Comparison of Nitrogen Fertilization Methods and Rates for Subsurface Drip Irrigated Corn in the Semi-Arid Great Plains

D. D. Tarkalson, J. O. Payero

Abstract. *In semi-arid areas such as western Nebraska, interest in subsurface drip irrigation (SDI) for corn is increasing due to restricted irrigation allocations. However, crop response quantification to nitrogen (N) applications with SDI and the environmental benefits of multiple in-season (IS) SDI N applications instead of a single early-season (ES) surface application are lacking. The study was conducted in 2004, 2005, and 2006 at the University of Nebraska-Lincoln West Central Research and Extension Center in North Platte, Nebraska, comparing two N application methods (IS and ES) and three N rates (128, 186, and 278 kg N ha^{-1}) using a randomized complete block design with four replications. No grain yield or biomass response was observed in 2004. In 2005 and 2006, corn grain yield and biomass production increased with increasing N rates, and the IS treatment increased grain yield, total N uptake, and gross return after N application costs (GRN) compared to the ES treatment. Chlorophyll meter readings taken at the R3 corn growth stage in 2006 showed that less N was supplied to the plant with ES compared to the IS treatment. At the end of the study, soil NO_3-N masses in the 0.9 to 1.8 m depth were greater under the IS treatment compared to the ES treatment. Results suggested that greater losses of NO_3-N below the root zone under the ES treatment may have had a negative effect on corn production. Under SDI systems, fertigating a recommended N rate at various corn growth stages can increase yields, GRN, and reduce NO_3-N leaching in soils compared to concentrated early-season applications.*

Keywords. *Application method, Application rate, Biomass, Corn, Grain yield, Nitrogen, SDI, Subsurface drip irrigation.*

Irrigated agriculture is vital to crop production in the semi-arid and arid areas of the U.S. Irrigation stabilizes crop production in areas with deficient rainfall to supply crop water requirements. In Nebraska, restricted irrigation allocations have been implemented in some areas due to drought and lawsuit settlements with Kansas and Colorado. High levels of nitrate have also been detected in groundwater in a number of areas in Nebraska. Under these conditions, innovative and more efficient irrigation technologies can be used on some fields to sustain irrigated agriculture and protect the environment. Microirrigation is an example of current technology that can have advantages over other common irrigation systems. Advantages include improved water and nutrient management, increased crop yields, and improved crop quality (Ayars et al., 1999).

A form of microirrigation, subsurface drip irrigation (SDI), is obtaining increased interest for field crop production in the Great Plains. The use of SDI in field crop production has advanced due to the ability to bury the irrigation dripline in the soil. This makes it easier to perform cultural farming practices (Ayars et al., 1999) compared to other microirrigation systems that are normally installed on the soil surface. Most research and production use of microirrigation has been on trees and vines; limited research has been conducted on the use of SDI with field crops (Ayars et al., 1999). This research includes SDI economic studies (O'Brien et al., 1998), SDI system design (Sorensen et al., 2001; Bordovsky, 2007; Lamm and Trooien, 2005), irrigation management (Lamm and Trooien, 2003; Payero et al., 2006; Pablo et al., 2007; Vories and Tacker, 2007), and nitrogen management (Lamm et al., 2001, 2003). O'Brien et al. (1998) showed that under certain conditions, SDI can compete economically and in some cases have an economic advantage over center-pivot systems for continuous corn production. Bordovsky (2007) suggested that optimizing lateral dripline positions and orientations can improve irrigation water use effectiveness in cotton. Lamb and Trooien (2005) found that dripline depths of 0.20 to 0.61 m in silt loam soils were acceptable for corn production in western Kansas and surrounding areas. In studies conducted in Kansas, Lamm et al. (1995) found that careful irrigation with SDI can reduce net irrigation amounts by 25% compared to the established long-term net irrigation requirement while maintaining high corn grain yields. Pablo et al. (2007) determined that, on a sandy loam soil, an SDI dripline depth of 15 to 20 cm optimized water use efficiency in corn production.

Submitted for review in April 2008 as manuscript number SW 7464; approved for publication by the Soil & Water Division of ASABE in August 2008.

A joint contribution of the University of Nebraska-Lincoln, USDA-ARS, and the Queensland Government Department of Primary Industry and Fisheries. Names of commercial products are solely provided as information to the reader and do not imply endorsement or recommendation by the authors or their organizations.

The authors are **David D. Tarkalson,** Soil Scientist, USDA-ARS Northwest Irrigation and Soils Research Laboratory (NWISRL), Kimberly, Idaho; and **Jose O. Payero,** Senior Research Scientist and Irrigation Engineer, Queensland Department of Primary Industries and Fisheries (QDPI&F), Toowoomba, Queensland, Australia. **Corresponding author:** David D. Tarkalson, USDA-ARS NWISRL, 3793 North 3600 East, Kimberly, ID 83341; phone: 208-423-6503; fax: 208-423-6555; e-mail: david.tarkalson@ars.usda.gov.

Split applications of N through microirrigation systems can increase nitrogen use efficiency in crops compared to other fertilizer application methods (Haynes, 1985; Miller et al., 1976; Nakayama and Bucks, 1986; Phene et al., 1979). However, under a continuous field corn system Lamm et al. (2001) found no difference in grain yield or apparent aboveground biomass N uptake between N applied preplant and N applied over the growing season through an SDI system. Soil NO_3–N at the end of the season was distributed differently when N was preplant-applied compared to N applied through the SDI system. When the N was preplant-applied, most of the NO_3–N was located in the upper 0.3 m of the profile for all irrigation levels (75%, 100%, and 125% of evapotranspiration). However, when the N was applied through the SDI dripline, NO_3–N moved deeper into the soil profile as the irrigation amount increased.

The use of SDI in field crop production is increasing and is expected to continue to increase in the future (Ayars et al., 1999). With increasing use of SDI for field crop production, development of best management practices for SDI is important to maximize economic returns and protect the environment. This study was conducted to compare grain yield of corn, corn biomass production, nitrogen uptake of corn, and NO_3^-–N movement in the soil under two nitrogen application methods and three N application rates for corn grown with an SDI system.

Materials and Methods

Site Description

Field data for this study were collected in 2004, 2005, and 2006 at the University of Nebraska-Lincoln West Central Research and Extension Center in North Platte, Nebraska (41.1° N, 100.8° W, 861 m above sea level). The climate at North Platte is semi-arid, with average annual precipitation and reference evapotranspiration of approximately 508 and 1403 mm, respectively. On average, about 80% of the annual precipitation occurs during the growing season, which extends from late April to mid-October (USDA, 1978). The soil at the experimental site is a Cozad silt loam (fine-silty, mixed, mesic Fluventic Haplustoll).

Experimental Design

The experiment was conducted using a randomized complete block factorial design with two N application method treatments, three N rates, and four replications. Each experimental plot was 9.1 m wide × 72.2 m long, which accommodated twelve rows of corn. The N application methods consisted of N fertilizer applied during the early-season (ES) and in-season (IS). Nitrogen application rates were 128, 186, and 256 kg N ha^{-1} in 2004 and 128, 186, and 278 kg N ha^{-1} in 2005 and 2006 (table 1). In this article, the three N levels are referred to as N rate 1 (NR1, 128 kg N ha^{-1}), N rate 2 (NR2, 186 kg N ha^{-1}), and N rate 3 (NR3, 256 kg N ha^{-1} in 2004, and 278 kg N ha^{-1} in 2005 and 2006). The difference in NR3 in 2004 compared to 2005 and 2006 was due to a calculation difference. Both ES and IS treatments received less than 10% of the total N applied as a starter (10-34-0) at planting (table 1), 5 cm to the side and 5 cm below the seed zone. The remaining N for the ES treatment was knife-applied within 14 days after planting between corn rows as anhydrous ammonia (82-0-0) in 2004 and ammonium nitrate (34-0-0) in 2005 and 2006 (table 1). The remaining N for the IS treatment was applied periodically through the SDI system as urea am–

Table 1. Nitrogen fertilizer application rates (kg N ha^{-1}) and timings for 2004, 2005, and 2006.

Year	Application Method	N Rate (total kg N ha^{-1})	N Application Date and Growth Stage of Corn						
			11 May Planting[a]	12 May Pre-emergence[b]	21 July V16	28 July V18	84 Aug. R1	11 Aug. R2	16 Aug. R3
2004	Early-season	NR1 (128)	10	118	0	0	0	0	0
		NR2 (186)	10	176	0	0	0	0	0
		NR3 (256)	10	246	0	0	0	0	0
	In-season	NR1 (128)	10	0	36	28	18	18	18
		NR2 (186)	10	0	53	45	26	26	26
		NR3 (256)	10	0	77	61	36	36	36
			17 May Planting	27 May V1	1 July V8	14 July V14	28 July R1	4 Aug. R2	16 Aug. R3
2005	Early-season	NR1 (128)	10	118	0	0	0	0	0
		NR2 (186)	10	176	0	0	0	0	0
		NR3 (278)	10	268	0	0	0	0	0
	In-season	NR1 (128)	10	0	36	28	18	18	18
		NR2 (186)	10	0	53	45	26	26	26
		NR3 (278)	10	0	83	67	39	39	39
			11 May Planting	25 May V1	3 July V10	10 July V14	17 July VT		
2006	Early-season	NR1 (128)	10	118	0	0	0		
		NR2 (186)	10	176	0	0	0		
		NR3 (278)	10	268	0	0	0		
	In-season	NR1 (128)	10	0	36	29	52		
		NR2 (186)	10	0	53	45	78		
		NR3 (278)	10	0	82	67	120		

[a] Nitrogen applied 5 cm below and 5 cm to the side of the seed.
[b] On 19 July 2004, 6 kg N ha-1 of the total from each N rate was applied through the SDI system.

monium nitrate (32-0-0) (tables 1 and 2). In 2004 and 2005, the last N application from the IS treatment took place at the R3 growth stage (milk stage). In 2006, a cutoff date for N applications was set for the VT growth stage (tasseling).

Cultural Practices

Corn hybrid Kaystar KX-8770Bt was planted in 2004, and KX-8615Bt was planted in 2005 and 2006. Both hybrids had a comparative relative maturity of 112 days. The crop was planted at 0.76 m row spacing at a seeding rate of approximately 74,000 seeds ha^{-1}. Corn was planted on 11, 17, and 11 May and reached physiological maturity on 13 October, 23 September, and 16 September in 2004, 2005, and 2006, respectively. To control weeds, a recommended rate of herbicide mixture (Lumax + Banvel + Atrazine 90 DF + crop oil) was applied when the crop was at the four-leaf stage. Insect control in 2004 and 2005 consisted of one application of the insecticide Force 3G at planting time. In 2006, Counter was applied at planting for insect control. The target insects were the corn rootworm beetle (*Diabrotica virgifera virgifera* LeConte) and the European corn borer (*Ostrinia nubilalis* (Hübner)).

Irrigation System and Irrigation Scheduling

All the experimental plots were irrigated using an SDI system that was installed just prior to planting in 2003. Surface-irrigated soybean was grown in the field in 2002, and a deficit-irrigated corn crop was grown in 2003. The SDI laterals were spaced every 1.52 m (every other crop row) and were installed at a depth of approximately 0.4 m from the soil surface. Drip laterals were 15 mil TSX 515-12-340 thinwall dripperlines (T-Tape) with emitters spaced every 30 cm and an inside diameter of 1.6 cm. The nominal flow of each emitter was 0.77 L h^{-1} at a nominal pressure of 55 kPa. Irrigation water was filtered using a 152 mm diameter screen filter (Agricultural Products, Inc.) with a 200-mesh screen. Irrigation was supplied through a manifold instrumented with flowmeters, electric/manual valves, pressure regulators, and air vents installed in the supply line to each plot. Irrigation depths and timing to each plot were controlled manually. The mainline of the SDI system was also instrumented with a chemigation system that allowed application of the liquid nitrogen fertilizer with the irrigation water. The chemigation system consisted of a fertilizer storage tank, a piston chemical injection pump, and a chemigation check valve. The storage tank was instrumented with a standing pipe that allowed volumetric calibration of the flow rate of the injection pump.

Irrigation amounts and timing were scheduled to supplement rainfall and meet crop water requirements (crop evapotranspiration, ET_c) aimed at producing maximum yield. If necessary, irrigation was applied a maximum of three times a week. Irrigations were scheduled using a computer program that was written in Microsoft Visual Basic (Payero et al., 2005). Inputs to the program included daily weather data, rainfall, irrigation date and amounts, initial water content in the soil profile at crop emergence, and crop- and site-specific information such as planting date, maturity date, soil parameters, maximum rooting depth, etc. Weather data were obtained from an automatic weather station located within 1.5 km of the research site. Daily weather data included daily maximum and minimum air temperature, relative humidity, wind speed, rainfall, and solar radiation. Rainfall data were also collected manually from rain gauges installed at each of the four field corners. The computer program calculated daily ET_c and the water balance in the crop root zone using the procedure described in FAO-56 (Allen et al., 1998; Wright, 1982). Readers are referred to the original sources for additional details. According to this procedure, ET_c can be obtained as the product of the evapotranspiration of a grass-reference crop (ET_o) and a crop coefficient (K_c). ET_o is calculated using the weather data as input to the Penman-Monteith equation, and the K_c is used to adjust the estimated ET_o for the reference crop to that of other crops at different growth stages and growing environments. In this study, the dual K_c approach was used, which separated the two components of ET_c, namely evaporation (E) and transpiration (T). For corn, this procedure linearly reduced ET_c when the soil water depletion in the crop root zone exceeded 55% (taken from table 22 in FAO-56) of total available water. The dual K_c procedure also accounted for the sharp increases in E due to a wet soil surface following rain or irrigation. This procedure, therefore, permitted calculation of daily ET_c under water-limiting conditions and when soil water was not limiting (ET_w). Water contents in the soil profile at 0.3 m depth increments were directly measured several times during each season using the neutron probe method to a depth of 1.5 m 2004 and 3 m in 2005 and 2006. This information was used to establish the soil water profile at the start of the season and to make sure that the computer model was accurate in estimating soil water.

Grain Yield, Biomass, and Nitrogen Uptake

At physiological maturity, eight plants from each plot were hand-harvested to determine aboveground total biomass production, total N content, and N partitioning into the different plant components (grain, stover, and cob). Plants were cut at ground level, the ears were separated from the stover, and ear and stover samples from each plot were transported to the lab for further processing and analyses. In the lab, the stover samples from each plot were weighed, chopped using a heavy-duty plant chopper, and a subsample was collected and weighed. The subsamples were oven-dried at 70°C until they reached a constant weight (approx. seven days), and then the weight was recorded. The ear samples were placed in a greenhouse and air-dried to a moisture content of approximately 15% to 16%. The ear samples were weighed and shelled by hand. The grain and cob samples were oven-dried at 70°C until they reached a constant weight (approx. seven days), and then the weight was recorded. Oven-dried grain, stover, and cob samples were ground for total N analysis. Total N was determined by combusting 50 mg of sample from each plant in a Flash EA 1112 elemental analyzer (CE Elantech, Lakewood, N.J.). Crop grain yield was determined by harvesting the center three rows (70.1 m long) of each plot using a plot combine with a three-row corn head. The combine was instrumented with an HM-400 harvest data system (Juniper Systems, Inc., Logan, Utah), which measured grain yield, grain moisture, and test weight.

Table 2. Prices for nitrogen fertilizers ($ kg N^{-1}) in 2004, 2005 and 2006.

Year	10-34-0	82-0-0	32-0-0	34-0-0
2004	2.91	0.53	0.70	--
2005	3.28	--	0.79	0.93
2006	3.47	--	0.91	1.15

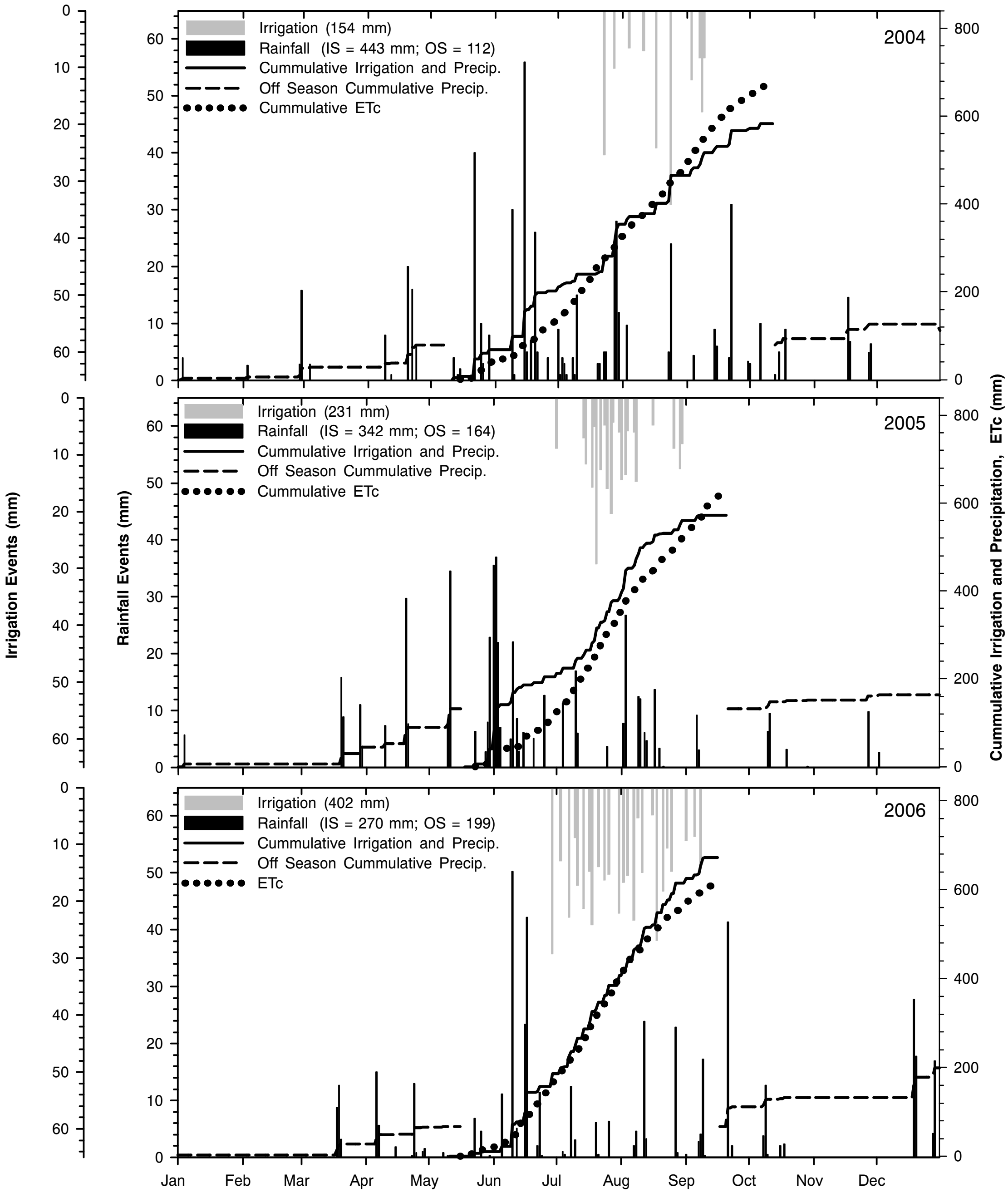

Figure 1. Irrigation, precipitation, and evapotranspiration (ET) data from research area in 2004, 2005, and 2006. ET_c is the actual crop ET. During 2004, 2005, and 2006 $ET_c = ET_w$ (ET assuming water is not limiting). The in-season (IS) time period was from emergence to physiological maturity. The off-season time period was the remaining time during the year.

Gross return after nitrogen costs (GRN) was calculated as:

$$GRN = (GY \times GP) - (NR \times NP) - (NApC) \qquad (1)$$

where

GRN = gross return after nitrogen costs ($ ha^{-1})
GY = grain yield (kg ha^{-1})
GP = grain price ($ kg grain^{-1})
NR = nitrogen application rate (kg ha^{-1})
NP = nitrogen price ($ kg N^{-1})
NApC= nitrogen application costs.

The following costs were used in estimating GRN: GP = $0.118 kg^{-1} ($3 bu^{-1}), and NP varied by year (table 2).

NApC (ES) costs were estimated at $19.40, $19.95, and $20.50 ha^{-1} for 2004, 2005, and 2006 (a 2.7% average rate of inflation was used to increase costs over time). Cost included overhead (depreciation, interest, insurance, housing, and repairs), fuel, and labor (Schnitkey and Lattz, 2006). Cost excluded allowances for profit.

NApC (IS) costs were estimated based on reported energy usage fees of $0.0458, $0.0688, $0.0956 kWh^{-1} from the Nebraska Public Power District, a 0.5 hp 0.373 kW fertigation pump, and recorded fertigation pump times for 2004, 2005, and 2006.

Chlorophyll Meter Readings

Chlorophyll meter readings were taken at the V10 (2 July), V14 (10 July), and R3 (2 Aug) growth stages in 2006 from each plot using a Minolta SPAD-520 chlorophyll meter. The chlorophyll meter estimated the relative amount of chlorophyll present in plant leaves. N content of plant leaves is related to chlorophyll content in plant leaves. Research showed correlations (R) between measured SPAD readings and N content in plant leaves between 0.89 and 0.91 (Wood et al., 1992; Anderson et al., 1993). Within each plot, 20 readings were taken on 20 leaves midway between the collar of the latest fully expanded leaf that had formed at the leaf/stalk junction and the tip of the leaf, and midway between the midrib and edge of the leaf. The 20 readings were averaged to give one value per plot.

Soil Nitrate-N

Nitrate–N in the soil profile was quantified at the beginning (spring 2004) and end (spring 2007) of the study. At the beginning of the study, a composite sample of three soil cores (38 mm diameter) was collected from each plot at depths of 0-0.2, 0.2-0.6, 0.6-0.9, 0.9-1.2, 1.2-1.5, 1.5-1.8, and 1.8-2.1 m. Every row received fertilizer under the ES treatment, and every other row received fertilizer under the IS treatment. At the end of the study, a composite sample of three cores (38 mm diameter) was collected from each plot at the same depths as samples collected at the beginning of the study. However, two locations in each plot were sampled, approximately 10 and 76.2 cm laterally from the SDI dripline. Soil samples were air dried, ground to pass through a 2 mm sieve, and analyzed for NO_3–N concentration (Keeney and Nelson, 1982). Average bulk density (BD) values determined in the spring of 2002 and the NO_3–N concentrations for each sampling depth were used to determine the mass of NO_3–N in the soil (BD values for the 0-0.2, 0.2-0.6, 0-0.9, 0.9-1.2, 1.2-1.5, 1.5-1.8, and 1.8-2.1 m depths were 1.37, 1.33, 1.33, 1.29, 1.31, 1.31, and 1.31 g cm^{-3}, respectively). In 2006, the concentrations of NO_3–N from the two lateral sample locations within each plot were averaged to account for the potential variation in nitrate movement between the two application method treatments.

Statistical Analyses

Data conformed to the assumptions of analysis of variance (ANOVA). Analysis of variance and separation of means by the least significant difference method was conducted using Statistix 8 (Analytical Software, 2003). Significance was determined at the 0.05 probability level.

Results and Discussion

Rainfall and Irrigation

A total of 41, 31, and 29 rainfall events and 10, 21, and 25 irrigation events occurred during the growing season in 2004, 2005, and 2006, respectively (fig. 1). Rainfall contributed 65%, 54%, and 43% and irrigation contributed 23%, 37%, and 64% of the cumulative ET_c during the growing season in 2004, 2005, and 2006, respectively (fig. 1).

Soil Water

The soil water balance model and neutron probe data showed that soil water was adequate to not limit plant growth (figs. 2 and 3). For each year, the root zone water depletion (based on the water balance model) averaged over the entire root zone was never greater than 50% of the available water (fig. 2). This depletion level refers to the point at which 50% of the plant-available water remains in the root zone, which is commonly used to trigger irrigation. To maximize yields not limited by water, the actual soil water depletion needs to be consistently below the 50% depletion level. Direct soil

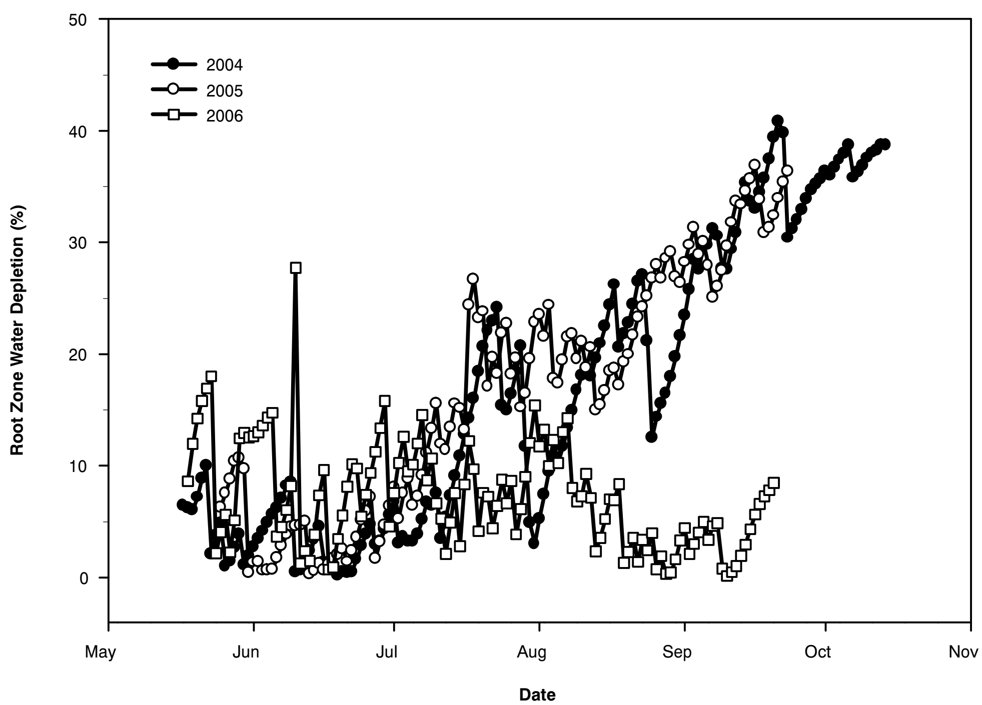

Figure 2. Root zone water depletion during the growing season in 2004, 2005, and 2006. Root zone depletion is calculated as a % of total available water in the crop root zone.

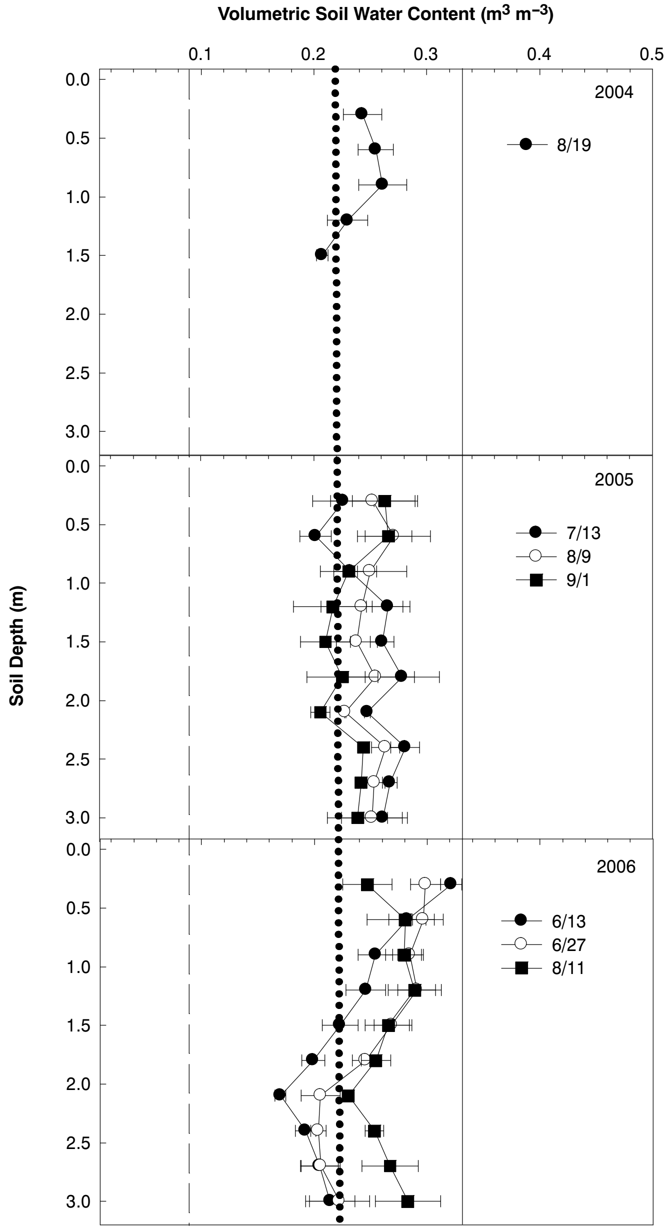

Figure 3. Volumetric soil water at different depths in the field in 2004, 2005, and 2006. Values at each depth are the average of all three replications. Error bars indicate standard errors of the averages. The solid vertical line represents the volumetric soil water at field capacity (0.35 m^3 m^{-3}), the dotted line represents volumetric soil water at 50% of field capacity (0.22 m^3 m^{-3}), and the dashed line represents the volumetric soil water at permanent wilting point (0.09 m^3 m^{-3}).

water measurements using a neutron probe showed that most volumetric soil water contents were below the 50% depletion level at most depths on the dates sampled during all three years (fig. 3).

Corn Grain Yields

Analysis of variance of the effects of N application rate and application method on corn grain yield and biomass was conducted for 2004, 2005, and 2006 separately due to variation in the NR3 application rate in 2004 compared to 2005 and 2006. The N rate and application method main effects and the interaction were not significant in 2004 ($P > 0.05$). In 2004, there were no differences in grain yield between the ES and IS application methods or between N application rates (table 3). The average corn grain yield in 2004 over all N application rates and application methods was 13.29 Mg ha^{-1}. Based on the University of Nebraska-Lincoln N recommendations for corn, the total N requirement for the corn at a yield level of 13.29 Mg ha^{-1} was 322.8 kg N ha^{-1}. Soil NO_3-N masses at the start of the study were similar across the entire research area and averaged 67.3 kg ha^{-1} in the 0 to 1.8 m depth (see discussion under Soil Nitrate-N later in the Results and Discussion section). This represents only 20.8% of the total crop N requirement and likely did not cause the lack of grain yield difference in 2004. In 2005 and 2006, the N rate and application method main effects were significant ($P < 0.05$) and the grain yields under IS were 4.6% and 9.9% greater than under ES, respectively (table 3). In 2005, grain yields increased with each increase in N application rate (table 3). In 2006, the grain yield was maximized at the NR2 application rate (table 3).

Table 3. Corn grain yield (Mg ha^{-1}) and analysis of variance for effects of N application rate (NR) and N application method (AM) in 2004, 2005, and 2006.

NR (kg N ha^{-1})	2004			2005			2006		
	ES[a]	IS[a]	Mean[b]	ES	IS	Mean	ES	IS	Mean
NR1 (128)	13.12 (0.25)	13.55 (0.33)	13.34	9.77 (0.30)	10.17 (0.24)	9.97 a	10.02 (0.36)	11.69 (0.44)	10.86 a
NR2 (186)	13.36 (0.46)	12.78 (0.89)	13.07	10.68 (0.21)	11.27 (0.34)	10.98 b	11.63 (0.36)	12.75 (0.11)	12.19 b
NR3 (278)[c]	13.78 (0.38)	13.14 (0.60)	13.46	11.97 (0.17)	12.53 (0.18)	12.25 c	12.27 (0.18)	13.20 (0.23)	12.74 b
Mean[b]	13.42	13.16		10.80 a	11.32 b		11.31 a	12.55 b	
ANOVA (d.f.)[d]					Pr > F				
NR (2)		0.6887			<0.0001			0.0001	
AM (1)		0.4958			0.0190			0.0002	
NR × AM (2)		0.4447			0.9124			0.4664	

[a] Numbers in parentheses are standard errors of the treatment means.
[b] For a given year, application method means and N rate means followed by the same letter are not significantly different using $LSD_{(0.05)}$, No letters are due to insignificant F test.
[c] In 2004, NR3 was 256 kg N ha^{-1}.
[d] d.f. = degrees of freedom.

The lack of yield difference between N rates and application methods in 2004 was likely a result of ample amounts N being released from the soil organic matter fraction (Halvorson et al., 2005). A higher rate of N mineralization in 2004 possibly masked N inputs irrespective of application rate. The soil NO_3-N masses did not account for this, but it is likely that the N mineralization could have occurred after the sampling time. Soybeans were grown on the plot area in 2002, followed by a corn crop in 2003 that did not receive N fertilizer inputs. Although not measured in 2003, the quantity of biomass from stover remaining in the field after grain harvest was likely lower compared to a fertilized crop. During the 2003 growing season, significant visual N deficiencies were observed through the entire growing season, and plants were uniformly stunted. This reduced biomass could have resulted in less nitrogen immobilization in the soil during the 2004 growing season (Blackmer, 1997). Research is needed to better predict and understand the mechanisms of N mineralization and supplying capacity of N from soils.

Gross Return After N Costs

In 2004, there were no differences in GRN between the ES and IS application methods at all N application rates (fig. 4). For NR1, NR2, and NR3, the GRN averaged over application method was \$1,463, \$1,396, and \$1,399 ha^{-1}, respectively. In 2005, the IS application method had a greater GRN compared to the ES at NR2 and NR3 (fig. 4). For NR2 and NR3, the GRN difference between the IS and ES application methods was \$113 and \$122 ha^{-1}, respectively. In 2006, the IS application method had a greater GRN compared to the ES at all N application rates (fig. 4). For NR1, NR2, and NR3, the GRN difference between the IS and ES application methods was \$246, \$194 and \$194 ha^{-1}, respectively. The higher cost of N application due to fuel and tractor costs for the ES treatment, compared to lower fertigation pump costs with IS, increased the GRN difference between the two treatments above the difference in grain yields.

Corn Biomass

The statistical analysis results for total biomass were similar to the results of the grain yields with the exception that the application method main effect in 2005 was not significant (table 4). In 2004 and 2005, there were no differences in total biomass between the ES and IS application methods (table 4). The total biomass averaged over N application rates and application methods in 2004 and 2005 were 30.06 and 17.04 Mg ha^{-1}. In 2006, the total biomass under the IS treatment was 4.8% greater than the ES treatment (table 4).

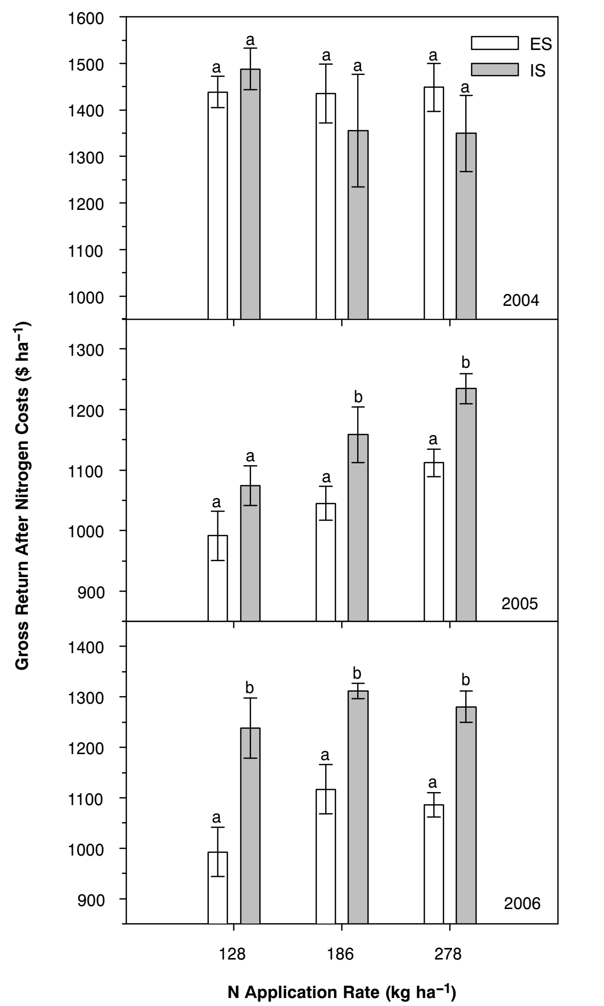

Figure 4. Gross return after N costs (\$ ha^{-1}) for each N application rate and N application method in 2004, 2005, and 2006. For each N application rate, N application methods with the same letter are not significantly different at the 0.05 probability level. ES and IS are early-season and in-season N application, respectively.

Table 4. Total corn biomass[a] ($Mg\ ha^{-1}$) (dry weight basis) and analysis of variance for effects of N application rate (NR) and N application method (AM) in 2004, 2005, and 2006.

NR ($kg\ N\ ha^{-1}$)	2004			2005			2006		
	ES[b]	IS[b]	Mean[c]	ES	IS	Mean	ES	IS	Mean
NR1 (128)	29.65 (0.48)	29.88 (0.89)	29.77	15.66 (0.41)	15.27 (0.40)	15.47 a	18.03 (0.85)	18.31 (0.53)	18.17 a
NR2 (186)	30.41 (1.27)	30.02 (2.90)	30.22	16.70 (0.25)	17.28 (0.42)	16.99 b	18.70 (0.70)	19.74 (0.32)	19.22 a
NR3 (278)[d]	30.49 (0.58)	29.91 (1.53)	30.20	18.45 (0.14)	18.88 (0.38)	18.67 c	19.72 (0.36)	21.25 (0.86)	20.49 b
Mean[c]	30.18	29.94		16.94	17.14		18.82 a	19.77 b	
ANOVA (d.f.)[e]					Pr > F				
NR (2)		0.9181			0.0000			0.0020	
AM (1)		0.9078			0.4237			0.0434	
NR × AM (2)		0.9602			0.2562			0.5051	

[a] Grain, cob, and stover mass (dry weight basis).
[b] Numbers in parentheses are standard errors of the treatment means.
[c] For a given year, application method means and N rate means followed by the same letter are not significantly different using $LSD_{(0.05)}$. No letters are due to insignificant F test.
[d] In 2004, NR3 was 256 $kg\ N\ ha^{-1}$.
[e] d.f. = degrees of freedom.

In 2004, there were no differences in total biomass between the three N application rates (table 4). In 2005, total biomass increased with each increase in N application rate (table 4). In 2006, the total biomass was similar for the NR1 and NR2 application rates, but greater at the NR3 application rate (table 4). The greater biomass in 2004, as compared to 2005 and 2006, was likely due to differences in weather; the growing season was approximately a month longer in 2004.

Corn N Uptake

The N rate and application method main effects and the interaction were not significant in 2004 (P > 0.05; table 5). In 2004, the average total N uptake over the N application rates and application methods was 265.9 $kg\ N\ ha^{-1}$ (table 5). In 2005 and 2006, the N rate and application method main effects were significant (P < 0.05; table 5). In 2005 and 2006, the total N uptake under IS was 10.4% and 15.2% greater than ES, respectively (table 5). The differences in 2005 and 2006 were a result of greater grain yields under the IS treatment. Greater N uptake under the IS treatment will potentially result in less NO_3–N leaching in the soil profile compared to the ES treatment.

Chlorophyll Meter SPAD Readings

Main effects of N rate and application method were significant (P < 0.05), and the subplot main effect of SPAD reading time as well as the SPAD reading time by application method interaction were also significant (table 6). The significant interaction is presented in figure 5. Chlorophyll meter SPAD readings in 2006 were greater for the ES application method at the V10 and V14 growth stages compared to the IS application method. However, at the R3 growth stage, the IS application method had a greater SPAD reading compared to the ES application method. These data indicate that, in 2006, the corn in the ES treatments had a greater N uptake early in the season (vegetative growth stages), but the corn in the IS treatment had a greater N uptake during the reproductive stages. Thus, the higher grain yield and total biomass for the IS treatment was possibly due to an adequate N supply during the later growth stages compared to the ES treatment. The ES treatment likely had a decreased N supply due to N losses later in the season. In 2006, the apparent reduced N uptake during the vegetative growth stages (to a point) was not as critical as reduced N availability during reproductive growth stages. A greater supply of N may have been needed earlier in the growing season under the IS treatment. In hindsight, supplying a portion of the total N around planting for the IS treatment likely would have offset the difference in plant N content during the vegetative growth stages.

Table 5. Total N uptake ($kg\ ha^{-1}$) of corn and analysis of variance for effects of N application rate (NR) and N application method (AM) in 2004, 2005, and 2006.

NR ($kg\ N\ ha^{-1}$)	2004			2005[a]			2006		
	ES[b]	IS[b]	Mean[c]	ES	IS	Mean	ES	IS	Mean
NR1 (128)	235.1 (23.4)	251.4 (9.6)	243.3	109.9 (4.9)	126.0 (5.5)	118.0 a	119.2 (4.8)	153.4 (7.6)	136.3 a
NR2 (186)	268.2 (9.5)	290.4 (32.0)	279.3	143.0 (1.8)	165.4 (7.6)	154.2 b	160.9 (5.3)	196.2 (6.6)	178.6 b
NR3 (278)[d]	281.2 (3.6)	269.2 (14.3)	275.2	175.0 (6.3)	185.8 (5.3)	180.4 c	195.9 (7.2)	211.6 (14.7)	203.8 c
Mean[c]	261.5	270.3		142.6 a	159.1 b		158.6 a	187.1 b	
ANOVA (d.f.)[e]					Pr > F				
NR (2)		0.1058			0.0000			0.0000	
AM (1)		0.4654			0.0001			0.0001	
NR × AM (2)		0.6865			0.3773			0.3753	

[a] Total N uptake in 2005 excludes N in cobs. In 2004 and 2006, N in uptake in cobs averaged 2.6 $kg\ ha^{-1}$.
[b] Numbers in parentheses are standard errors of the treatment means.
[c] For a given year, application method means and N rate means followed by the same letter are not significantly different using $LSD_{(0.05)}$. No letters are due to insignificant F test.
[d] In 2004, NR3 was 256 $kg\ N\ ha^{-1}$.
[e] d.f. = degrees of freedom.

Table 6. Analysis of variance (P > F) for chlorophyll meter readings (SPAD) for N application rate (NR), N application method (AM), and interaction main effects during the 2006 growing season.

ANOVA[a]		d.f.[b]	Pr > F
Main plots	NR	2	0.0003
	AM	1	0.0507
	NR × AM	2	0.8865
Subplot	SPAD time (ST)	2	0.0001
	ST × NR	4	0.0543
	ST × AM	2	0.0000

[a] A split-plot in time analysis was conducted. The error term used to test the main plot main effects and the interaction was Rep × NR × AM. The error term used to test the subplot main effect and the interactions was Rep × ST × NR × AM.
[b] d.f. = degrees of freedom.

Soil Nitrate-N

2004 Pre-Study Soil Nitrate-N

The N rate and application method main effects and two-way interaction for pre-study soil NO_3-N masses were not different for the 0-0.9 and 0.9-1.8 m depths (ANOVA data not shown). This indicates that prior to treatment initiation there were no pre-established differences in soil NO_3-N from previous management. The soil NO_3-N in the 0-0.9 and 0.9-1.8 m depths averaged 36.9 kg ha^{-1} (standard deviation = 17.6) and 30.4 kg ha^{-1} (standard deviation = 5.5) over all treatments, respectively.

2007 Post-Study Soil Nitrate-N

The N rate and application method main effects and the two-way interaction for soil NO_3-N masses were not significant at the 0-0.9 m depth (table 7). The average mass of NO_3-N in the 0-0.9 m profile averaged across all N application rates and application methods was 51.3 kg ha^{-1}. Although not significant, there was a trend for increasing NO_3-N masses as N application rate increased in the 0-0.9 m depth (table 7). At the 0.9-1.8 m depth, the N rate and application method main effects and the two-way interaction were significant. The masses of NO_3-N in the 0.9-1.8 m depth increased as N rate increased for both application method treatments (table 7). Soil NO_3-N and yield data indicate that under higher, yield-optimizing N application rates, soil NO_3-N increased compared to sub-optimal N application rates. The higher soil NO_3-N under the higher N rates will be subject to leaching below the root zone during the off-season. The significant interaction is a result of no differences in NO_3-N masses between ES and IS treatments at NR1, but at NR2 and NR3 the IS application method had greater masses of NO_3-N than the ES application treatment

Table 7. Analysis of variance and soil nitrate-N mass (kg ha^{-1}) for N application rate (NR) and N application method (AM) from samples taken after the 2006 growing season.

Soil Depth (m)	N Application Method	NR (kg N ha^{-1})		
		NR1 (128)	NR2 (186)	NR3 (278)
0-0.9	Early-season	44.3 (5.5)[a]	44.7 (3.6)	63.8 (11.0)
	In-season	46.3 (2.3)	55.9 (12.6)	52.6 (4.3)
	ANOVA (d.f.)[b]		P > F	
	NR (2)		0.1718	
	AM (1)		0.9058	
	NR × AM (2)		0.2559	
0.9-1.8	Early-season	18.8 (2.2) a[c]	26.4 (1.9) a	39.5 (3.2) a
	In-season	23.3 (2.8) a	36.0 (2.9) b	60.7 (5.7) b
	ANOVA (d.f.)[b]		P > F	
	NR (2)		0.0000	
	AM (1)		0.0001	
	NR × AM (2)		0.0276	

[a] Numbers in parentheses are standard errors of the treatment means.
[b] d.f. = degrees of freedom.
[c] Within each N rate, N application methods followed by the same letter are not significantly different using LSD at the 0.05 level.

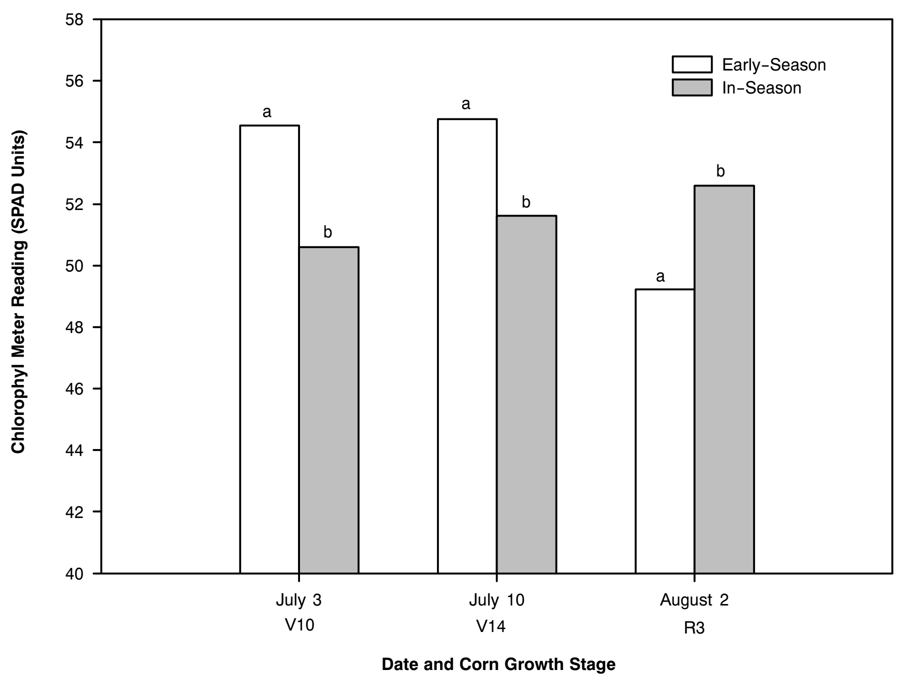

Figure 5. Chlorophyll meter readings during the 2006 growing season for the in-season and early-season application treatments. Values are the average three N application rates and four replications. For a given date or growth stage, columns with the same letter are not significantly different based on LSD (p = 0.05).

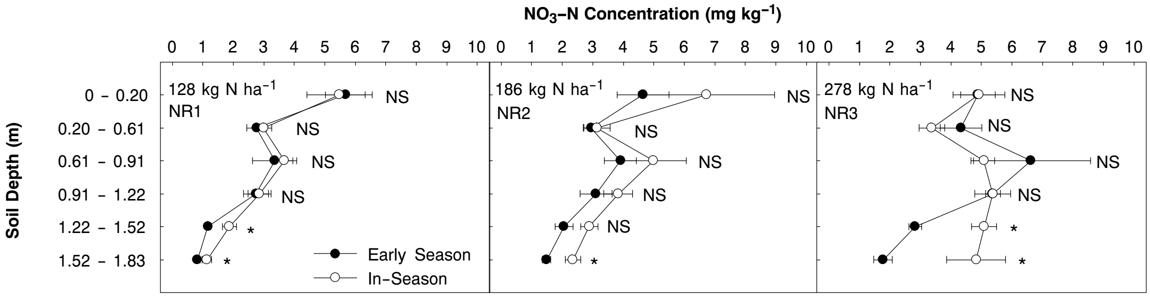

Figure 6. Concentrations of soil NO_3–N at depth increments in plots receiving N application rates of 128, 186 and 278 kg ha^{-1} during early-season or in-season application methods in 2006. Each concentration is the average of four replications. Mean separations (LSD; p = 0.05) were conducted between application method for each depth. Error bars indicate standard errors of the treatment means. Open circles and closed circles represent the ES and IS treatments, respectively.

(table 7). Nitrate–N masses in the 0.9-1.8 m depth for the IS application method were 26.7% and 34.9% greater at NR2 and NR3 compared to the ES application method, respectively.

At all three N application rates, concentrations of NO_3–N measured at depths of 0-0.2, 0.2-0.6, 0.6-0.9, 0.9-1.2, 1.2-1.5, and 1.5-1.8 m were greater for the IS application method than the ES application method in the lower depths of the soil profile; no differences were observed in the upper depths (fig. 6). These data suggest that less movement of NO_3–N below the root zone occurred with the IS treatments. The reduced movement of NO_3–N from the root zone under IS indicates that N application rates could be lowered for subsequent crops and increased fertigation of N can occur earlier in the season to ensure adequate N supply to the crop.

Soil samples were taken from all plots following the 2004 and 2005 cropping seasons. However, the data are not presented in this article due to the inability to fairly compare the application method treatments. Every row received N in the ES treatment, but only every other row (the SDI dripline row) received N in the IS treatment. Because soil samples were only taken in the SDI dripline row (the row receiving N in the IS treatment, and not receiving N in the ES treatment) following the 2004 and 2005 cropping season, soil NO_3–N masses were unevenly weighted between treatments. Soil NO_3–N masses from the row with no SDI dripline were not available to provide a means to compare the treatments on an equivalent basis. This article does not account for the increased residual NO_3–N effects on yield for the different application rate treatments. However, the main focus of this article is to compare the application method treatments, and this was accomplished by comparing the application methods at each application rate treatment.

Conclusion

In-season applications of N using SDI resulted in increased corn grain yields, biomass production, and N uptake during two years of this study under optimum N supplies compared to ES application. The IS treatment also increased chlorophyll content during the reproductive growth stages, and resulted in higher nitrate–N content in the 1.8 m root zone at the end of the study. These data suggests that under the ES treatment, greater losses of NO_3–N below the root zone may have occurred compared to the IS treatments. However, NO_3–N leaching was not directly measured, and other N cycle mechanisms such as denitrification and immobilization cannot be ruled out. Further research is needed to better understand the fate of N in this system. The increased retention of NO_3–N in the root zone under in-season fertigation with SDI could result in reduced N application rates to achieve maximum yield in subsequent corn crops. Maintaining an adequate N supply in soil for corn is important to maximize yield. The ability of the SDI systems to supply N during the entire growing season helped ensure optimum N use efficiency compared to applying all N early in the season. Corn production response to added N can vary from year to year depending on supplies from fertilizer and N mineralization in the soil. Continued research is needed to better predict the N supply from the organic fraction of soils and to determine optimum timing of N applications under SDI to maximize N uptake and reduce N leaching.

Acknowledgements

Funding for this project was provided by the U.S. Department of the Interior, Bureau of Reclamation, and the University of Nebraska-Lincoln. Special thanks to Jim Petersen and Don Davidson for their efforts in this research, and to the University of Nebraska-Lincoln West Central Research and Extension Center for supplying the research location and research support.

References

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. Irrigation and Drainage Paper No. 56. Rome, Italy: FAO.

Analytical Software. 2003. Statistix. Ver. 8. Tallahassee, Fla.: Analytical Software.

Anderson, D., D. Bullock, G. Hohnson, and C. Taets. 1993. Evaluation of the Minolta SPAD-520 chlorophyll meter for on-farm N management of corn in Illinois. In *Proc. Illinois Fertilizer Conf. Proc.* Urbana, Ill.: University of Illinois at Urbana-Champaign, Department of Crop Sciences.

Ayars, J. E., C. J. Phene, R. B. Hutmacher, K. R. Davis, R. A. Schoneman, S. S. Vail, and R. M. Mead. 1999. Subsurface drip irrigation of row crops: A review of 15 years of research at the Water Management Research Laboratory. *Agric. Water Mgmt.* 42(1): 1-27.

Blackmer, A. M., 1997. Soil fertility: What about N credits following soybean? Integrated Crop Management IC-478-R7. Ames, Iowa: Iowa State University. Available at: www.ipm.iastate.edu/ipm/icm/1997/6-16-1997/ncredsoyb.html. Accessed 8 April 2008.

Bordovsky, J. P. 2007. SDI installation for evaluation crop row direction and lateral offset distance. In *Proc. 2007 ASABE Annual Intl. Meeting*, ASABE Paper No. 072193. St. Joseph, Mich.: ASABE.

Halvorson, A. T., F. C. Schweissing, M. E. Bartolo, and C. A. Reule. 2005. Corn response to nitrogen fertilization in a soil with high residual nitrogen. *Agron. J.* 97(4): 1222-1229.

Haynes, R. J. 1985. Principles of fertilizer use for trickle irrigated crops. *Fert. Res*. 6(3): 235-255.

Keeney, D. R., and D. W. Nelson. 1982. Nitrogen: Inorganic forms. In *Methods of Soil Analysis: Part 2. Chemical and Microbiological Properties*, 643-698. 2nd ed. A. L. Page, ed. Madison, Wisc.: ASA and SSSA.

Lamm, F. R., and T. P. Trooien. 2003. Subsurface drip irrigation for corn production: A review of 10 years of research in Kansas. *Irrig. Sci.* 22(3-4): 195-200.

Lamm, F. R., and T. P. Trooien. 2005. Dripline depth effects on corn production when crop establishment is nonlimiting. *Applied Eng. in Agric.* 21(5): 835-840.

Lamm, F. R., H. L. Manges, L. R. Stone, A. H. Khan, and D. H. Rogers. 1995. Water requirement of subsurface drip-irrigated corn in north-west Kansas. *Trans. ASAE* 38(2): 441-448.

Lamm, F. R., T. P. Trooien, H. L. Manges, and H. D. Sunderman. 2001. Nitrogen fertilization for subsurface drip-irrigated corn. *Trans. ASAE* 44(3): 530-542.

Lamm, F. R., A. J. Schlegel, and G. A. Clark. 2003. Development of a best management practice for nitrogen fertigation of corn using SDI. *Applied Eng. in Agric.* 20(2): 211-220.

Miller, R. J., D. E. Rolston, R. S. Rauschkolb, and D. W. Wolg. 1976. Drip irrigation of nitrogen is efficient. *California Agric.* 30: 16-18.

Nakayama, F. S., and D. A. Bucks. 1986. *Trickle Irrigation for Crop Production*. F. S. Nakayama and D. A. Bucks, eds. Amsterdam, The Netherlands: Elsevier.

O'Brien, D. M., D. H. Rogers, F. R. Lamm, and G. A. Clark. 1998. An economic comparison of subsurface drip and center pivot sprinkler irrigation systems. *Applied Eng. in Agric*. 14(4): 391-398.

Pablo, R. G., M. K. O'Neill, B. D. McCaslin, M. D. Remmenga, J. G. Keenan, and B. M. Onken. 2007. Evaluation of corn grain yield and water use efficiency using subsurface drip irrigation. *J. Sust. Agric.* 30(1): 153-172.

Payero, J. O., S. R. Melvin, and S. Irmak. 2005. Response of soybean to deficit irrigation in the semi-arid environment of west-central Nebraska. *Trans. ASAE* 48(6): 2189-2203.

Payero, J. O., S. R. Melvin, S. Irmak, D. D. Tarkalson. 2006. Yield response to deficit irrigation in a semiarid climate. *Agric. Water Mgmt.* 84(1-2): 101-112.

Phene, C. J., J. L. Fouss, and D. C. Sanders. 1979. Water nutrient herbicide management of potatoes with trickle irrigation. *American Potato J.* 56(1): 51-59.

Schnitkey, G., and D. Lattz. 2006. Machinery cost estimated: Field operations. Urbana, Ill.: University of Illinois, Farmdoc Project. Available at: www.farmdoc.uiuc.edu/manage/machinery/machinery_field_operations.html. Accessed 16 November 2007.

Sorensen, R. B., F. S. Wright, and C. L. Butts. 2001. Subsurface drip irrigation system designed for research in row crop rotations. *Applied Eng. in Agric.* 17(2): 171-176.

USDA. 1978. Soil survey of Lincoln County, Nebraska. Washington, D.C.: USDA Soil Conservation Service, in cooperation with University of Nebraska Conservation and Survey Division.

Vories, E. D., and P. L. Tacker. 2007. Drip irrigation of corn in northeast Arkansas. In *Proc. 2007 ASABE Annual Intl. Meeting*, ASABE Paper No. 072197. St. Joseph, Mich.: ASABE.

Wood, C. W., D. W. Reeves, R. R. Duffield, and K. L. Edmisten. 1992. Field chlorophyll measurements for evaluation of corn nitrogen status. *J. Plant Nut.* 15(4): 487-500.

Wright, J. L. 1982. New evapotranspiration crop coefficients. *J. Irrig. Drain. Div. ASCE* 108(1): 57-74.