LONG-TERM RESPONSE OF CORN TO LIMITED IRRIGATION AND CROP ROTATIONS

N. L. Klocke, J. O. Payero, J. P. Schneekloth

ABSTRACT. *Dwindling water supplies for irrigation are prompting alternative management choices by irrigators. Limited irrigation, where less water is applied than full crop demand, may be a viable approach. Application of limited irrigation to corn was examined in this research. Corn was grown in crop rotations with dryland, limited irrigation, or full irrigation management from 1985 to 1999. Crop rotations included corn following corn (continuous corn), corn following wheat, followed by soybean (wheat-corn-soybean), and corn following soybean (corn-soybean). Full irrigation was managed to meet crop evapotranspiration requirements (ETc). Limited irrigation was managed with a seasonal target of no more than 150 mm applied. Precipitation patterns influenced the outcomes of measured parameters. Dryland yields had the most variation, while fully irrigated yields varied the least. Limited irrigation yields were 80% to 90% of fully irrigated yields, but the limited irrigation plots received about half the applied water. Grain yields were significantly different among irrigation treatments. Yields were not significantly different among rotation treatments for all years and water treatments. For soil water parameters, more statistical differences were detected among the water management treatments than among the crop rotation treatments. Economic projections of these management practices showed that full irrigation produced the most income if water was available. Limited irrigation increased income significantly from dryland management.*

Keywords. *Corn, Corn yield, Crop rotation, Deficit irrigation, Evapotranspiration, Irrigation, Limited irrigation, Soil water.*

Limited irrigation techniques, where irrigation amounts limit full production, are beginning to be implemented in the Great Plains region of the U.S. as well as in many other water-short regions of the world. In the Great Plains region, aquifer recharge from precipitation is not in balance with withdrawals for irrigation. For example, water storage in the High Plains aquifer declined by 7% from predevelopment until 2002, although the resulting water level changes were not uniform across the aquifer (McGuire, 2004). Declines ranged from 3 to more than 45 m, which represented 15% to 60% dewatering of the aquifer in Kansas (Buchanan and Buddemeier, 2001). Aquifer declines, uncertain surface water supplies, new legal regulations, and more intense competition for water for non-agricultural uses lead to the need for limited irrigation. Water supply declines also contribute to lower grain yields and less profitability from less pumping capacity from wells (O'Brien et al., 2001; Lamm et al., 1994; Howell et al., 1989). The goal of the irrigator is to maximize the economic benefit from available water. Finding crop yields from full irrigation to limited irrigation is a first step toward finding the value of water to agricultural irrigators. Production costs then can be used to find the net economic return from the proposed irrigation strategy (Klocke et al., 2006). Crop yields from a given irrigation amount also will vary from year to year when variable precipitation impacts crop production.

Many studies evaluating the sensitivity of corn to water stress have found that stress during vegetative growth affects corn grain production less than during the reproductive or grain fill growth stages. Water stress for corn during vegetative growth reduces plant stature, but the crop can recover with adequate water during reproductive phases (Robins and Domingo, 1953; Denmead and Shaw, 1960; Abrect and Carberry, 1993; Otegui et al., 1995; NeSmith and Ritchie, 1992; Cakir, 2004; Grant et al., 1989). Some researchers have suggested that water stress during vegetative growth may "condition" corn for later water stress (Stewart et al., 1975; Barrett and Skogerboe et al., 1978; Kang et al., 2000).

No-till crop management, in which crop residues are left on the surface for the next crop, offer a method to reduce soil water evaporation, making more soil water available for transpiration crop yields (Klocke et al., 2007). Better utilization of crop residues can reduce risk for limited irrigation because more water is directed to crop transpiration rather than soil water evaporation (Russel, 1939; Unger and Parker, 1976; Bond and Willis, 1969; Chung and Horton, 1987; Adams et al., 1976; Fryer and Koshi, 1971; Steiner, 1989; and Todd et al., 1991).

The first major aquifer withdrawals in southwest Nebraska occurred during the last half of the 1970s due to expansion of irrigation with the rapid adoption of sprinkler irrigation through center pivots and less than normal precipitation. Groundwater management districts began to impose restrictions on pumping to curb further declines. Field research was

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needed to anticipate irrigated crop production if more drastic mandates for more drastic pumping restrictions occurred.

A field study was designed to test crop management that (1) took advantage of delayed irrigation during crop vegetative growth, (2) limited irrigation when water applications would not be able to supply the full potential of crop yields, and (3) used no-till practices to reduce soil water evaporation and achieve other soil and water conservation benefits. The project's goal was to evaluate limited irrigation and no-till in a cropping system that used best management practices based on past research to maximize profitability. Multi-year crop performance results were needed to determine the risk for adopting limited irrigation practices. Research results then could be converted to probabilities of production returns from limited irrigation. The specific objectives of this study were to: (1) find relationships of irrigation and crop yield, (2) determine crop evapotranspiration (ETc), (3) measure soil water gains non-growing season and soil water use during the growing season, (4) predict the probabilities for achieving grain yields, and (5) evaluate the long-term economic feasibility of corn grown in rotations following corn, wheat, or soybean with no-till practices and dryland, limited irrigation, or full irrigation management.

Methods

Crop rotation research with full irrigation, limited irrigation, and dryland management was conducted at the West Central Research and Extension Center of the University of Nebraska-Lincoln at North Platte, Nebraska (41.1° N, 100.8° W, 860 m above sea level) (Schneekloth et al., 1991; Hergert et al., 1993). The semiarid climate in North Platte is characterized by frequent and rapid changes in weather conditions throughout the year. The average annual precipitation is approximately 508 mm, which is 36% of annual reference ET (ETr) using alfalfa as the reference crop (Kincaid and Heermann, 1984). Approximately 80% of the annual precipitation occurs during the summer growing season, which extends from late April until mid-October. The predominate soil texture is Cozad silt loam (fluventic Haplustoll) with pH of 7.5. Plant-available soil water holding capacity is 0.17 m^3 m^{-3} for volumetric soil water contents from 32% for field capacity to 15% for permanent wilting over 0 to 3 m of soil depth. The land slope is less than 1%.

The three crop rotations were continuous corn (CC), wheat-corn-soybean (WCS), and corn-soybean (CS). All rotations were managed with no-till practices and non-limiting fertility and pest management. Corn was planted directly into the previous crop's residue with a no-till planter equipped to apply starter fertilizer. The rest of the nitrogen was applied near the four to six leaf growth stage. Pre-emergence and post-emergence herbicides were applied as needed.

During 1980, a solid set irrigation system was installed, which included an underground piping network delivering water to sprinkler heads on the top of 3 m tall risers. The sprinklers were installed on a square grid of 12 × 12 m with a wetted radius of 12 m. The nominal plot area was 12 × 12 m, surrounded by another 12 m of buffer between plots that served as a border to separate plots with different water treatments. Crop rotations and irrigation treatments were fully established by 1985. Corn yields were measured from hand-harvested samples taken from randomly selected adjacent two rows, each 6 m long. Subsamples were taken for grain water content.

Irrigation to meet full crop ET (ETc) was scheduled from measurements of soil water deficits in each crop rotation treatment. An annual water allocation was restricted to 150 mm for the limited irrigation treatments unless there was sufficient soil water to achieve full ETc. Limited irrigation was scheduled to favor applications during critical growth stages for crop development. For corn, irrigation was reduced or withheld during the vegetative period and concentrated on reproduction and grain fill.

Soil water was measured weekly to a depth of 1.8 m in 0.3 m increments with the neutron attenuation method (Evett and Steiner, 1995). Precipitation, net irrigation, and changes in soil water from one measurement to the next were used to calculate weekly ETc. Drainage was assumed to be minimal within the one-week sampling interval of soil water and was not included in the soil water balance. Water runoff and run-on to the plots were observed to be zero. ETr, referenced to alfalfa, was estimated with a Penman combination model, which used maximum and minimum daily air temperatures, relative humidity, solar radiation, and daily wind run as inputs (Kincaid and Heermann, 1984).

The experimental design was three main blocks for full irrigation, limited irrigation, and dryland (dryland), replicated by years. Within each main block, all combinations of all crops in all rotations were randomized in four replications. Each phase of each rotation was present in each year. Data were analyzed with PROC ANOVA to find the least significant differences at 5% probability (SAS, 2006).

Economic Projections

Net returns to land, management, and irrigation equipment were estimated from the Crop Water Allocator (CWA), which was developed for western Kansas (Klocke et al., 2006; Stone et al., 2006). The CWA determines net economic return from combinations of selected crops and available water supply. Inputs to the CWA included commodity prices, maximum expected grain yields, irrigation application efficiency, and irrigation and crop production costs.

Results and Discussion

Precipitation and Alfalfa-Reference Evapotranspiration

Cropping season precipitation (table 1) was the sum of all precipitation that occurred from October in the year preceding corn planting through September of the growing season. Cropping season precipitation as a percentage of long-term average annual precipitation provided a characterization of wetter or drier years. The criterion for wetter and drier years was ±93% of the average cropping season precipitation, which divided the years into approximately two equal groups. Years 1985, 1989, 1990, 1991, 1994, and 1997 were considered drier than the long-term average. Years 1986, 1987, 1988, 1992, 1993, 1995, 1996, and 1998 were considered wetter. Precipitation during the growing season also was a factor for crop yields. Drier years had less than 300 mm of rain during May through September, while the precipitation in the wetter years for the same time period was 300 to 600 mm. Another indicator of crop performance was rainfall

Table 1. Monthly precipitation (mm) at North Platte, Nebraska.

Year	Jan.-Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.-Dec.	Annual	Oct.-Apr.[a]	May-Sept.[b]	Oct.-Sept.[c]	% Avg.[d]
1985	24	55	83	11	70	29	100	78	450	--	293	--	---
1986	42	137	86	51	65	36	36	62	515	257	274	531	105
1987	86	28	79	127	67	33	47	87	554	176	353	529	104
1988	42	53	123	94	88	112	55	19	586	182	472	654	129
1989	39	2	52	126	28	54	31	10	342	60	291	351	69
1990	49	44	71	54	34	3	10	64	329	103	171	275	54
1991	32	63	107	28	34	4	46	89	403	159	219	378	74
1992	123	0	50	67	90	116	0	28	474	212	323	535	105
1993	40	43	37	147	94	121	12	84	578	111	411	522	103
1994	11	45	26	89	126	25	19	86	428	140	285	425	84
1995	23	76	128	74	43	0	62	10	416	185	307	492	97
1996	9	17	106	79	162	88	164	22	647	36	599	635	125
1997	11	23	38	70	69	76	32	78	397	56	285	341	67
1998	42	16	51	104	77	52	22	74	439	136	307	443	87
Avg.	41	43	74	80	75	54	45	57	468	140	328	470	93

[a] Off-season precipitation from the previous October through the current April.
[b] Growing season during the current year.
[c] Total cropping season precipitation.
[d] Total cropping season precipitation as a percentage of annual long-tern average (508 mm).

for April, May, and June because this water accumulated closest to crop water needs was more effective than earlier precipitation. For example, 1995 was classified as wetter overall; however, adequate early growing season rainfall was followed by very dry months of July and August, which coincided with periods of high ET demand.

Below average ETr, during the cropping season (table 2) occurred in 1992, 1993, 1995, and 1996, corresponding to wetter years except for 1998. Above-average ETr during the cropping season occurred in 1989, 1990, 1991, 1994, 1997, and 1998.

Irrigation

Full irrigation amounts generally were inversely related to rainfall patterns in July and August (table 3). Soil water deficits created by crop water use were replenished with rainfall and/or irrigation. During September 1989, season-ending irrigation on the fully irrigated treatments may not have been effective for crop use. Starting in 1992, irrigation needs declined in the wetter years when rainfall patterns during the growing season replaced irrigation. An exception occurred during 1995, considered as a wetter cropping season, when lack of rainfall in July and August led to more irrigation.

Crop production and soil water parameters were compared using year, irrigation treatment, and crop rotation as independent variables for 1986-1998 (table 4) when data from the continuous corn and wheat-corn-soybean rotations were grown. The same data were compiled during 1992 though 1998 were compiled when all three rotations were available for comparisons (table 5). Comprehensive soil water data were not available during 1988, 1990, 1991, and 1996.

Cropping season precipitation plus irrigation for the full and limited irrigation treatments correlated with ETr (table 4). Irrigation plus precipitation ranged from 437 mm to 773 mm during the nine years of record. This range was 72% to 128% of the mean. An indication of atmospheric demand for ETc was ETr for the growing seasons, which ranged from 3.96 to 7.72 mm day^{-1} and from 61% to 121% of the mean. The years 1992-1998 with three crop rotations (table 5) had similar trends as all the years for the CC and WCS rotations. Combined irrigation and precipitation were 79% to 127% of the average, while ETr was 67% to 130% of the average. Average irrigation plus precipitation and ETr were less during 1992-1998 than the full years of record.

Table 2. Monthly alfalfa-reference evapotranspiration (ETr) (mm) at North Platte, Nebraska.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual	Oct.-Apr.[a]	May-Sept.[b]	Oct.-Sept.[c]
1989	67	37	112	202	223	216	238	184	155	125	80	40	1677	--	1015	--
1990	60	64	95	142	150	254	211	188	178	125	69	39	1575	606	981	1587
1991	40	86	123	142	153	183	221	215	163	120	41	43	1529	623	936	1558
1992	45	60	105	157	211	145	162	154	168	109	32	31	1378	571	839	1410
1993	23	22	79	115	158	185	176	152	130	96	60	46	1243	411	801	1213
1994	32	45	129	155	218	216	198	193	171	100	63	33	1552	562	996	1559
1995	36	71	99	112	101	205	220	245	146	105	71	49	1459	514	917	1431
1996	44	86	104	176	124	195	176	145	102	101	39	38	1330	636	741	1377
1997	49	45	149	127	188	206	220	156	138	113	58	35	1483	548	907	1455
1998	37	46	74	159	187	188	185	182	201	78	53	52	1443	522	943	1465
1999	47	95	115	109	182	195	240	164	124	126	81	48	1525	549	905	1454
Avg.	44	60	108	145	172	199	204	180	152	109	59	41	1472	554	907	1451

[a] Off-season ETr from the previous October through the current April.
[b] Growing season total for current May through September.
[c] Cropping season from the previous October through the present September.

Table 3. Annual irrigation (mm) applied to corn at North Platte, Nebraska, during 1985-1999.

	Limited Irrigation			Full Irrigation		
Year	CC[a]	WCS	CS[b]	CC	WCS	CS
1985	165	165	--	345	345	--
1986	157	157	--	399	399	--
1987	152	152	--	391	391	--
1988	150	150	--	254	254	--
1989	152	152	--	546	493	--
1990	152	152	--	323	323	--
1991	157	157	--	287	287	--
1992	109	116	103	76	76	76
1993	51	51	0	51	0	51
1994	0	0	0	152	178	178
1995	147	127	241	387	381	394
1996	N/A[c]	N/A	N/A	N/A	N/A	N/A
1997	111	88	76	139	139	160
1998	101	101	101	152	152	203
1999	76	76	76	99	99	99
Average	120	118	85	257	251	166
% of Full	47	47	51	--	--	--

[a] CC = continuous corn, WCS = winter wheat-corn-soybean, and CS = corn-soybean.
[b] Corn-soybean rotation was initiated during 1992.
[c] Data not available in 1996.

Grain Yield

Grain yields over years (tables 4 and 5) included data from dryland, limited irrigation, and full irrigation treatments. Average corn grain yields were 74% to 134% of the mean for 1986-1992 and 73% to 134% of the mean for 1992-1998 (tables 4 and 5). More or less, corn production followed the pattern of wetter and drier years, except for 1995, which had the least precipitation in July and August. Corn yields were statistically different among water treatments and increased with additional irrigation. Corn yields from the WCS rotation were significantly more (0.7 Mg ha^{-1}) than CC during 1986-1998, which corresponded to off-season gains and in-season use of soil water. More soil water was accumulated and consumed in the WCS rotation because more time was available to accumulate soil water after winter wheat harvest than after the corn or soybean harvest. During 1992-1998, corn yields from the CC, WCS, and CS rotations were not statistically different. Soil water use was more for the WCS rotation, but off-season gains were the same.

Irrigation water use efficiency (IWUE = [irrigated yield – dryland yield] / [irrigation amount]) was calculated only for the limited and full irrigation treatments. IWUE was consistently more for limited irrigation than full irrigation because the first increment of irrigation was used more efficiently than additional irrigation. Full irrigation had more possibility for deep percolation and soil water evaporation from more frequent surface wetting. The effect of crop rotation on IWUE produced mixed results.

Soil Water

Growing season use of soil water (tables 4 and 5) tended to correlate with off-season gains in soil water. Available soil water holding capacity in the deep silt loam soil contributed to the ability to store water. Limited and full irrigation treatments stored the same amount of water when all rotations were compared, but the dryland treatment stored significantly more water because roots grew deeper, creating more soil

Table 4. Results for corn in the continuous corn (CC) and wheat-corn-soybean (WCS) rotations at North Platte, Nebraska, during 1986-1998.[a]

	Yield[b] (Mg ha^{-1})	IWUE[c] (kg m^{-3})	CS[d] Precip. (mm)	Total Irrig. (mm)	Irrig. and Precip. (mm)	Off-Season SW Gain[e] (mm)	SW Use[f] (mm)	SW Use[f] (mm day^{-1})	ETc/day[g] (mm day^{-1})	ETr/day[g] (mm day^{-1})	Etc/ETr
(a) Year as an independent variable over water treatments and rotations											
1986	9.4 cd	1.70 d	394	278	672	237 b	180 b	1.97 b	5.9 c	7.41	0.80 d
1987	9.9 c	2.72 bc	501	272	773	261 a	168 bc	1.86 bc	6.6 b	7.64	0.87 cd
1989	8.2 e	3.48 ab	349	336	685	89 d	100 d	1.09 d	5.7 cd	7.00	0.82 d
1992	12.9 a	0.24 e	535	94	629	--	143 c	1.19 d	4.2 ef	3.96	1.06 b
1993	9.8 c	2.71 c	479	38	517	179 c	147 c	1.67 bc	5.6 cd	5.34	1.05 b
1994	9.3 cd	--	380	83	463	61 de	100 d	1.02 d	4.0 f	6.32	0.64 f
1995	7.1 f	2.51 c	416	260	676	193 c	329 a	4.76 a	10.0 a	7.72	1.30 a
1997	10.4 b	2.72 bc	318	119	437	--	10 e	0.28 e	4.5 e	6.26	0.72 e
1998	9.1 d	4.22 a	427	127	554	54 e	88 d	1.42 cd	10.0 a	6.06	0.89 c
$LSD_{0.05}$	0.65	0.76	--	--	--	31	29	0.46	0.47	--	0.07
(b) Irrigation as an independent variable over years and rotations											
Dryland	7.8 c	--	422	0	442	205 a	193 a	2.50 a	4.9 c	6.40	0.77 c
Limited	10.6 b	3.00 a	422	107	549	152 b	146 b	1.68 b	5.6 b	6.40	0.88 b
Full	11.8 a	2.01 b	422	250	672	112 c	82 c	0.91 c	6.8 a	6.40	1.06 a
$LSD_{0.05}$	0.38	0.38	--	--	--	20	17	0.27	0.27	--	0.04
(c) Rotation as an independent variable over years and water treatments											
CC	9.2 b	2.87 a	422	179	620	115 b	125 b	1.53 b	5.6 b	6.4	0.88 b
WCS	9.9 a	2.14 b	422	179	620	198 a	156 a	1.86 a	5.9 a	6.4	0.93 a
$LSD_{0.05}$	0.31	0.38	--	--	--	17	14	0.22	0.22	--	0.03

[a] Means followed by the same letters in the same column and independent variable are not significantly different.
[b] Average yield included dryland, limited, and full irrigation.
[c] IWUE = irrigation water use efficiency (irrigated yield - dryland yield)/(irrigation amount).
[d] Cropping season precipitation from Oct. 1 of previous year to Sept. 30 of current year.
[e] Off-season soil water accumulation from previous fall through the current spring.
[f] Growing season stored soil water use.
[g] ETc and ETr = crop and reference ET during soil water measurement period.

Table 5. Results for corn in the continuous corn (CC), wheat-corn-soybean (WCS), and corn-soybean (CS) rotations at North Platte, Nebraska, for 1992-1998.[a]

	Yield[b] (Mg ha^{-1})	IWUE[c] (kg m^{-3})	CS[d] Precip. (mm)	Total Irrig. (mm)	Irrig. and Precip (mm)	Avg. FASW[e]	Off-Season SW gain[f] (mm)	In-Season SW use[g] (mm)	In-Season SW use[g] (mm day^{-1})	ETc/day[h] (mm day^{-1})	ETr/day[h] (mm day^{-1})	Etc/ETr
(a) Year as an independent variable over water treatments and rotations												
1992	13.1 a	0.77 c	535	93	628	0.73 b	--	135 b	1.12 c	4.1 cd	3.96	1.03 b
1993	9.9 c	3.20 ab	479	34	513	0.85 a	173 a	143 b	1.62 b	5.75 b	5.34	1.07 b
1994	9.3 d	--	380	85	465	0.70 b	64 b	91 c	0.92 c	3.95 d	6.32	0.63 e
1995	7.2 f	2.55 b	416	280	696	0.74 b	191 a	335 a	4.85 a	9.80 a	7.72	1.26 a
1997	10.5 b	2.58 b	318	119	437	0.68 b	--	11 d	0.29 d	4.51 c	6.26	0.72 d
1998	8.5 e	3.66 a	427	135	562	0.68 b	57 b	81 c	1.30 bc	5.28 b	6.06	0.87 c
$LSD_{0.05}$	0.47	0.69				0.06	34	32	0.49	0.49	--	0.07
(b) Irrigation as an independent variable over all years and rotations												
Dryland	8.8 c	--	426	0	426	0.62 c	177 a	184 a	2.60 a	4.83 c	5.95	0.82 c
Limited	11.3 b	2.93 a	426	85	511	0.82 a	94 b	114 b	1.39 b	5.38 b	5.95	0.91 b
Full	11.6 a	2.18 b	426	164	590	0.74 a	94 b	99 b	1.07 b	6.48 a	5.95	1.07 a
$LSD_{0.05}$	0.33	0.43				0.046	30	23	0.35	0.35	--	0.052
(c) Crop rotation as an independent variable over years and water treatments												
CC	10.6a	2.75a	426	123	549	0.75a	109a	124b	1.59a	5.51a	5.95	0.92a
WCS	10.6a	2.11b	426	117	543	0.76a	121a	148a	1.86a	5.75a	5.95	0.96a
CS	10.5a	2.80a	426	132	558	0.67b	134a	125b	1.61a	5.44a	5.95	0.91a
$LSD_{0.05}$	0.33	0.53				0.046	30	23	0.35	0.35		0.052

[a] Means followed by the same letters in the same column and independent variable are not significantly different.
[b] Average yield included dryland, limited, and full irrigation.
[c] IWUE = irrigation water use efficiency [(irrigated yield - dryland yield)/(irrigation amount)] for limited and full irrigation.
[d] Total cropping season rainfall (previous Oct. through the following Sept.).
[e] FASW = average fraction of available soil water in 1.8 m of soil depth during the growing season.
[f] Off-season soil water accumulation from previous fall through the current spring.
[g] Growing season stored soil water use.
[h] ETc and ETr = crop and reference ET during soil water measurement period.

water storage volume to hold off-season precipitation. Dryland corn extracted water from as much as 2 m deep into the soil, while fully irrigated corn extracted most of its water from the top 1 m of soil (data not shown). When the CC and WCS rotations were compared, soil water gains were significantly different from each other. Time available for soil water accumulation was longer in the WCS rotation because corn followed winter wheat rather than corn.

Stored soil water use during the growing season as a fraction of ETc ranged from 6% to 49% for 1986-1998 (table 4). Stored soil water contributed 49% of ETc in 1995 when little rainfall occurred during July and August. The soil water data collection period during 1997 was shorter than the other years, which may have reduced the stored soil water contribution to ETc. During the other years, soil water contribution to ETc was more consistent, from 14% to 33%. Stored soil water use was 15%, 27%, and 52% of ETc for full irrigation, limited irrigation, and dryland, respectively. Less stored soil water contributed to ETc as more irrigation was added. Stored soil water was 27% to 32% of ETc across the three crop rotations.

Average fraction of available soil water (FASW) remaining in 1.8 m of soil depth during the growing season was calculated for 1992-1998 when data were available (table 5). There was no statistical difference among years except for 1993, when above normal rain in June may have contributed to more soil water. The FASW for limited and full irrigation was significantly more than dryland FASW. Corn following soybean had significantly less FASW than the CC and WCS rotations. Soil water extraction by soybean at the end of the growing season tended to be more than the other two rotations.

ETc and ETc/ETr (tables 4 and 5) increased significantly for each water treatment from dryland to full irrigation. However, ETc and ETc/ETr remained nearly constant across crop rotations. Additional irrigation was used to increase ETc, and more off-season soil water accumulation from dryland management also contributed to more ETc.

Relative Grain Yield

Limited irrigation and dryland corn yields were scaled as a fraction of fully irrigated yields from the same year (fig. 1).

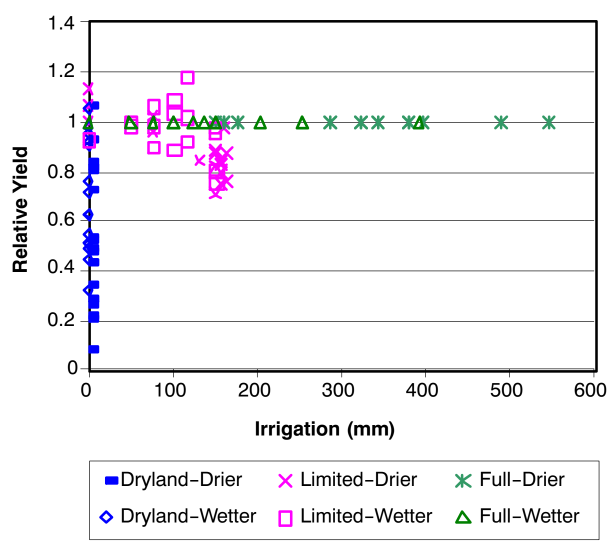

Figure 1. Crop yields as a fraction of fully irrigated yields for the drier years of 1985, '89, '90, '91, '94, '97, and '98 and the wetter years of 1986, '87, '88, '92, '93, '95, and '99.

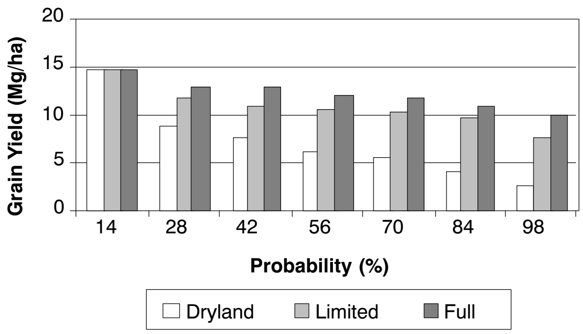

Figure 2. Percentage of time that crop yields exceed a given amount. Results based on yield history for the years 1985-1999.

The years 1990, 1991, and 1999 were added to the data set because yield and irrigation data were available. Data from all crop rotations were used because preceding analysis indicated little difference in corn production during the years following corn, wheat, or soybean. The range of relative yields from dryland management (*y*-axis of fig. 1) was 0.10 to 1.15 in the drier years and 0.20 to 1.05 in the wetter years, which indicated somewhat more variation in yields from the drier years. The limited irrigation applications generally were more during the drier years than the wetter years. Limited irrigation increased relative yields compared with dryland yields and decreased the risk for yield results because added irrigation reduced the range of yields to 0.2 to 1.2 for the wetter years and 0.75 to 1.15 for the drier years. The range of full irrigation applications demonstrated that irrigation scheduling was necessary to capitalize on water conservation during the wetter years and match ETc during drier years.

Yield Probability

Corn yields were ranked from maximum to minimum by water treatments for all years and crop rotations. The ranked data were divided into seven groups of probability values by years (fig. 2). Annual rainfall was 640, 610, 560, 510, 460, 430, and 410 mm for the 14%, 28%, 42%, 56%, 70%, 84%, and 98% probability levels, respectively (NOAA, 2007). Corn yields for each grouping of vertical bars would be expected to exceed that amount *X* years out of 100 years. For the least probability or wettest years (14 out of 100 years), all water treatments had similar yields. As probability increased from wet to dry years, irrigated corn yields decreased, but the dryland yields decreased more dramatically.

Economic Implications

One set of economic input values for the WCS rotation (table 6) was used to evaluate the net economic return from an equal division of land among wheat, corn, and soybean with the CWA. CWA optimized the distribution of irrigation among the crops with annual water allocations of 300 mm for full irrigation and 150 mm for limited irrigation (table 7a). Calculated yields from CWA, as a function of water treatments, matched field data except for dryland corn (table 7b and 7c). Net economic returns for corn to land, management, and irrigation equipment increased from dryland to full irrigation, but net returns for dryland wheat were more than dryland corn (table 7d). Relatively high operating cost for dryland corn decreased income potential. Even though operating costs were the most for irrigated corn (table 7e), corn had the most net return from limited and full irrigation, which indicated that corn would be the predominate crop for the example's commodity prices.

Table 7. Outputs from Crop Water Allocator (CWA).

	Dryland	Limited	Full
(a) Irrigation (mm)			
Wheat	0	142	201
Corn	0	155	363
Soybean	0	147	277
Average	0	148	280
(b) Yields from field study (Mg ha^{-1})			
Wheat	2.4	4.2	4.3
Corn	5.8	10.2	12.6
Soybean	1.5	3.1	4
(c) Yields predicted by CWA (Mg ha^{-1})			
Wheat	2.1	3.8	4.2
Corn	3.6	10.2	13.5
Soybean	1.5	3.1	4
(d) Net return (\$ ha^{-1})[a]			
Wheat	131	206	203
Corn	87	722	925
Soybean	67	246	285
Average	94	389	471
(e) Operating costs with irrigation (\$ ha^{-1})			
Wheat	191	372	432
Corn	446	828	1069
Soybean	241	402	541
Average	293	534	680

[a] Net return to land, management, and irrigation equipment.

Summary

Corn was grown in a no-till cropping system using best management practices to apply water to limited and full irrigation treatments. Limited irrigation was initiated late in the vegetative growth stage or early in the reproductive stage, while full irrigation was applied to meet ETc during the growing season. The limited irrigation treatment received no more than 150 mm, which was applied to favor supplying water during the reproductive and grain fill growth stages. Continuous corn (CC), wheat-corn-soybean (WCS), and corn-soybean (CS) crop rotations were grown in the dryland,

Table 6. Input values for determining net return with Crop Water Allocator (CWA).

	Value	Units	Comment
Irrigation system application efficiency	100	%	Net irrigation values were used
Annual precipitation	530	mm	Default crop response to irrigation
Irrigation allocation[a]	0, 150, 280	mm	Dryland, limited, full
Maximum expected grain yield	13, 4, 4	Mg ha^{-1}	For corn, soybean, wheat
Commodity prices	32, 54, 33	\$ Mg^{-1}	For corn, soybean, wheat
Irrigation operating cost	0.13	\$ ha^{-1} mm^{-1}	

[a] From average irrigation amount for wheat, corn, soybean field results.

limited irrigation, and full irrigation treatments. Corn yields were statistically different among dryland, limited irrigation, and full irrigation treatments and increased with added irrigation. When the CC, WCS, and CS rotations were compared, corn yields were statistically the same across water treatments. ETc was significantly different among water treatments and increased with additional irrigation, but there was no crop rotation effect on ETc. Irrigation water use efficiency (IWUE), defined as the additional crop yield over dryland production divided by irrigation, was significantly more from limited irrigation than full irrigation. The CC and CS rotation had statistically the same IWUE, but the IWUE for both the CC and CS rotations was significantly more for than the WCS rotation.

From soil water parameter measurements, more statistical differences were detected among the water management treatments than among the crop rotation treatments. Corn in the WCS was able to use more stored soil water than the CC or CS rotations, which may have led to less dependence on irrigation. The dryland treatment accumulated significantly more soil water during the non-growing season than the limited or fully irrigated treatments because the dryland corn was forced to extract more soil water deeper into the soil profile, leaving more room for water storage. Available soil water as a fraction of available water capacity (FASW) during the growing season was similar for the two irrigation treatments but significantly less in dryland treatment. Dryland yields, as a fraction of fully irrigated yields, resulted in more yearly variation than limited irrigation yields, decreasing the income risk for limited irrigation compared with dryland. Over the years of the study, a wide range in water applications to the full irrigation treatment demonstrated the need to schedule irrigations to match crop water needs; otherwise, over and under irrigation could occur. When crop yields from all years and rotations were ranked from maximum to minimum values within each water treatment, yield results were predicted on the basis of probabilities. During the wettest years with low probability of occurrence, dryland, limited irrigation, and full irrigation yields were nearly the same. As probabilities to achieve yields increased, indicating drier and drier years, dryland yields were 25% of fully irrigated yields, and limited irrigation yields were 75% of fully irrigated yields at 98% probability of occurrence.

Net economic returns were calculated for one example of the WCS rotation using one set of inputs. When the cropland was divided equally among wheat, corn, and soybean, economic projections showed that full irrigation produced the most income if water was available. Limited irrigation increased income significantly from dryland management. Dryland net return from the WCS rotation was 25% of full irrigation's net return, while limited irrigation net return was 83% of full irrigation. Even though operating costs were the most for irrigated corn compared with wheat and soybean, corn had the most net return from limited and full irrigation.

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