FIELD SCALE LIMITED IRRIGATION SCENARIOS FOR WATER POLICY STRATEGIES

N. L. Klocke, J. P. Schneekloth, S. R. Melvin, R. T. Clark, J. O. Payero

ABSTRACT. *Approaches to reducing irrigation inputs to crops have been studied for the past 50 to 60 years in research settings. Fewer efforts have been made to document limited irrigation responses over a number of seasons on commercial fields. This study compared farm−based irrigation management (FARM) with best management practices (BMP), late initiation of irrigation (LATE), and a restricted allocation (ALLOC). These irrigation management strategies each occupied 1/8 of a center pivot system in southwest Nebraska in continuous corn production, on four cooperating farms, which were replicated at the same sites for 3 to 6 years. Irrigation variables were achieved by irrigating or not irrigating, or by speeding up or slowing down the center pivot. When the grain yields and irrigation amounts were normalized each year using the FARM treatment as the basis, on average for three of four locations, the BMP treatment yielded equal to the FARM treatment, the LATE treatment yielded 93% of the FARM treatment and the ALLOC yielded 84% of the FARM treatment. At the same time, it took 76% and 57% of the water for the LATE and ALLOC treatments, respectively, to achieve these yields. The adjusted gross returns (yield × price – irrigation treatment costs) of the irrigation treatments were analyzed for each location. When the gross returns were normalized using the FARM treatment as the basis, FARM and BMP returns were equal across combinations of high and low input commodity prices and pumping costs. The LATE treatment gross return was 95% of FARM return. The gross return for the ALLOC treatment was 85% to 91% of the FARM treatment. The higher the water costs, the lower the difference between the highest and lowest returning water treatments. Relationships between evapotranspiration and grain yield were developed for two sites over the limited range of water applications of the projects. Regressions indicated more variability between the commercial field data and research plot environments. Much of this difference may have been due to yearly replication in this study rather than plot−to−plot replication in the research center study. Yield and irrigation data were normalized on the basis of the FARM treatment. Normalized yield – irrigation results over years and locations for three of the four locations showed declining yields as irrigation decreased. The same regression was used to normalize the locations with soil textures from fine sand to sandy loam, which suggested that the three locations behaved similarly with respect to the management treatments.*

Keywords. *Limited irrigation, Water conservation, Water management, Irrigation scheduling, Irrigation requirements, Evapotranspiration, Irrigation research, Irrigation systems.*

Great Plains farmers face increasing challenges from limited and variable water supplies for sustaining irrigated crop yields and profitability. Water tables are declining in many areas and surface water supplies are over appropriated and unreliable. Present approaches to irrigated food production are not sustainable. For example, Texas irrigated cropland declined from 2.8 to 2.0 million ha (6.9 to 4.9 million acres) between 1969 and 1992 (Census of Agriculture, 1992). Kansas had 0.61 million ha (1.5 million acres) in 1969, grew to 1.4 million ha (3.5 million acres) in the late 1970's, and was back to 1.2 million ha (3.0 million acres) in 1992. Water tables have declined 9 to 15 m (30 to 50 ft) in southwest Nebraska. Since irrigation predevelopment, saturated thickness has reduced by over 30 m (100 ft) in some portions of the High Plains Aquifer in southwestern Kansas (Kansas Geological Survey, 1999). Texas irrigators depleted the Ogallala aquifer by 6 to 14 m (20 to 45 ft) in the period from 1969 through 1991 (Ashworth, 1991).

Limited irrigation occurs when a producer is unable to meet the evapotranspiration (ET) demand of the crop with irrigation on the entire field. The result is less than maximum potential production of that crop. There are several reasons why producers resort to limited irrigation management. Declining water tables lead to restricted well delivery capacity and the resulting diminished capacity of the irrigation system. Falling water tables in Kansas and Texas have reduced well capacities and forced irrigators to move to crops with lower water requirements or reduce irrigated area. Water policy can also restrict water for irrigation. For example, a natural resource district in southwestern Nebraska has responded to groundwater declines by reducing water

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allocations to all irrigators, effectively limiting applications to some crops. Multi−year allocations have allowed for “banking” water from one year to the next, but irrigators are planning for water shortages. In Kansas, some river basins and many aquifer systems have been closed for further irrigation development. In some instances, “junior” or holders of newer groundwater rights are not able to use all of their water in preference to “senior” or holders of older water rights. More challenges and competition for water are looming.

Researchers have been working for the past 30 years to develop relationships between the water use by crops and the grain yield that these crops produce. Furthermore, they have examined the response of corn to water stress during the three major growth stages, vegetative, flowering, and seed fill. Robins and Domingo (1953) identified the sensitivity of corn to water stress during the pollination period at Prosser, Washington. They stressed corn at soil water contents near wilting point for two days during the pollination period and caused 22% reduction in grain yield. Six to eight days of this type of stress caused 50% yield reduction. Stewart et al. (1975) established linear relationships between ET and grain yield for corn at Davis, California. They also supported the research findings that corn may be water stressed during the pollination period without major yield loss, provided the crop has experienced little ET deficit in the late vegetative period. They went on to say that corn is conditioned to water stress during pollination if there have been prior deficits. Barrett et al. (1978), who worked in the Grand Valley of Colorado, found a “severe depression of yield caused by stress during the pollination period. If deficits have also occurred in the vegetative period, the crop may be somewhat conditioned to stress and the detrimental effect of the pollination period stress may be lessened in terms of water use efficiency.” Stegman (1982) recommended irrigation management strategies where soil water depletions are near field capacity at planting, no more than 60% to 70% during early vegetative growth, 30% to 40% during 12 leaf to blister kernel, and 50% to 60% for later grain fill, based on research in North Dakota. Schneekloth et al. (1991) applied limited irrigation to crop rotations including continuous corn and corn−soybean−wheat in west−central Nebraska and developed relationships between crop water use and grain yield. The management strategy was initiation of limited irrigation during late vegetative growth. Irrigation was limited to approximately one half of normal application for corn. The limited irrigated continuous corn yielded 81% of the fully irrigated corn and corn following winter wheat yielded 85% of fully irrigated corn in rotation. Research on crop yield−water use relationships has traditionally been conducted with small plot trials in controlled settings. Demonstrations at the field scale are needed to show whether limited irrigation management can work. Irrigators have questions about the response time to irrigating with commercial irrigation systems that researchers do not face. They worry about the crop “burning up” when the irrigation system will not be able to catch up. Irrigators need positive proof of potential results in order to accept changes in management.

OBJECTIVES

The objectives of this research were:

1. To determine crop production results from full and limited irrigation management strategies on farm scale fields.
2. To project economic returns from these irrigation management strategies on farm scale fields.
3. To determine the relationships between crop production and both irrigation and crop water use in farm scale production.
4. To determine the slopes and variability in the crop production relationships including yield versus crop water use and yield versus irrigation amount.

METHODS

COOPERATOR SELECTION

The local extension personnel for the project selected four cooperators. They were excellent managers with interest in water issues and very proficient crop producers. During initial interviews, they expressed concern with the possibility of portions of their field being under water stress. The monetary payback provided by project funds to compensate for reduced grain yields due to treatment effects eased their concern, but public viewing of water stressed portions of their fields was still disconcerting. Without the compensation from the grant, the project would not have been possible on a field scale basis.

SITES

In 1996, sites near Arapahoe, Dickens, and Elsie, Nebraska were selected for the project. One site near Benkleman, Nebraska was added in 1999. The study was continued through 2001. Corn was grown at all of those sites each year except for the Dickens site in 2000, which was planted to soybeans. Only corn data are reported in this article. These sites were irrigated with center pivot systems and were used to determine corn yield response to four different irrigation management strategies. The tillage and cropping practices that the farmer already had in place were continued as conventional systems. Typically, tillage consisted of one or two disking operations followed by planting. The Arapahoe site used less tillage than the other sites. Timing and amount of irrigation water applied were the only management variables that changed among the water strategies (described later) at any of the sites.

SITE DESCRIPTIONS

The soil texture, soil water holding capacity (field capacity to wilting point), topography, field area, and well capacity characteristics of the four sites are listed in table 1.

IRRIGATION MANAGEMENT STRATEGIES

The following four irrigation management strategies were compared at each of the sites:

- Current farm management (FARM) – irrigation water was applied according to the farmer’s current management strategy. These strategies ranged from irrigations from the capacity of the well to following evapotranspiration demand.

Table 1. Site description.

Site	Soil Texture	Water Holding Capacity (mm/m)	Field Slope (%)	Field Area (ha)	Well Capacity (L/min)
Arapahoe	Holdredge silt loam	167	0−2	22[a]	1890
Benkleman	Jamen loamy sand	150	0−1	52	2550
Elsie	Woodly fine sandy loam	125	0−5	25[a]	2270
Dickens	Valentine fine sand	92	0−5	53	3880

[a] The field at the Arapahoe site was divided among a wheat−corn−soybean rotation, which included the furrow irrigated corners of the quarter section, all serviced by one well. This resulted in an irrigation capacity of 29 L/min−ha (3.1 gpm/acre). This capacity was effectively increased since each crop in the rotation has a different timing for peak water use. The field at the Elsie site was divided equally between irrigated corn and either wheat or soybean. The combined irrigation capacity of the Elsie Site was 45 L/min−ha (4.8 gpm/acre). The irrigation capacities of the Benkleman and Dickens sites were 50 and 74 L/min−ha (5.3 and 7.9 gpm/acre), respectively.

- Best management practices (BMP) – included bi−weekly soil water monitoring, prediction of crop water use (ET), and maintenance of plant available soil water (in the active root zone) between 50% depletion and field capacity (minus a rainfall allowance during the vegetative and reproductive growth stages). Late season management targeted 60% depletion of soil water in the root zone at crop maturity (i.e. black layer for corn).
- Late initiation (LATE) – emphasized water application during the crops reproductive growth stage. Irrigation was not applied until two weeks prior to tassel emergence for corn unless soil water became 70% depleted during the vegetative growth stage. Once the crop reached the reproductive growth stage, LATE was managed the same as BMP.
- Limited allocation (ALLOC) – managed the same as LATE except only 250 mm (10 in.) applied as a target per season in Dickens and 150 mm (6 in.) in the other three locations. The allocation was intended to be an average over the years of the project and increase in the dry years and decrease in the wet years. This allocation was applied during a period beginning with the reproductive growth stage and continuing into the grain fill growth stage (approximately five weeks). The allocation was projected as a possible future target for local natural resource districts.

PHYSICAL LAYOUT OF PLOTS AND PLOT MANAGEMENT

Each half circle of the cooperators' center pivot was divided into four pie−shaped areas. The farmer did have the option to pick the location of the treatment that he would manage according to his current practices. The best management treatment was paired with the farmer treatment (fig. 1). In each case, soil conditions and cropping history tended to favor the FARM treatment.

Differences in water applications were achieved by speeding up or slowing down the center pivot system at the intersection of each treatment. On some occasions the center pivot could be turned on, turned off, or reversed, if necessary. To perform these functions, automated control panels, available as system options from center pivot manufacturers, were furnished to the farmers as part of the project.

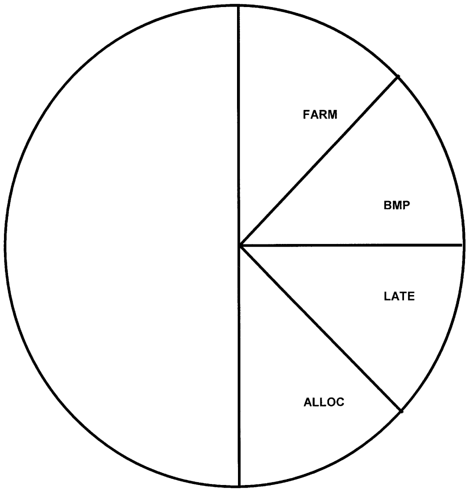

Figure 1. Arrangement of irrigation management treatments under the center pivot.

The plots were in the same physical location each year. Subsoil water content was not replenished at the end of the growing season or at the start of the next year. Precipitation was the only recharge available to the soil profile during the non−growing season.

DATA COLLECTION TECHNIQUES

Rainfall was collected at each site with a Tenite rain gauge. The farmers read and recorded the rainfall. Rainfall records were stored at the rain gauge site so that the project technicians could update irrigation schedules during field visits.

Gross irrigation was measured with a propeller flow meter equipped with a totalizer. These measurements, along with travel speeds of the center pivot systems, were used to set the timers for the irrigation sets. Volumetric soil water content was measured with the neutron attenuation method. The measurements were taken from the surface to a depth of 3 m (10−ft) in 0.3 m (1−ft) increments, except in 2001 when a sampling depth of 1.8 m (6 ft) was used. A sampling time interval of 2 weeks was followed. Percolation was assumed to be negligible and irrigation efficiency was assumed to be 85%. Evapotranspiration was estimated with a calculated water balance of rainfall, net irrigation, and change in volumetric soil water content.

Grain yields were measured by hand harvested plots, combine yield monitors, and complete plot harvest (table 2). Hand harvests were two 3−m (10−ft) rows randomly chosen from 6 locations within each irrigation plot.

Table 2. Harvest methods used at each location for each year of study.

Site	1996	1997	1998	1999	2000	2001
Dickens	Hand	Hand/yield monitor	Yield monitor	Yield monitor	No corn	Yield monitor
Elsie	Hand	Hand/yield monitor	Yield monitor	Yield monitor	Yield monitor	Yield monitor
Benkleman				Yield monitor	Yield monitor	Yield monitor
Arapahoe	Hand	Hand	Hand	Hand	Hand	

ECONOMIC ANALYSIS

The economic analysis was based on a partial budget approach. Only costs that differed due to the irrigation management strategy were included. Those costs included cost for applying the irrigation water (referred to as water cost) and harvest costs including grain hauling and grain drying. Water costs per acre−inch were initially estimated by assuming a 38−m (125−ft) lift and 241−kPa (35−psi) discharge pressure at the well head. Water costs were based on 2001 crop budgets for Nebraska (Selley et al., 2001) and included a charge for pumping related depreciation on the pump, power unit, and center pivot. Irrigation labor, irrigation system repairs, and fuel cost were also included in the initial estimate of water cost. The initial estimates for water costs from the budgets were $0.08/ha−mm ($5/acre−in.) for a center pivot. The cost of power and the type of power source impact the costs as do the total lift and type of irrigation system. Since these costs can vary between locations and as fuel prices change, a sensitivity analysis to pumping costs was conducted using $0.04 and $0.08/ha−mm ($2.50 and $7.50/acre−in.) as alternatives to the basic $0.08/ha−mm ($5.00/acre−in.) water cost.

In practice, fertilizer and seeding levels may vary between irrigation management systems; however, producers implementing these systems in the demonstration/research projects treated the entire field with the same planting and other cultural practices regardless of irrigation management. Artificially varying the fertilization and seeding rates could bias input costs that would not be reflected in crop yield data. As a result, those costs were not included. Harvest costs were based on custom rates (Jose and Brown, 2002) and were broken into two charges, $8/ha ($20/acre) and $3.54/Mg ($0.09/bu) exceeding 8.7 Mg/ha (130 bu/acre). Drying corn is a common procedure in the area. It was assumed that 4% grain moisture content would be removed by drying at a cost of $1.18/point/Mg ($0.03/point/bu) removed (Selley et al., 2001). This procedure permits a more accurate reflection of costs when yields vary between treatments.

Sensitivity analyses for the alternate management systems were also conducted. Costs per ha−mm (acre−in.) of water were varied since water costs do vary between users and years due to fuel type, fuel cost, pumping lift, and type of system. Four corn prices were used based on the actual corn prices received by Nebraska producers over the years of the study, 1996−2001 (Mark et al., 2003). The corn prices were $74.60, $84.50, $92.30, and $104.10/Mg ($1.90, $2.15, $2.40, and $2.65/bu). During the years of the study, actual corn prices varied from $68.80 to $71.80/Mg ($1.75 to $2.64/bu). We used $74.60/Mg ($1.90/bu) as the low since that price reflects the government loan rate and most producers will obtain that level by either using commodity loans or loan deficiency payments (LDP). Corn yield was also permitted to vary for the sensitivity analysis for each site according to the actual yield for a given year.

A standard analysis of variance was conducted on the adjusted gross returns to determine whether or not differences between management strategies were significant. Data used for the tests were arrays of adjusted gross returns generated by multiplying crop yield in each year by four corn prices, minus appropriate harvest and drying costs and water costs for the given year. This multiplication resulted in arrays that varied in size by site and water management option from 12 numbers for sites with 3 years of data (Benkelman) to 24 numbers for Elsie, which had 6 years of data.

RESULTS

OVERALL YIELD AND WATER APPLICATION

Table 3 shows average corn yields for four project sites with center pivots during 1996−2001. The annual yields and gross irrigations were influenced by rainfall amounts (table 4) at the sites. For the four sites, FARM and BMP average yields ranged from 13.2 to 14.1 Mg/ha (196 to 210 bu/acre). Cooperators at these sites had historically been using amounts of irrigation water at or near BMP levels. This point is important because reductions in water use from BMP levels can significantly affect yields.

A statistical analysis was performed comparing the grain yields for the water management strategies from each of the demonstration sites, Dickens, Elsie, Benkleman, and Arapahoe (table 5). The data were first screened for significance of water management treatment differences with a single factor ANOVA. Years were used as replications. Only two locations, Elsie and Dickens, had five common years of observations. The probability levels for significance tended to follow the number of years that data were available from each site. After Arapahoe, Benkleman had the shortest record (3 year) and lowest probability for significant differences and

Table 3. Grain yield summary for management strategies at Dickens, Elsie, Benkleman, and Arapahoe.

Location	Irrigation			
	FARM (Mg/ha)	BMP (Mg/ha)	LATE (Mg/ha)	ALLOC (Mg/ha)
Dickens				
1996	13.0	13.3	12.8	12.9
1997	11.9	10.0	9.8	9.1
1998	13.9	13.9	11.7	10.4
1999	13.4	13.4	12.7	11.8
2001	14.1	13.5	13.2	11.8
Average	13.6	13.4	12.0	11.2
Elsie				
1996	14.7	14.6	14.6	14.4
1997	11.8	11.8	11.1	9.1
1998	12.8	12.8	11.8	9.8
1999	12.8	12.8	12.1	11.1
2000	13.8	13.8	11.4	8.9
2001	13.5	13.3	13.5	12.2
Average	13.2	13.2	12.4	10.9
Benkleman				
1999	12.8	13.4	12.3	12.0
2000	13.8	13.8	11.4	8.9
2001	15.5	15.3	15.1	13.8
Average	14.0	14.1	13.0	11.6
Arapahoe				
1996	10.6	10.9	11.9	11.3
1997	13.3	13.3	14.1	13.1
1998	12.7	12.7	13.5	12.8
1999	13.8	14.1	13.9	13.9
Average	12.6	12.7	13.3	12.8

Table 4. Gross irrigation and growing season rainfall (mm) at field sites.

Location	Irrigation Treatments				
	FARM	BMP	LATE	ALLOC	Rain
Benkleman					
1999	201	183	140	89	302
2000	401	401	307	206	188[a]
2001	371	371	295	180	160
Average	325	318	246	157	216
Dickens					
1996	229	229	198	185	498
1998	457	457	315	254	254
1999	305	343	226	226	422[a]
2001	559	445	417	315	132
Average	389	368	290	246	320
Elsie					
1996	191	191	102	102	544
1997	312	295	198	122	325
1998	284	269	218	152	262
1999	178	178	152	127	404
2000	401	401	307	206	152
2001	297	264	254	216	216
Average	277	267	206	155	318
Arapahoe					
1996	152	152	51	51	643
1997	381	305	254	203	269[a]
1998	203	203	127	127	206
1999	89	89	102	51	437
Average	206	188	135	109	389

[a] Data from official weather station

Elsie with the longest record (6 year) had the greatest probability for significant differences. The Elsie grain yield data were further analyzed with paired two tailed t−tests to identify significant differences between the means of the water management schemes. With the longer record available at Elsie, the treatments began to sort themselves statistically. The FARM and BMP treatments were similar while LATE and ALLOC became more identified as unique.

Table 5. Grain yield statistics for field sites.

a. Summary of Single Factor ANOVAs

Site	F	P−Value
Dickens	2.1914	0.1288
Elsie	3.3173	0.0408
Benkelman	1.3890	0.3148
Arapahoe	0.2667	0.8481

b. Summary of t−Tests: Paired Two Sample for Means for Elsie

Treatment	Mean	Paired t Test[a]
Farm	13.2	a
BMP	13.2	ab
LATE	12.4	b
ALL	10.9	C

[a] Means with common letters are not significantly (a ≤ 0.1) different.

SPECIFIC RESULTS BY INDIVIDUAL SITES

Arapahoe

Arapahoe had the highest probability for rainfall of all the sites and was located farthest east. Grain yields for 1996 to 1999 for all four irrigation treatments are in table 3. These data show that the LATE irrigation treatment tended to have the highest yields except in 1999 when the treatments were all similar.

In 1996, precipitation during July and August was above normal. Soil samples were taken in the fall of 1996 for residual soil nitrate levels. Higher nitrate concentrations were found below 1.8 m (6 ft) in FARM and BMP, as compared to LATE and ALLOC treatments. Leaching was suspected in all irrigation management strategies, but was greater in FARM and BMP because the soil water content was closer to field capacity in mid−July during above−normal precipitation. Measured soil water increases below 1.5−m (5−ft) depths in an adjacent dryland cornfield tended to substantiate the observation of leaching in the irrigated plots.

Over the course of the study, FARM and BMP irrigation application amounts (table 4) tended to reduce and come closer to the amounts of the LATE treatment. By the end of the study, the yields were similar, as were the irrigation applications. As farmers observed study results, they began to modify their own management in subsequent years. Even so, the early season rainfall patterns, through added leaching effects, helped favor the LATE irrigation treatment. Early leaching and farmer management made the trends at Arapahoe different from the other three sites. Comparisons were difficult to make between Arapahoe and the other three sites; therefore, Arapahoe was considered separately from the other three sites for the rest of this discussion.

Dickens

Grain yields and irrigation amounts for FARM and BMP were similar in 3 of 5 years. Grain yields in 1996 were similar for all water treatments. This was due to above−normal precipitation during the reproductive growth stages starting in early July. When precipitation was above normal during the reproductive growth stage, reducing irrigation during the vegetative growth stage had little or no impact upon grain yield, although pumping costs were reduced. With above−normal precipitation in 1996, leaching of nitrogen fertilizer was observed by changes in coloration of the corn crop. After large rains, the vegetation began to appear as a lighter green. The crop was fertigated to alleviate the nitrogen stress, even though irrigation was not required to meet crop water needs. These fertigations applied approximately 63.5 ha−mm/ha (2.5 acre−in./acre) of water.

Grain yields for LATE and ALLOC were less than BMP and FARM in 1998 and 1999. Growing season precipitation in 1998 was below normal. A rainfall depth of 150 mm (6 in.) occurred in three separate events of 50 mm (2 in.) each. Much of this precipitation was unusable by the crop because of drainage beyond the root zone. With the low water holding capacity of fine sand, both LATE and ALLOC treatments were under water stress for much of the vegetative growth stage. Irrigation was needed to prevent soil water from dropping below 70% depletion and to maintain some crop growth. Yields for LATE and ALLOC were 2.1 and 3.4 Mg/ha (32 and 51 bu/acre) less than BMP and FARM, respectively, for 1998.

During 1999, precipitation was near normal in June, below normal in July, and above normal during August. However, much of the precipitation that occurred in August was unusable since two of the precipitation events were greater than 76 mm (3 in.). Most of the irrigation water (all treatments) was applied during July [188 mm (7.4 in.) for BMP and FARM; 140 mm (5.5 in.) for LATE and ALLOC]. All treatments received an additional 38 mm (1.5 in.) of applied water in May and June, and 84 mm (3.3 in.) in August and September. Grain yields for LATE and ALLOC were 0.67 and 1.55 Mg/ha (10 and 23 bu/acre) less than BMP and FARM, respectively.

Benkleman

Grain yields for the irrigation management strategies in 1999 were 12.8 Mg/ha (191 bu/acre) for FARM, 13.4 Mg/ha (199 bu/acre) for BMP, 12.3 Mg/ha (183 bu/acre) for LATE, and 12.0 Mg/ha (178 bu/acre) for ALLOC (table 3). The amount of irrigation applied to each of the treatments was 198, 170, 140, and 89 mm (7.8, 6.7, 5.5, and 3.5 in.) for FARM, BMP, LATE, and ALLOC, respectively. A portion of the area [approximately 2 ha (5 acre)] within LATE and ALLOC had a significant reduction in yield. Harvest yield maps indicated lower grain yield in this 2−ha (5−acre) area in prior years. Grain yields for LATE and ALLOC were 12.6 Mg/h (188 bu/acre) when adjusted to exclude the lower yields from these 2 ha (5 acre).

Rainfall during June was adequate to meet crop ET; however, no precipitation was received during the first 30 days of July. The amount of soil water that was available to the crop was enough to meet ET needs for 18 days, with no crop stress observed for LATE and ALLOC.

Elsie

Yields for FARM and BMP were similar each of the six years. The amount of irrigation applied to FARM was 17 and 15 mm (0.7 and 0.6 in.) more than BMP in 1997 and 1998, respectively, and equal to BMP in 1996 and 1999. FARM irrigation management tended to result in more water being applied during the vegetative growth stage while BMP applied more water during the reproductive growth stage. The application of more water during the vegetative growth stage by FARM was done to reduce the risk of crop stress. However, the BMP strategy increased soil water use, which encouraged more extensive root development.

Yields for LATE and ALLOC were similar to BMP and FARM in 1996. In 1997 to 1999, grain yields for LATE were 0.7 Mg/ha (10 bu/acre) less than BMP and FARM. The savings in irrigation due to management changes from BMP to LATE ranged from 25 mm (1 in.) in 1999 to 89 mm (3.5 in.) in 1996. Grain yields from ALLOC were about 2.7 Mg/ha (40 bu/acre) less than BMP in 1997 and 1998, and 1.7 Mg/ha (25 bu/acre) less than BMP in 1999. Reductions in the amount of irrigation water used for ALLOC compared to FARM ranged from 50 to 190 mm (2 to 7.5 in.).

In 1996, precipitation and small amounts of irrigation during the pollination and grain fill growth stages met ET rates for the crop with no observed water stress for either LATE or ALLOC. Irrigation began in late June and ended during July when precipitation exceeded crop needs. In 1997, precipitation during June was more than crop ET during vegetative growth stage. This caused root development to be limited. Precipitation during July and August was below normal. As a result of these factors, water stress was observed during late August in ALLOC and resulted in a larger reduction in grain yield as compared to 1998 and 1999. Little precipitation occurred during the vegetative and early reproductive growth stages during 1998 and 1999. No precipitation occurred from 10 June to 25 July during 1998 and from 2 July to 1 August in 1999. These periods coincided with the greatest ET for corn. Severe water stress was observed in 1998 prior to tassel emergence for both LATE and ALLOC, while moderate water stress was observed in 1999.

In 1999, most of the LATE management field area yields were similar to BMP and FARM. However, the areas of the field with soil water holding capacities (WHC) lower than the average WHC of the field had decreases in grain yield from 1.3 to 3.4 Mg/ha (20 to 50 bu/acre). Variability in grain yield increased as water became limited with water management strategies such as LATE and ALLOC.

NORMALIZED GRAIN YIELD VERSUS IRRIGATION

The FARM irrigation treatment was used as the base for normalization of the grain yield and gross irrigation over the years of the study data represented in figures 2 and 3. The Arapahoe data are quite scattered with a trend for higher grain yield with less irrigation, as shown with the regression of the normalized data in figure 2. Early season rainfall plus early irrigation by the FARM management helped reverse the expected trend. Also, early irrigation and rainfall likely contributed to leaching of nitrogen which suppressed grain yield. LATE irrigation treatment became optimum with respect to grain yield. The other three sites show the slope of the trend in the opposite direction from the Arapahoe site (fig. 3). The regressions of the normalized yield versus gross irrigation data for all years at Dickens, Benkleman, and Elsie were almost identical (table 6). In the latter three sites with more gross irrigation, there was more return in grain yield. These three sites were farther west with lower rainfall probabilities than the Arapahoe site.

This result was surprising with the range of soil textures involved, but the irrigation treatments covered the range of 60% to 100% of gross irrigation requirements. The treatment regression was not extended into the drier end of the irrigation spectrum.

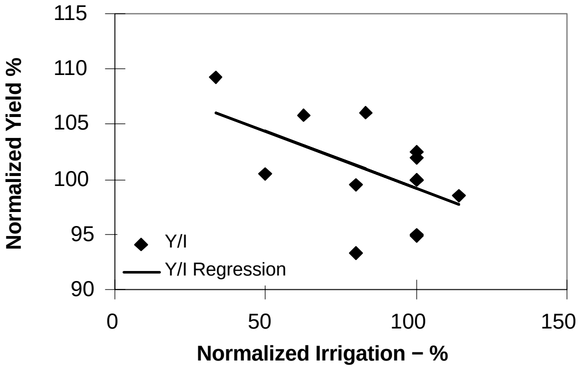

Figure 2. Normalized regression of grain yield vs. irrigation for Arapahoe.

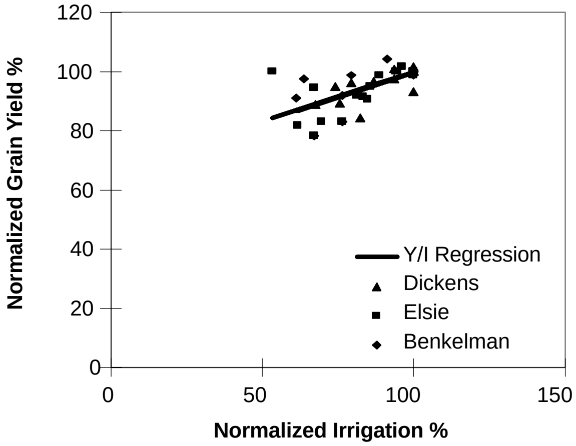

Figure 3. Normalized regression of grain yield vs. irrigation for Elsie, Dickens, and Benkleman.

Another factor that contributed to the 89% of full yield response at these 60% irrigation levels was the use of soil water (table 7). Off−season water accumulation and utilization was very important to the LATE and ALLOC treatments. Even the corn in the sandy soils at Dickens was able to exploit soil water.

YIELD VERSUS EVAPOTRANSPIRATION

Yield versus evapotranspiration relationships for Elsie and Dickens are shown in figure 4, and the details of the regression analysis are shown in table 6. Only the Elsie and Dickens sites had long−term soil water data for ET calculations by the water balance method. The resulting slopes of regressions of the data are “flatter” than we would normally expect. The data from this study did not cover the full range of growing conditions from dryland to a fully irrigated crop. Lack of dryland data tended to allow the regression line to shift in favor of the data represented.

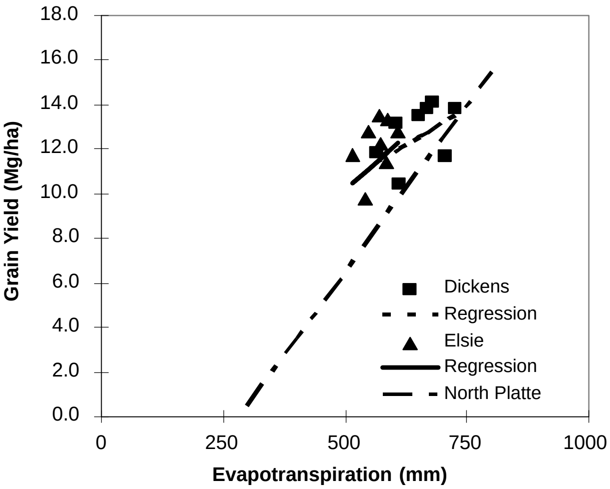

Figure 4. Grain yield vs. evapotranspiration for Dickens, Elsie, and research site at North Platte.

Table 6. Elements of regressions for grain yields vs. irrigation and ET.

Normalized Yield vs. Normalized Gross Irrigation			
Site	Slope	Y−Int.	r^2
Dickens	0.33	66	0.58
Elsie	0.34	66	0.48
Benkleman	0.32	68	0.42
Arapahoe	−0.1	110	0.3
Combined Dickens, Elsie & Benkleman	0.33	67	0.48
Yield vs. ET			
Elsie (98,01)	0.02	0.26	0.34
Dickens (98,01)	0.01	3.4	0.39
(Research Site) North Platte (86,87,89)	0.03	−8.5	0.82

Table 7. Stored soil water used during growing seasons (mm).

Irrigation Treatment	Benkleman 2001	Dickens 1996−1998, 2000	Elsie 1996−1998, 2001	Weighted Average
FARM	104	−1	5	15
BMP	74	56	18	30
LATE	99	81	43	64
ALLOC	170	117	94	112

The data and regressions are shown to compare the variability of the results in large−scale commercial farms as compared with small−scale research plots having similar irrigation treatments. The linear regressions yielded r^2 regression coefficients of 0.34 and 0.39 for Elsie and Dickens, respectively. The plot scale research data reported by Schneekloth et al. (1991) were the result of a three−year study of full irrigation, limited irrigation, and dryland management at North Platte, Nebraska, and located within 30 to 60 miles of the Dickens and Elsie sites. This study produced an r^2 of 0.82 with a combined data set of three years. Stewart et al. (1975) and Stegman (1982) also reported r^2 values of 0.64 and 0.71, respectively, with similar research settings. The lower regression coefficients from the field show the difficulty in obtaining precision in field scale data, the design limitations of this experiment in using years for statistical replications, and the variability that exists when scaling up from small to larger plot work.

The yield−ET relationships from small plot research at North Platte and field scale work at Elsie and Dickens are compared in figure 4 and table 6. The negative y−intercept value of −8.5 Mg/ha (−126 bu/acre) produced an x−intercept of approximately 280 mm (11in.). The negative value implies that it takes 270 mm (11 in.) of water to produce grain. The North Platte yield−ET relationships were produced with the full range of management from dryland to full irrigation. The large−scale field yield−ET relationships were produced with only the upper end of the irrigation spectrum and mainly to illustrate the variability in results from plot−scale to large−scale operations and field variability.

ECONOMIC RESULTS

Results are presented by site since the cultural practices were not controlled between farmers and were different. In addition, the soils at all sites were different and the years of data available differed between sites. Table 8 shows these results by site and for each water cost level. The years of data available by site are shown in parentheses following each site name. The data shown in table 8 reflect the overall averages for all years and prices combined for each irrigation management strategy. Results by price are not shown since the four prices used did not result in any differences in the ranking of strategies by site.

Table 8. Adjusted gross annual returns ($/ha−yr) for three water costs ($/ha−mm) by site for combined crop prices and years, and irrigation management treatment.

Irrigation Management	Water Cost per ha−mm		
	$0.04	$0.08	$0.12
Arapahoe (1996−1999)			
FARM	$139	$130	$122
BMP	$141	$133	$126
LATE	$150[a]	$145[a]	$139[a]
ALLOC	$145	$141	$136
Benkleman (1999−2001)			
FARM	$151	$138	$125
BMP	$153[a]	$140[a]	$127[a]
LATE	$141	$131	$122
ALLOC	$128	$122	$156
Dickens (1996−1999 and 2001)			
FARM	$140[a]	$124[a]	$109[a]
BMP	$135	$121	$107
Late	$127	$116	$103
ALLOC	$121	$111	$101
Elsie (1996−2001)			
FARM	$143	$132	$121
BMP	$143[a]	$133[a]	$122[a]
LATE	$137	$128	$120
ALLOC	$121	$115	$109

[a] Designates the highest adjusted gross return for each water cost at the respective site.

For all but one site, the differences in adjusted gross returns between water management strategies were not significant ($P > 0.10$). The Elsie site adjusted gross returns were different for the $0.04/mm−ha ($2.50/acre−in.) ($P < 0.02$) and $0.08/mm−ha ($5.00/acre−in.) ($P < 0.1$) water costs. As water cost increased, P levels increased or decreased depending on which management strategy had the highest adjusted gross returns. For example, the FARM and BMP strategies at Elsie were similar for all water costs and had the greatest returns. Since these two strategies were intended to meet ET during the entire growing season, they used the most water. As water costs increased, the P levels went up ($0.04, $P < 0.02$; $0.08 $P < 0.10$; $0.12 $P > 0.3$). In other words, the adjusted gross returns became more similar among all strategies as water costs increased. This would be expected where the higher water using strategies had the highest returns. P values for the Arapahoe site were just the opposite although all non−significant ($0.04, $P > 0.6$; $0.08, $P = 0.4$; $0.12, $P < 0.23$). In the Arapahoe case, the strategy with the highest adjusted gross returns (ALLOC) was one of the lowest in water use. As water costs increased, the adjusted gross returns diverged and thus the P values decreased.

The standard deviations of the array of adjusted gross returns for each management strategy at each site were calculated but are not reported. In general, the lower water using strategies had higher deviations in adjusted returns. Those deviations were primarily due to the variation in crop yields between years.

The data in table 8 show trends that are consistent. The highest adjusted gross returns occurred with lower water using strategies at sites with higher water holding capacity soils. Higher water using strategies had the highest adjusted gross returns at the sites with lowest water holding capacity soils. Based on the adjusted gross returns, producers at different sites may choose (if permitted a choice) different water management strategies. If forced to reduce water use, producers' net returns at Benkleman, Dickens, and Elsie would reduce their adjusted gross income by $1.00−$13.00/ha−yr ($2.50−$32.20/acre−yr) by choosing the late initiation strategy. At the Arapahoe site, the late initiation strategy was actually the highest returning strategy. The higher the water cost, the lower the differences between the highest and less returning strategies.

SUMMARY

Table 9 summarizes the results over three locations and years, giving weight in the averages to the number of years of data at each location. The Arapahoe site was not used in this summary because the FARM treatment did not maximize production as was the case in the other three treatments. Using the FARM water management treatment as the basis of comparison, LATE management took 76% as much gross irrigation across locations and years, produced 93% as much grain, and produced 94−97% as much adjusted gross revenues as the FARM management. The ALLOC management took 57% as much gross irrigation, produced 84% as much grain, and produced 85−91% as much adjusted gross revenue as the FARM management. Irrigation water use efficiency, (IWUE), or the grain produced from each mm of irrigation water, increased 0.03 to 0.05 Mg/ha−mm (13 to 18.5 bu/acre−in.) over the FARM to ALLOC irrigation treatments.

CONCLUSIONS

There was an increasing return in grain yield from decreasing water applications at the Arapahoe site only. It was suspected that above average rainfall late in the growing season, plus excessive early irrigation in the FARM and BMP treatments may have contributed to early season nitrate leaching. Moreover, a suspected shortage of available nitrogen later in the growing season led to decreased yields in those two treatments. Deep soil sampling in 1996 confirmed this nitrogen shortage possibility. Decreasing

Table 9. Summary information as weighted averages (by years) and percentages of FARM treatment over Dickens, Elsie and Benkleman locations.[a]

Irr. Mgt.	Irrigation		Grain Yield		IWUE		Gross Return (%) at		
	mm	%	Mg/ha	%	Mg/ha−mm	%	0.04[b]	0.08	0.12
FARM	323	100	13.5	100	0.034	100	100	100	100
BMP	307	95	13.5	100	0.036	104	99	100	100
LATE	246	76	12.6	93	0.043	126	94	95	97
ALLOC	183	57	11.3	84	0.049	142	85	88	91

[a] Benkleman 1999−2001; Dickens 1996−1999, 2001; Elsie 1996−2001.
[b] Irrigation water cost ($/ha−mm).

return in grain yield from decreasing water applications was found at the other three sites. When the grain yields and irrigation amounts were normalized each year using the FARM treatment as the basis, the general trend was that the BMP treatment yielded the same as the FARM treatment, the LATE treatment yielded 93% of the FARM treatment and the ALLOC yielded 84% of the FARM treatment. At the same time, it took 95%, 76%, and 57% of the water for the BMP, LATE, and ALLOC treatments, respectively, to achieve these yields. The normalized trends, as shown by regressions of the data were nearly identical among the locations of Elsie, Benkleman, and Dickens even though there was a range in soils with water holding capacities from 92 to 150 mm/m (1.1 to 1.8 in./ft).

The adjusted gross returns (yield × price – irrigation treatment costs) of the irrigation treatments were analyzed for each location. When the gross returns were normalized using the FARM treatment as the basis, FARM and BMP returns were equal across combinations of high and low input commodity prices and pumping costs. The LATE treatment gross return was 95% of FARM return. The gross return for the ALLOC treatment was 85% to 91% of the FARM treatment. Higher returns to the FARM management in terms of grain yields still overcame pumping and other input costs. The higher the water cost, the lower the differences between the highest and less returning strategies.

Relationships between evapotranspiration and grain yield were developed for two sites over the limited range of water applications of the projects. Since very limited irrigation and dryland treatments were not included in the study, a completely realistic regression could not be formulated. However, the regressions indicated more variability from the commercial field data than the research plot environment. Much of this difference may have been due to yearly replication in this study rather than plot−to−plot replication in the research center study.

Yields and irrigation data were normalized on the basis of the FARM treatment. Normalized yield−irrigation results over years and locations for three of the four locations showed declining yields as irrigation decreased. The same regression was used to normalize the locations with soil textures from fine sand to sandy loam. This analysis suggests that the three locations behaved similarly with respect to the management treatments.

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