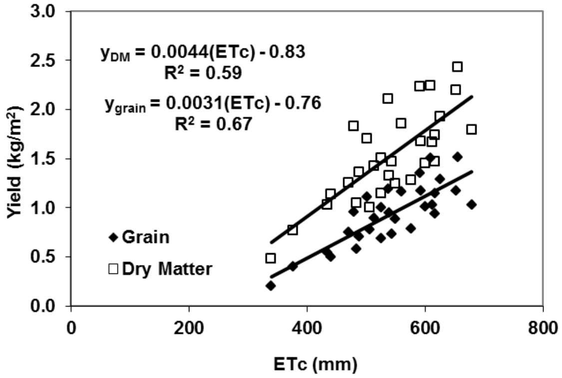

Figure 3. Relationship of grain and dry matter yields with crop evapotranspiration (ETc).

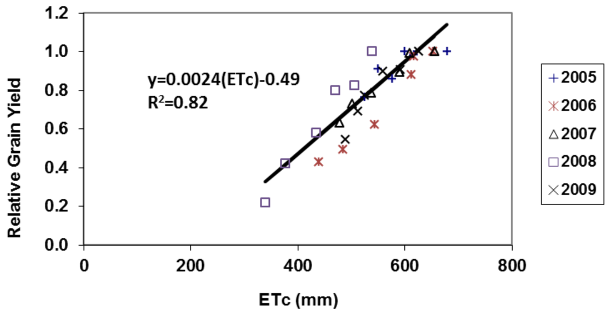

Figure 4. Relationship of relative grain yield with crop evapotranspiration (ETc).

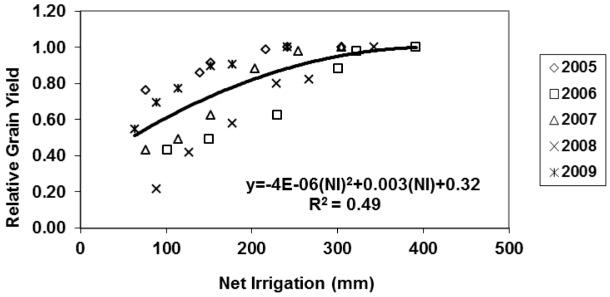

Figure 5. Relative grain yield response to net irrigation (NI).

1.2 m in the wettest treatment. Soil water content at the beginning of the growing season in the wettest treatment was 81 mm more than in the driest treatment. The previous years' ending soil water content was 10 mm more in corn after corn than in corn after sunflower. At the beginning of the next growing season, the soil in corn after corn held 25 mm more water than corn after sunflower, which led to a net gain of 15 mm more accumulated soil water. The difference in soil water at the beginning of the season between the two cropping sequences led to additional irrigation in corn following sunflower (table 4).

Fallow efficiency, the ratio of soil water gain and precipitation, was the same (0.39) for the two crop sequences and the same across irrigation treatments (0.4) except for the highest level of irrigation (0.3). This showed that 60% to 70% of the precipitation was lost through soil water evaporation or drainage during the non-growing season. Soil water content at the end of the growing season decreased as irrigation decreased and was less in corn after sunflower than in corn after corn. Apparently, the extra irrigation on corn after sunflower did not lead to equal season-ending soil water content. Soil water used during the growing season was 58 mm more with the least irrigation than with the most irrigation. This confirms that the crop that received less irrigation was able to extract more water from deeper in the soil profile. This increase in soil water use translated into additional water in combination with irrigation and precipitation and led to more ETc and in turn to more crop yield. Corn after corn used slightly more soil water than corn after sunflower. Growing season drainage was minimal, which demonstrated that irrigation management did not lead to excessive leaching below 2.4 m. How effectively the crop could utilize stored soil water was one factor contributing to the diminishing return in yield from more irrigation.

SUMMARY

A field study of fully irrigated to deficit-irrigated corn was conducted during 2005-2009 in southwest Kansas, where corn was grown in a five-year rotation of corn-corn-wheat-grain sorghum-sunflower. Only the corn after sunflower and corn after corn years were presented. Irrigation treatments were delineated by the irrigation frequency from 5 to 17 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 event delivered 25 mm of water to the soil surface. The progression of crop growth stages among irrigation treatments during the season was very similar in most years; however, late dent in one year and maturity in three years occurred sooner in the drier treatments than in the wetter treatments. Grain and dry matter yields from year to year averaged over irrigation treatments and crop sequence were highly correlated with maximum leaf area index, which possibly reflected the severity of hail events that occurred in four of the five years of the study. However, dry matter accumulation per plant did not vary across irrigation treatments. Grain yield decreased as irrigation decreased and the sunflower-corn sequence yielded slightly more than the corn-corn sequence. Surface residue coverage measured from the previous year's crop was 38% for sunflower and 61% for corn. ETc, calculated as the residual in a biweekly soil water balance, decreased as irrigation decreased. Productivity, the ratio of yield and ETc (also known as water use efficiency) decreased as irrigation decreased and was similar for the two crop sequences.

Productivity was compared among six field studies, four of which were conducted in the Texas panhandle (1987-1998), one in western Nebraska (1986-1998), and the current study in western Kansas (2005-2009). The increases in grain yields with increasing irrigations and growing season precipitation were very similar across locations. Productivity was slightly more for full irrigation and 50% of full irrigation in the Nebraska and Kansas studies than in Texas. No-till methods were used at the Nebraska and Kansas locations in contrast to the Texas studies, where tillage left bare soil surfaces. Crop residues in Nebraska and Kansas may have reduced non-productive soil water evaporation and shifted this water into productive crop transpiration.

Deficit irrigation treatments in this study were able to utilize more non-growing season precipitation because the previous crop extracted more soil water from deeper in the profile than the fully irrigated treatment, leaving more room to store the subsequent precipitation. The deficit-irrigated treatments also extracted more soil water during the growing season.

Although regressions of grain and dry matter yields with ETc produced reasonable linear models, regression of relative grain yields with ETc produced better models with less variability. A curvilinear model of relative yield with irrigation had the greatest predictive value, particularly at the higher amounts of irrigation, which had much less year-to-year variability than the crops with less irrigation. Over the entire five years of the study, yield variability increased as irrigation decreased, illustrating greater income risk for the producer as irrigation decreases. Yield response to irrigation, over multiple years, provides essential information to build economic models of cropping alternatives, deficit irrigation management, and income risk. Further work needs to be done with these relationships in different regions to characterize the effects of environmental factors, especially precipitation.

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