Effects of Nitrogen Rate, Irrigation Rate, and Plant Population on Corn Yield and Water Use Efficiency

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ABSTRACT

Improper N and irrigation management are major factors contributing to water quality and shortage problems in the Great Plains. This study was conducted on the Irrigation Research Farm in Yuma, CO, from 1998 through 2000 to establish an accurate irrigation and N management system for corn (*Zea mays* L.) production in the Great Plains aimed at high yield and water use efficiency (WUE) simultaneously. A field experiment was conducted on a center-pivot–irrigated, well-drained Haxtun sandy loam soil (fine-loamy, mixed, superactive, mesic Pachic Argiustolls) by using a randomized complete block split-split plot design, with irrigation rates [0.60, 0.80, and 1.00 of the estimated evapotranspiration (ET)], N fertility rates (30, 140, 250, and 360 kg ha^{-1}, including N from soil, fertilizer, and irrigation water), and plant populations (57 000, 69 000, and 81 000 plants ha^{-1}) as the main-plot, split-plot, and split-split plot treatments, respectively. A combination of 0.80ET to 1.00ET, 140 to 250 kg N ha^{-1}, and 57 000 to 69 000 plants ha^{-1} population provided optimum corn yield. Irrigation treatment 0.80ET, accompanied by 140 to 250 kg N ha^{-1}, and 57 000 to 69 000 plants ha^{-1} population was the best management system for optimum WUE. No significant differences in water extraction from the soil profile for the entire season and soil moisture content at harvest between the 0.80ET and 1.00ET irrigation treatments were additional indications that 0.80ET is superior to 1.00ET. To preserve the Ogallala Aquifer, the best management system aimed at optimum WUE should be used for corn production in the Great Plains region.

Irrigation and fertilization provide effective means to increase crop yield in the Great Plains (Wienhold et al., 1995; Norwood, 2000). However, improper irrigation and fertilization management is also a major contributor to water contamination and water resource shortages (Ludwick et al., 1976; Al-Kaisi et al., 1997, 1999). Increasing uses of irrigation and fertilization in the Great Plains have raised concern regarding ways of managing water and nutrients (especially N) more efficiently to overcome excessive irrigation and nutrient losses.

Like many other regions in the Great Plains, northeastern Colorado mainly depends on the Ogallala Aquifer for irrigation. The traditional irrigation amount and N fertility rate (64 cm of water, including rainfall and 250 kg N ha^{-1}, including N from soil, fertilizer, and irrigation water during the growing season) for corn production are probably related to water quality problems (nitrate contamination of groundwater). Furthermore, depletion of the Ogallala Aquifer has been accelerated by the extensive use of irrigation in this region. Therefore, protecting both quality and quantity of the aquifer is crucial for the survival of agriculture in northeastern Colorado.

The relationships of corn yield and nitrate leaching with irrigation, N fertilization, and plant population have been extensively investigated. Irrigation effectively increases corn yield although WUE expressed as corn yield to total water use ratio decreases as irrigation rate increases (Stone et al., 1987, 1993; Hergert et al., 1993). Nitrogen fertilization also increases corn yield when N supply by soil is low (Wienhold et al., 1995; Sexton et al., 1996). Nitrogen fertilizer applied at rates higher than the optimum requirement for crop production may cause an increase in nitrate accumulation below the root zone and pose a risk of nitrate leaching (Linville and Smith, 1971; Lund et al., 1974; Ludwick et al., 1976). Otherwise, little nitrate will be available for leaching (Pratt et al., 1972). Increasing plant population usually increases corn yield until an optimum number of plants per unit area is reached (Lang et al., 1956; Holt and Timmons, 1968; Lutz et al., 1970; Thomison et al., 1992). Optimum plant population is related to soil moisture availability (Holt and Timmons, 1968; Karlen and Camp, 1985), N fertility, and other environmental factors. Optimum plant population for corn production increases with the increase of available N until plant population at approximately 50 000 plants ha^{-1} (Lang et al., 1956; Colyer and Kroth, 1968; Thomison et al., 1992; Eckert and Martin, 1994).

Several studies have investigated the effect of irrigation and N interactions on corn production, WUE, and N leaching (Russelle et al., 1981; Martin et al., 1982; Eck, 1984; Sexton et al., 1996). In general, increase in soil moisture enhances corn yield response to N fertilization, especially when high N rates are applied (Burman et al., 1962; Eck, 1984). In addition, N uptake was strongly influenced by water supply (Martin et al., 1982). Russelle et al. (1981) reported that the optimum N rate for maximum corn yield was the same under different irrigation treatments. However, N fertilization increases WUE on N-deficient soils where water is adequate (Viets, 1962; Olsen et al., 1964).

Irrigation and N fertilization effects or their interactions are usually evaluated in terms of corn yield (Eck, 1984; Norwood, 2000); only a few studies (Sexton et al., 1996) used both corn yield and nitrate leaching to identify an appropriate N application rate, recommending N rate to obtain 95% of optimum yield. Little information is available about the integrated best management practices of irrigation, N rates, and plant populations to achieve high corn yield and high WUE as well as low N loss.

The primary objective of this study was to evaluate

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Abbreviations: CAMS, computer-aided management system; ET, evapotranspiration; WUE, water use efficiency.

the impacts of N fertility rates, irrigation rates, and plant populations on corn yield and WUE to develop a best management system for high corn yield and WUE simultaneously.

MATERIALS AND METHODS

Site Description

This study was conducted on the Irrigation Research Farm belonging to the Irrigation Research Foundation in Yuma (40°9′ N, 102°43′ W; 1251 m above mean sea level), CO, in cooperation with Colorado State University, during the growing seasons of 1998 through 2000. The soil on the site was classified as a Haxtun sandy loam (fine-loamy, mixed, superactive, mesic Pachic Argiustolls). The Haxtun soil is deep and well drained. It formed in moderately course-textured eolian material over mixed eolian and alluvial material. The total precipitation for the 1998, 1999, and 2000 seasons was 34, 36, and 38 cm, respectively, which was calculated based on the period from October of the previous year to September of the current year. The site was planted to continuous irrigated corn with minimum tillage (>30% crop residue) before the experiment began.

Experimental Design

A randomized complete block split-split plot design with three replicates was used each season. Irrigation treatments were randomly assigned to the main plots, N fertility rates were assigned to the split plots, and plant population rates were assigned to the split-split plots.

Irrigation scheduling was conducted using a center-pivot sprinkler system equipped with a computer-aided management system (CAMS) based on the daily water use (ET) developed from on-farm weather station data. The irrigation circle was divided into three sectors, and the three irrigation treatments were randomly assigned to the three sectors where they were kept in the same place each year. Within each sector, there were three replicates of the same irrigation treatment. Because of the center-pivot sprinkler system, it was too complicated to replicate the irrigation treatments as for a normal randomized complete block design. Because the field used for this experiment was uniform, this unique arrangement of irrigation replicates would not result in any significant additional errors to the results. The three irrigation treatments (rainfall included) were 0.60, 0.80, and 1.00 of the estimated ET, which represented 38, 51, and 64 cm of total water applied during the growing season.

Four N fertility rates (30, 140, 250, and 360 kg N ha^{-1}) and three plant populations (57 000, 69 000, and 81 000 plants ha^{-1}) were used each season. Four N rates were randomly nested within each main plot of irrigation treatment, and three plant populations were randomly nested within each split plot of N rates. Soil testing showed high variability in initial soil N concentrations in the field before experiment in 1998 and in residual soil N concentrations before corn planting in 1999 and 2000. To achieve a genuine response to different N fertility rates, N treatments were allocated to the plots that had initial soil N or residual soil N levels close to the experiment-designed N rates each season. Nitrogen fertilizer rates were calculated based on the designated N fertility rates and by crediting soil NO_3–N content in the top 1.22 m. Nitrogen in the irrigation water also was credited to N fertility rate. Nitrogen fertilizer rates were split into two applications: 60% was applied during ripping, and the remainder was applied through the center-pivot sprinkler system before tasseling by using a CAMS. The CAMS was installed on the center pivot, allowing application depth to be as shallow as 0.25 cm. In addition, a starter of 30 kg N ha^{-1} plus equal P, K, and micronutrients was applied to all treatments each season. Irrigation scheduling for the three irrigation treatments was conducted based on the maximum ET rate (1.00ET) where CAMS was used to achieve the application rate. The other two irrigation treatments (0.80ET and 0.60ET) were applied at the same time and in proportion to 1.00ET.

A split-split plot consisted of 12 rows of corn with a length of 15 m. Corn (cv. Midwest 7620) was planted in 76-cm row widths on 28 Apr. 1998, 19 May 1999, and 28 Apr. 2000. The plants were planted at the same distance from each other for each plant population. Weed, pest, and disease control were done in a timely manner.

Plant Sampling

Corn plant samples were collected at six-leaf (V6), 12-leaf (V12), tasseling (VT), and physiological maturity (R6) growth stages as defined by Ritchie et al. (1997) on a split-split plot basis in all 3 yr. Plant sampling area for each season consisted of two adjacent rows, 4.6 m in length for each split-split plot. This 4.6-m length of corn was divided into three 1.53-m subsections. At the V6 growth stage, two plants were cut from each subsection at ground level, giving a total of six plants per split-split plot. For the V12 and VT growth stages, one plant per subsection was cut, totaling up to three plants per split-split plot. At the R6 growth stage, all remaining plants from each subsection were cut, and each sample was partitioned into plant (stalk + leaves) and grain. The plant sampling at the R6 growth stage was conducted only in 1999 and 2000. The edge plants resulting from previous sampling activities for all leaf stages were excluded from subsequent samplings. We made sure that each plant collected at each growth stage was growing between two original plants to eliminate uneven competition. Plant samples were dried in a forced-air oven at 65°C for at least 3 d before weighing. After physiological maturity, grain yield was determined by hand harvesting an area of two rows, 6.1 m in length, each on a split-split plot basis. Grain samples were collected from the yield samples for the determination of moisture content. Corn yield was adjusted to moisture content of 155 g kg^{-1}.

Moisture Measurement and Water Management

Soil moisture was monitored on a weekly basis by using a neutron probe (Depth Moisture Gauge model 4300; Troxler Electronics Lab., Research Triangle Park, NC) based on a volumetric basis. Access tubes were installed in the center of each split-split plot of each plant population at 250 kg N ha^{-1} under each irrigation treatment. Three access tubes were installed for each irrigation treatment, one tube per plant population. Soil moisture was monitored weekly, starting immediately after corn emergence until harvest at the soil depth intervals of 0 to 30, 30 to 60, 60 to 90, 90 to 120, and 120 to 150 cm. During the growing season, soil moisture measurements were taken before and immediately after each irrigation event (1- to 2-d lag period).

Irrigation water was applied using a center-pivot system equipped with a CAMS to achieve the desired application rate. The irrigation scheduling was done with the Crop Flex program (King et al., 1991) by using data collected from the local weather station to estimate daily crop water use (ET). The Crop Flex program estimates crop water use (ET) by using the modified Penman equation (Jensen et al., 1971) along with polynomial functions to generate crop coefficients based on the fraction of time from planting to full cover and days after full cover (Duke, 1987). Highest rate was applied using the manageable or allowable water depletion, which refers to the acceptable soil moisture depletion (40–50%) of available soil moisture at different growth stages by using the water balance approach, which includes estimated ET, soil moisture changes, precipitation, and drainage to determine irrigation amount. The following water balance relationship was used in determining the irrigation amount:

$$I + P - R = \mathrm{ET} + D + \mathrm{SW}$$

where the terms on the left-hand side of the equation represent the applied irrigation water (I), precipitation (P), and surface runoff (R). The sum of these three terms represents the net addition of water to the soil profile over a time period of interest. On the right side of the equation are estimated ET, drainage or deep percolation (D), and the water storage change (SW) of soil moisture profile. Each of the terms in the equation represents water flows or storage changes over some arbitrary time interval. All of the terms in the equation are positive except for D and SW, which may be either positive or negative, depending on the direction of the water flow (upward or downward flow) (Jury et al., 1991, p. 122–123). Surface runoff in this study was negligible due to the control of water application by using the CAMS. Deep percolation or drainage did not occur, based on application amounts to satisfy only the depleted soil moisture (40–50%) at the top three depths in the soil profile and the monitoring of soil moisture at the 120- to 150-cm depth, where no increase in soil moisture was found. In general, the irrigation rate range during the growing season for 1.00ET treatment was 2.54 to 3.81 cm of water per application based on the irrigation-scheduling program estimation. The dominant rainfall rate per event during 3 yr of the study in the area was less than 2.5 cm, which is lower than the amount of water required to replenish the top 90 cm of the soil profile to field capacity. Therefore, excessive water or drainage became negligible.

Water use efficiency was calculated based on the following relationship:

$$\mathrm{WUE} = \mathrm{GY}/\mathrm{ET}$$

where WUE is water use efficiency (kg ha^{-1} cm^{-1}); GY is grain yield (kg ha^{-1}) from a given irrigation, N rate, and plant population treatment; and ET is the seasonal or total water use (cm) for each irrigation treatment. Daily rainfall was obtained from the on-farm weather station each season.

Laboratory Analysis

Total N concentrations in the plant (including whole plant and grain) samples at each growth stage were determined using automated combustion (Miller and Kotuby-Amacher, 1996, p. 71–72). Soil NO_3–N content before the experiment in spring 1998, for depth 0 to 150 cm in increments of 30 cm, was determined using Colorado State University Soil Test Laboratory standard procedures (Keeney and Nelson, 1982, p. 649 and 676). Nitrogen uptake by plant was calculated based on the total N concentrations in plant or grain multiplied by their respective mass (dry matter or grain weight).

Statistical Analysis

Plant N uptake data at the V6, V12, and VT growth stages were analyzed using an analysis of variance (ANOVA) appropriate for a randomized complete block split-plot design with irrigation treatment as the main-plot factor and plant population as the split-plot factor. Separate ANOVAs were performed for each dependent variable. Plant N uptake at the R6 growth stage and grain yield at harvest were analyzed using a randomized complete block split-split plot model with irrigation as the main factor, N rate as the split factor, and plant population as the split-split factor. All data for each measurement were combined across years if possible. Mean separation of treatment effects in this study was accomplished using Fisher's protected least significant difference (LSD) test. Probability levels lower than 0.05 were categorized as significant. All data analyses in this study were accomplished using the SAS System for Windows, version 8 (2) (SAS Inst., 2001).

RESULTS AND DISCUSSION

Discussion of the results in the following sections is based on the order of statistical significance, which ranges from the highest-level interaction to the main effects of treatments. If there was a statistically significant interaction, then the main effect of the treatments that were involved in this interaction was not presented. For example, statistical analysis showed that irrigation treatment × year interaction and N rate × year interaction were the highest-level interactions that were statistically significant in N uptake at the R6 growth stage for both plant and grain (Table 1); thus, these interactions were the only results we presented and discussed here to evaluate water supply, N rate, and year effects on N uptake at the R6 growth stage. For corn yield and WUE, irrigation treatment × N rate × year interaction and irrigation treatment × population × year interaction were the highest-level interactions that were statistically significant (Table 1); therefore, the results were presented in a format corresponding to these significant interactions. The same rule was applied to the ANOVA for soil moisture extraction during the entire season, and for moisture content at harvest, although the ANOVA table for these measurements is not presented.

Plant Nitrogen Uptake

Positive plant N uptake response to irrigation treatments was only observed late in the season under normal production environments (Tables 2 and 3). Irrigation effects on N uptake were not observed at the V12 or VT growth stage (Table 2). Irrigation effects on both plant and grain N uptake varied with years at R6 growth stage (Table 3). In 1999, the 0.80ET and 0.60ET treatments reduced plant N uptake significantly compared with 1.00ET. However, no significant differences were observed in N uptake in 2000. The responses of grain N uptake to different irrigation treatments were similar to plant N uptake at the R6 growth stage in both years where no significant differences were observed (Table 3).

Nitrogen rate effects on plant N uptake were significant at the middle and late growth stages (Tables 2 and 3). Plant N uptake at the V6 and V12 growth stages was not increased by an increase in N rates but was increased as the N rate increased up to 140 kg ha^{-1} at the VT growth stage. Nitrogen uptake by plant and grain at the R6 growth stage was statistically identical for the N rates of 140, 250, and 360 kg ha^{-1} in both 1999 and 2000.

Plant population effects on N uptake were more evi-

Table 1. Analysis of variance combined over years for N uptake at R6 growth stage, grain yield, and water use efficiency (WUE).

	N uptake at R6 stage							
	Plant		Grain		Grain yield		WUE	
Source	df	*F*	df	*F*	df	*F*	df	*F*
Year	1	317.0**	1	219.7**	2	33.2**	2	27.0**
Replicate	2	5.4	2	4.2	2	1.9	2	1.4
Error A	2	1.4	2	4.1*	4	13.2***	4	16.3***
Irrigation treatment (I)	2	14.8**	2	8.7**	2	96.1***	2	6.0*
I × year	2	7.5*	2	5.8*	4	5.0*	4	3.3*
Error B	8	2.3*	8	3.1**	12	8.2***	12	11.0***
N rate (N)	3	3.0*	3	6.5**	3	50.0***	3	51.2***
N × year	3	9.6***	3	3.7*	6	11.7***	6	13.6***
I × N	6	1.7	6	1.8	6	3.3**	6	6.4***
I × N × year	6	0.8	6	1.2	12	2.3*	12	4.0***
Error C	36	0.9	36	1.4	54	1.5*	54	1.7**
Population (P)	2	3.6*	2	2.3	2	7.4***	2	5.2**
P × year	2	3.2*	2	0.8	4	3.1*	4	3.4*
I × P	4	2.6*	4	0.9	4	5.4***	4	3.3*
N × P	6	0.3	6	0.9	6	0.4	6	0.3
I × P × year	4	0.6	4	1.0	8	2.7**	8	2.5*
N × P × year	6	0.7	6	0.6	12	0.7	12	0.8
I × N × P	12	1.6	12	0.5	12	1.7	12	1.6
I × N × P × year	12	0.9	12	0.4	24	1.1	24	1.2
Error D	96		96		144		144	

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.

dent early in the season (Tables 2 and 3). Nitrogen uptake at the V6 growth stage increased as plant population increased up to 81 000 plants ha^{-1}. Similarly, N uptake under 57 000 plants ha^{-1} at the V12 and VT growth stages was significantly lower than that at 69 000 and 81 000 plants ha^{-1}. Plant N uptake at the R6 growth stage was significantly reduced by changing the population from 81 000 to 57 000 plants ha^{-1} whereas no differences were observed between 69 000 and 81 000 plants ha^{-1} in 1999 or 2000. In contrast, plant population did not affect grain N uptake in either year.

In general, plant N uptake response to irrigation treatments, N rate, and plant population at various growth stages seemed to be more related to an increased dry matter production than to an increase in N concentrations in plants.

Table 2. Effects of irrigation treatment, N rate, and plant population on N uptake at V6, V12, and VT growth stages averaged over 1998 to 2000.

	N uptake		
	Growth stage		
Treatment (Unit)†	V6	V12	VT
	kg ha^{-1}		
Irrigation treatment			
0.60ET‡	14a§	138a	122a
0.80ET	10c	135a	126a
1.00ET	11b	134a	126a
N rate (kg ha^{-1})			
30	12a	135a	117b
140	11b	137a	125a
250	11b	137a	127a
360	11b	135a	129a
Plant population (plants ha^{-1})			
57 000	9c	118b	109c
69 000	12b	144a	137a
81 000	13a	145a	128b

† Treatment means are averaged over all other treatments.
‡ ET, evapotranspiration.
§ Means in column within irrigation treatment, N rate, or plant population followed by the same letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD test.

Grain Yield

The effect of interaction between irrigation treatments and N rates on grain yield was significant and varied by year (Table 4). In 1998, 0.80ET and 0.60ET consistently resulted in lower yield than 1.00ET treatment, regardless of N rate. Average yield decreases were 43% with 0.60ET and 25% for 0.80ET relative to 1.00ET. In 1999, yield differences between 0.80ET and 1.00ET were not significant. However, 0.60ET produced yield 45% lower than the 1.00ET averaged over the four N rates. In 2000, grain yield under 0.80ET was similar at low N rates of 30 and 140 kg ha^{-1} but 15 to 23% lower at high N rates of 250 and 360 kg ha^{-1} compared with 1.00ET. Irrigation treatment 0.60ET resulted in a significant yield decrease that averaged 47% compared with 1.00ET.

Table 3. Effects of irrigation treatment, N rate, and plant population on plant and grain N uptake at R6 growth stage from 1999 to 2000.

	Plant N uptake		Grain N uptake	
Treatment (Unit)†	1999	2000	1999	2000
	kg ha^{-1}			
Irrigation treatment				
0.60ET‡	117b§	62a	100b	47a
0.80ET	127b	74a	132a	51a
1.00ET	169a	75a	138a	50a
N rate (kg ha^{-1})				
30	117b	78a	110c	45a
140	140a	64b	127b	49a
250	146a	72ab	136ab	54a
360	148a	67ab	121bc	49a
Population (plants ha^{-1})				
57 000	131b	65b	126a	50a
69 000	142a	71a	127a	49a
81 000	141a	74a	118a	48a

† Treatment means are averaged over all other treatments.
‡ ET, evapotranspiration.
§ Means in column within irrigation treatment, N rate, or plant population followed by the same letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD test.

Table 4. Effects of irrigation treatment and N rate on grain yield from 1998 to 2000.

Year	Irrigation treatment†	Total water applied	Grain yield, N rate (kg ha^{-1}): 30	140	250	360
		cm	Mg ha^{-1}			
1998	0.60ET‡	38	4.46Cb§	7.25Ca	8.16Ba	8.24Ca
	0.80ET	51	7.74Bc	9.23Bb	9.62Bab	10.66Ba
	1.00ET	64	11.07Ac	12.02Acb	12.86Aab	13.52Aa
1999	0.60ET	38	5.95Bc	7.52Bb	9.31Ba	5.04Bc
	0.80ET	51	12.16Ab	12.47Aab	13.49Aa	12.66Aab
	1.00ET	64	12.57Aa	12.29Aa	13.30Aa	12.76Aa
2000	0.60ET	38	3.53Bc	4.29Bbc	4.98Cab	5.85Ca
	0.80ET	51	6.17Ac	7.22Abc	7.49Bb	8.67Ba
	1.00ET	64	7.02Ac	8.48Ab	9.72Aa	10.24Aa

† Treatment means are averaged over plant populations.
‡ ET, evapotranspiration.
§ Means in column within irrigation treatment in each year followed by the same uppercase letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD test. Means in row within N rate in each year followed by the same lowercase letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD test.

Grain yield response to N rate was affected by irrigation and year (Table 4). In 1998, yield with the application of 140 or 360 kg N ha^{-1} was not statistically different from that at 250 kg N ha^{-1} regardless of irrigation treatment. In 1999, grain yield showed no significant response to any increase in N rate above 250 kg ha^{-1} when the 0.80ET and 1.00ET irrigation treatments were applied (Table 4). In 2000, applying 140 kg N ha^{-1} produced comparable yield to 250 kg N ha^{-1} but only at 0.60ET and 0.80ET (Table 4). Application of 360 kg N ha^{-1} resulted in statistically identical or even higher yield than 250 kg N ha^{-1} under all three irrigation treatments. These results are similar to those of Burman et al. (1962) and Eck (1984) who observed significant and positive impacts of soil moisture on corn yield response to N rates.

The 3-yr results, in general, showed that 250 kg N ha^{-1}, which is the common N fertility rate currently used in northeastern Colorado, can be replaced by 140 kg N ha^{-1} for corn production under the three irrigation treatments. Nitrogen rate impacts on yield were not significantly influenced by plant populations. Our results agreed to some degree with those of Russelle et al. (1981) that the optimum N rate for maximum corn yield was the same under different irrigation conditions. The same optimum N rate for maximum yield under different irrigation conditions could be explained by the decrease in N use efficiency as soil moisture content decreased.

Although irrigation effects on yield were influenced by plant population (Table 5), yield showed a strong decreasing trend, with decreases in irrigation in 1998 and 2000 no matter which plant population was used. In 1999, however, the yields of 0.80ET and 1.00ET did not differ at any population. Yield response to plant population varied with irrigation treatment and growing season (Table 5) but was not affected by N fertilization rate (data not shown). In 1998 and 2000, there were generally no significant yield differences among the three plant populations at 0.60ET or 0.80ET. Under 1.00ET, however, plants with population of 69 000 plants ha^{-1} produced comparable yield, but plants under 57 000 plants ha^{-1} had a significant yield reduction of 16% in 1998 and 10% in 2000 compared with 81 000 plants ha^{-1}. In contrast, no yield differences due to plant population were observed regardless of irrigation treatment in 1999. Karlen and Camp (1985) also reported that plant population significantly responded to water management for corn yield. It seemed that yield response in 1999 was mainly due to irrigation treatment rather than N rate or plant population changes.

In general, grain yield responded similarly as N uptake at the middle (VT) and late (R6) growth stages to irrigation treatment, N rate, and plant population. It is appropriate to recommend that 0.80ET to 1.00ET (51–64 cm of total water use) combined with 140 to 250 kg N ha^{-1} and plant population of 57 000 to 69 000 plants ha^{-1} are the best management systems for corn production aimed at maximum grain yield under the studied environments. The 3-yr results of this study suggest that 0.80ET was sometimes comparable to 1.00ET, but 0.60ET was not competitive with 0.80ET or 1.00ET in terms of grain yield. The latter agreed with Hergert et al. (1993) that corn yield under full irrigation was significantly greater than under limited irrigation.

Table 5. Effects of irrigation treatment and plant population on grain yield averaged over 1998 to 2000.

Year	Irrigation treatment†	Total water applied	Grain yield, Plant population (plants ha^{-1}): 57 000	69 000	81 000
		cm	Mg ha^{-1}		
1998	0.60ET‡	38	7.15Ca§	7.22Ca	6.71Ca
	0.80ET	51	9.46Ba	9.25Ba	9.22Ba
	1.00ET	64	10.82Ab	13.44Aa	12.85Aa
1999	0.60ET	38	7.20Ba	6.78Ba	6.87Ba
	0.80ET	51	12.75Aa	12.85Aa	12.50Aa
	1.00ET	64	12.60Aa	12.67Aa	12.92Aa
2000	0.60ET	38	4.18Cb	4.64Cab	5.17Ca
	0.80ET	51	7.06Ba	7.62Ba	7.49Ba
	1.00ET	64	8.20Ab	9.28Aa	9.12Aa

† Treatment means are averaged over N rates.
‡ ET, evapotranspiration.
§ Means in column within irrigation treatment in each year followed by the same uppercase letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD test. Means in row within plant population in each year followed by the same lowercase letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD test.

Table 6. Effects of irrigation treatment and N rate on water use efficiency (WUE) from 1998 to 2000.

Year	Irrigation treatment†	Total water applied	WUE			
			N rate (kg ha^{-1})			
			30	140	250	360
		cm	kg ha^{-1} cm^{-1}			
1998	0.60ET‡	38	116.9Bc§	190.3Ab	214.3Aab	216.3Aa
	0.80ET	51	152.5Ac	181.9Ab	189.3Aab	209.8Aa
	1.00ET	64	174.2Ab	189.3Aab	202.7Aa	213.0Aa
1999	0.60ET	38	156.2Cc	197.2Bb	244.4Aa	132.0Cc
	0.80ET	51	239.5Aa	245.7Aa	265.4Aa	249.1Aa
	1.00ET	64	198.0Ba	193.5Ba	209.6Ba	200.9Ba
2000	0.60ET	38	92.9Ab	112.7Ab	130.7Aab	153.5Aa
	0.80ET	51	121.6Ab	142.1Ab	147.6Aab	170.8Aa
	1.00ET	64	110.5Ab	133.5Ab	153.0Aab	161.4Aa

† Treatment means are averaged over plant populations.
‡ ET, evapotranspiration.
§ Means in column within irrigation treatment in each year followed by the same uppercase letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD test. Means in row within N rate in each year followed by the same lowercase letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD test.

Water Use Efficiency

There was a significant interaction between irrigation treatment and N rate for WUE, and it varied with growing season (Table 6). In 1998, WUE did not differ among the three irrigation treatments at any N rate except 30 kg N ha^{-1}. However, in the 1999 season, 0.80ET had WUE 25% greater than 1.00ET averaged over all N rates. The 0.60ET treatment had WUE similar to 1.00ET at the 140 kg N ha^{-1} rate. In 2000, there were no significant WUE differences among the three irrigation treatments regardless of N rates.

The interaction effect between irrigation treatment and plant population on WUE was also significant and varied with year (Table 7). In 1998, 0.80ET and 0.60ET had WUE 10 to 16% lower than 1.00ET when corn was planted under populations of 69 000 and 81 000 plants ha^{-1}. In 1999, 0.80ET resulted in a WUE increase of 20% compared with 1.00ET averaged over the three plant populations; and 0.60ET had lower WUE than 1.00ET at the plant populations of 69 000 and 81 000 plants ha^{-1}. In 2000, 0.80ET and 1.00ET were comparable in WUE regardless of plant populations, but 0.60ET had lower WUE under populations of 57 000 and 69 000 plants ha^{-1} compared with 1.00ET and 0.80ET.

Table 7. Effects of irrigation treatment and plant population on water use efficiency (WUE) from 1998 to 2000.

Year	Irrigation treatment†	Total water applied	WUE		
			Plant population (plants ha^{-1})		
			57 000	69 000	81 000
		cm	kg ha^{-1} cm^{-1}		
1998	0.60ET‡	38	187.3Aa§	189.6Ba	176.2Ba
	0.80ET	51	186.4Aa	182.2Ba	181.7Ba
	1.00ET	64	170.5Ab	211.6Aa	202.2Aa
1999	0.60ET	38	188.8Ba	177.7Ca	180.4Ca
	0.80ET	51	250.9Aa	252.8Aa	246.2Aa
	1.00ET	64	198.5Ba	199.7Ba	203.4Ba
2000	0.60ET	38	109.7Bb	121.8Bab	135.7Aa
	0.80ET	51	138.9Aa	150.0Aa	147.6Aa
	1.00ET	64	129.3Ab	146.1Aa	143.6Aab

† Treatment means are averaged over N rates.
‡ ET, evapotranspiration.
§ Means in column within irrigation treatment in each year followed by the same uppercase letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD test. Means in row within plant population in each year followed by the same lowercase letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD test.

The 3-yr results generally suggest that 0.80ET had WUE equal to or even greater than 1.00ET and 0.60ET, regardless of N rate, and 0.60ET had comparable WUE as 1.00ET in some cases.

Water use efficiency response to N rate was influenced by irrigation treatment and year (Table 6). In 1998, 140 and 360 kg N ha^{-1} had comparable WUE as 250 kg N ha^{-1}. In 1999, WUE did not differ among the four N rates at 0.80ET and 1.00ET. In 2000, 30, 140, and 360 kg N ha^{-1} all had similar WUE as 250 kg N ha^{-1}. The results of this study generally agreed with the observations that N fertilization increases WUE on N-deficient soils where water is adequate (Viets, 1962; Olsen et al., 1964). Therefore, 140 kg N ha^{-1} can be used as an alternative to 250 kg N ha^{-1} for corn production in terms of WUE.

Similar to yield, WUE response to plant population varied with irrigation treatment and year (Table 7). In 1998 and 2000, when grain yield was within low to medium ranges, significant WUE response to plant population was generally not observed under 0.60ET and 0.80ET. However, 57 000 plants ha^{-1} had WUE 10 to 19% lower than 81 000 and 69 000 plants ha^{-1} under 1.00ET in both years. In 1999, a very high-yielding season, WUE was generally identical among the three populations, no matter which irrigation treatment was applied.

In general, 0.80ET accompanied by 140 to 250 kg N ha^{-1} and plant population of 57 000 to 69 000 plants ha^{-1} was the best combination for corn production aimed at maximum WUE in this study. This recommendation is slightly different in irrigation from our recommendation aiming at optimum grain yield. Because the decline of the Ogallala Aquifer in the Great Plains occurred rapidly due to extensive irrigation, the best management system aimed at maximum WUE should be used in corn production. In addition, efforts should be made to implement the best management system for maximum WUE in the entire area and for the long term. Therefore, the adoption of 0.80ET will be superior to 1.00ET in northeastern Colorado to maintain stable irrigated corn production for the long term.

Our recommendations for both optimum yield and WUE were based on the minimum levels of all of the variables to reach our goal. Some may argue that 1.00ET is not harmful to the Ogallala because any excess water will recharge the aquifer and be available for pumping again. However, 1.00ET increases energy costs for pumping water from wells. In addition, 1.00ET may increase the potential of underground water contamination by nitrate, pesticides, and other pollutants. Because the majority of farmers are not able to implement best management practices in irrigation scheduling to the level that were implemented in this study during irrigation events, 1.00ET will probably cause some overirrigation under current growers' irrigation management.

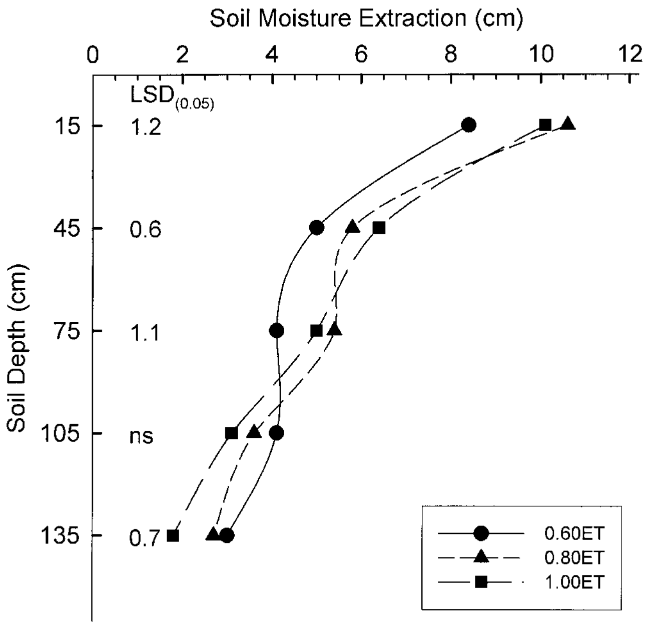

Fig. 1. Effects of different irrigation treatments on soil moisture extraction from soil profile during the entire season averaged over 1998 to 2000. ET, evapotranspiration.

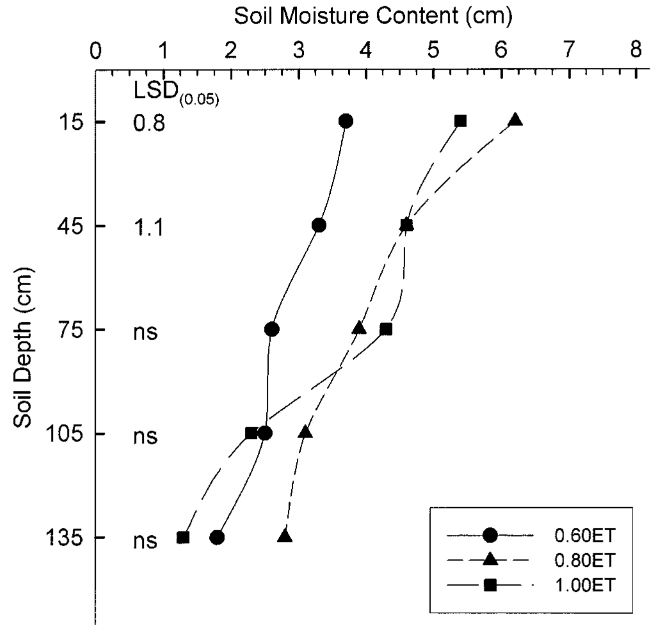

Fig. 2. Effects of different irrigation treatments on soil moisture content in soil profile at harvest averaged over 1998 to 2000. ET, evapotranspiration.

Similarly, the use of a higher N rate and plant population than our recommendations also may lead to maximum yield or WUE, but the production costs of additional fertilizer and seed will be increased, and the potential of Ogallala Aquifer contamination by nitrate may be increased. The effects of N rate, irrigation rate, and plant population on nitrate leaching were evaluated in this study and will be presented in another publication.

Soil Moisture Extraction

Initial soil moisture status was uniform across the field before this experiment began. Soil moisture extraction during the entire season averaged over 1998 to 2000 showed that the influences of irrigation on moisture extraction varied with soil depth (Fig. 1). The 0.60ET treatment had moisture extraction 19% lower on average within the top 60 cm of soil than 1.00ET (Fig. 1). The differences in moisture extraction were not observed between 0.80ET and 1.00ET treatments within the top 90 cm (Fig. 1). In addition, moisture extraction was the greatest from the top 30 cm compared with other soil depths regardless of irrigation treatment. The moisture extraction from the 0- to 30-cm depth accounted for 34 to 38% of the total moisture extraction from the soil profile down to 150 cm in depth. Plant population showed no significant effects on moisture extraction in any soil depth (data not shown).

Soil Moisture Content at Harvest

The 0.60ET treatment resulted in soil moisture content 28 to 40% lower at harvest for depths within the top 90 cm of soil compared with the other two irrigation treatments where most depths were at field capacity or greater (Fig. 2). Moisture content did not differ between 0.80ET and 1.00ET within the top 90 cm. Totaling the moisture content in the soil profile, soil profile moisture content at 0.60ET was 13.9 cm, which was 22 and 32% lower than those under 1.00ET and 0.80ET, respectively. No significant effects on soil moisture content at harvest due to plant population were observed regardless of depth interval (data not shown). The fact that 0.80ET and 1.00ET had soil moisture content near field capacity at harvest suggests both 0.80ET and 1.00ET might cause some overirrigation late in the season, perhaps because there was considerable rainfall late in the season that was out of our management control. Because soil moisture at harvest was available for the following crop, there would be some residual irrigation effects on crop production in the following season. These residual effects may need to be estimated to accurately measure the irrigation effects on crop production. No significant differences in water extraction for the entire season and soil moisture content at harvest between 0.80ET and 1.00ET were additional indications that 0.80ET is superior to 1.00ET.

CONCLUSIONS

Plant N uptake generally responded positively to irrigation, N rate, and plant population at the middle (VT) and late (R6) growth stages. The 0.80ET treatment was comparable to 1.00ET, but 0.60ET was not competitive with 1.00ET or 0.80ET in terms of corn yield. Nitrogen fertility of 250 kg N ha^{-1}, the common N rate currently used for corn production in northeastern Colorado, can be replaced by 140 kg N ha^{-1} regardless of irrigation treatment on this high-N-testing soil in most cases. Plant population of 57 000 plants ha^{-1} was an appropriate alternative to 81 000 plants ha^{-1} under 0.60ET and 0.80ET, but 69 000 plants ha^{-1} was needed to replace 81 000 plants ha^{-1} under 1.00ET. It is appropriate to recommend 0.80ET to 1.00ET (51–64 cm of total water use) combined with 140 to 250 kg N ha^{-1} and plant population of 57 000 to 69 000 plants ha^{-1} as the best management system for optimum corn yield under this environment.

The 0.80 irrigation treatment had the same or even greater WUE than 1.00ET and 0.60ET regardless of N fertility rate. Treatment 0.80ET accompanied by 140 to 250 kg N ha^{-1} and plant population of 57 000 to 69 000 plants ha^{-1} is the best management system for optimum WUE. This recommendation is slightly different in irrigation from the suggestion for optimum yield. To preserve the Ogallala Aquifer, the best management system aimed at maximum WUE should be recommended for corn production in this region.

Influences of irrigation on soil moisture extraction during the entire season and soil moisture at harvest varied with soil depth. Irrigation treatment 0.60ET resulted in lower moisture extraction within the top 60 cm and lower soil moisture content at harvest within the top 90 cm compared with 1.00ET. Some residual effects of irrigation on crop production could occur in the following season due to the differences in moisture content at harvest. No significant differences in water extraction from the soil profile for the entire season and soil moisture content at harvest between 0.80ET and 1.00ET treatments were additional indications that 0.80ET is superior to 1.00ET.

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