DEVELOPMENT OF A BEST MANAGEMENT PRACTICE FOR NITROGEN FERTIGATION OF CORN USING SDI

F. R. Lamm, A. J. Schlegel, G. A. Clark

ABSTRACT. *A four-year study was conducted in western Kansas on a deep, well-drained, loessial Keith silt loam (Aridic Argiustoll; fine silty, mixed, mesic) to develop a Best Management Practice (BMP) for nitrogen (N) fertigation for corn using subsurface drip irrigation (SDI).*

Residual ammonium- and nitrate-N levels in the soil profile, corn yields, apparent nitrogen uptake (ANU), and water use efficiency (WUE) were utilized as criteria for evaluating six different N fertigation rates, 0, 90, 135, 180, 225, and 275 kg/ha. A BMP was developed indicating an N fertigation level of 180 kg/ha with the total applied N including other N-sources of approximately 215 kg/ha. The BMP also states that irrigation is to be scheduled and limited to replace approximately 75% of crop evapotranspiration (ET_c).

Corn yield, ANU, and WUE all plateaued at the same level of total applied N that corresponded to the 180-kg/ha N fertigation rate. Average yield for the 180-kg/ha N fertigation rate was 13.4 Mg/ha. Corn yield to ANU ratio for the 180-kg/ha N fertigation rate was high (53:1). Results emphasize that high-yielding corn production also can be efficient in nutrient and water use. The BMP can be used for managing SDI fertigation of corn on the deep silt loam soils of western Kansas.

Keywords. *Microirrigation, Drip irrigation, Nutrient mangement, Water management.*

Groundwater quality is a major concern in the United States. The U.S. Environmental Protection Agency (EPA) estimated that nearly 52% of the community wells and 57% of the rural domestic wells contain nitrate-N (Langemeier, 1991). While only about 2% of these wells contain nitrate levels above the 10-mg/kg maximum contaminant level (MCL), the public is concerned by the presence of any nitrate-N in their drinking water. Batie and Deibel (1991) reported that high N concentrations in groundwater have been detected in agricultural producing areas all across the United States. Van Schilfgaarde (1990) reported that a Department of Interior survey of more than 600 irrigation and wildlife refuge projects had identified 22 sites in 13 different states where irrigation-induced water quality problems were likely to occur.

Technological improvements in agricultural production systems that have a high initial cost can still be profitable and economical. Duke et al. (1991) reported on several scenarios where improving the uniformity of center pivot sprinkler irrigation systems would be highly desirable from both an economic and environmental standpoint. Their results show irrigation non-uniformity such as over-irrigation resulting in nutrient leaching or underirrigation resulting in water stress can cause significant economic reductions. A properly designed and operated subsurface drip irrigation (SDI) system applying both water and nutrients as a line-source for the active crop roots represents the “state of the art” in terms of in-field uniformity. Accurately ”spoon feeding” the crop’s N needs through the growing season reduces the potential for groundwater contamination from nitrate and may also enhance crop yield (Bucks and Davis 1986). The initial cost of a SDI system for field crop production is relatively high when compared with other alternative irrigation systems. However, O’Brien et al. (1997) and Dhuyvetter et al. (1995) show realistic economic situations where SDI corn production systems can compare favorably with corn irrigated with center pivot sprinklers. These comparisons do not include possible reductions in fertilizer use or possible environmental savings associated with SDI.

Corn is a high resource user in terms of both water and N fertilizer. The integrated management of these two resources by SDI and fertigation could result in substantial savings. Even modest resource savings are important, considering that the costs of these two inputs may total more than US$ 185/ha. Combining the potential benefits from these two technologies (water and fertilizer savings), such as yield enhancement or greater in-field yield uniformity, and protection of groundwater quality, could result in a setting which is cost comparative with the more traditional forms of irrigation and fertilization.

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Groundwater quality degradation is a concern that will continually need to be addressed. In fact, in some areas with greater depths to the aquifer, the problems are just beginning to surface and will become worse as more nitrate-N currently within the vadose zone eventually reaches the aquifer. The EPA and other government agencies are encouraging the development and use of Best Management Practices (BMPs) to protect water quality while still providing producers a way to remain economically viable. This article proposes a BMP for field corn using fertigation and SDI for silt loam soils in western Kansas as supported by the research described herein.

Numerous approaches can be taken to improve N management in crop production. Some of these approaches include: 1) N source; 2) temporary immobilization; 3) split and/or multiple applications; 4) precision placement; and 5) combined management of irrigation and rainfall.

All of these approaches are effective to some degree and some are particularly well suited to certain regions and/or soil types. Elements of all these methods were considered in the development of this BMP.

Plants are capable of direct uptake of both ammonium and nitrate-N. Ammonium-N is relatively unleachable being held on the cation exchange complex, while nitrate-N moves with the soil water solution. Olson and Kurtz (1982) pointed out that if there is a preference of source by plants, it is probably ammonium-N early and for nitrate-N in latter growth stages. Early in the plant's life, the small root system is in the surface layers of the soil and ammonium-N is less likely than nitrate-N to be leached deeper into the soil away from the roots. Also the nitrification rate is reduced by the cool soil temperatures early in the season. Another possible reason for the preference of ammonium-N early in the life cycle is the enhancement of phosphorus (an important plant nutrient in early growth) uptake that occurs in the presence of ammonium-N (Blair et al., 1971). Although the amount of N used by seedling corn plants is small, since the root system is small and ammonium-N does not readily move in solution, a high concentration of fertilizer is needed in the root zone (Ritchie et al., 1989). This is often addressed by the application of starter fertilizers. Later in the plant's life, as soils warm and the nitrification rate increases, nitrate-N becomes the dominant source. Root growth into the deeper soil layers is also responsible for this preference, as the leachable nitrate-N is deeper in the soil than the ammonium-N. The important pollution-reducing management elements related to the N source in the development of this BMP are: 1) N form of starter fertilizer [Mixture of Urea Ammonium Nitrate (UAN 32-0-0) and Ammonium polyphosphate (10-34-0) in this article] is principally the non-leachable ammonium-N preferred by the crop in early life, 2) Injected source, UAN (32-0-0) contains approximately 25% nitrate-N, 25% ammonium-N and 50% urea-N (reduced in the first step to ammonium-N), so the deeply injected N contains both the readily absorbed nitrate-N and the less mobile ammonium-N which can be absorbed directly by the plant or microbially transformed to nitrate-N.

Temporary immobilization of N can be accomplished by the addition of a nitrification inhibitor to keep the N in the ammonium-N form. This immobilization is often used on sandy soils where leaching is a problem. However, Ferguson et al. (1991) pointed out that immobilization can be detrimental when applied with late side-dressed anhydrous ammonia on silt loam soils. Temporarily immobilizing the N at this time can reduce plant uptake. This reduced plant uptake would seem to indicate that more N would be left in the soil profile for possible overwinter leaching. The important pollution-reducing management element related to temporary immobilization in the development of this BMP is to not use nitrification inhibitors that may reduce plant uptake and thus leave more N in the soil. The advantages and disadvantages of temporary immobilization will instead be addressed by the multiple injections of UAN (32-0-0 in this study) containing both nitrate and ammonium-N.

Fertilizer applications for cereal grains are most effective when applied at the latest possible date compatible with quick uptake by the plant (Olson and Kurtz, 1982). The key is providing it in a readily available form in the presence of the root system. In some cases, this requirement means the N has to be applied well in advance of plant uptake. For example, surface-applied N may need to be applied preplant or early in the season so that it can be redistributed by rainfall to the deeper depths where roots will be concentrated during the latter part of the plant's growth cycle. However, with deep SDI installation, these management points (readily available N form and presence of active roots) can be easily addressed. Lamm et al. (2001), in a two-year study in northwest Kansas, observed no statistically significant differences in corn yields between weekly injections of N with a subsurface drip irrigation system as compared with the surface-applied preplant N banded in the furrow. However, they postulated that delaying the N injections until the first irrigation in mid to late June (approximately 40 days postemergence) decreases the chance of nitrate leaching during a period when precipitation exceeds crop water use. The important pollution-reducing management elements related to split/multiple applications in the development of this BMP are: 1) small amount of starter fertilizer (Mixture of UAN 32-0-0 and Ammonium polyphosphate10-34-0 in this study) reduces the pool of N available for leaching during periods when precipitation exceeds crop ET; 2) injected UAN (32-0-0 in this study) has about 25% of its nitrogen in the nitrate-N form which can be absorbed immediately by the plant roots; and 3) weekly just-in-time injections, reduce the pool of N available for leaching.

Precision placement is an effective means of increasing N use efficiency. Concentrations of N necessary for optimum plant growth, precisely placed in a limited soil volume, can reduce the total pool of nitrogen available for leaching. Nakayama and Bucks (1986) pointed out that injection of fertilizer through the drip irrigation system can increase fertilizer efficiency by placing the material where the roots are concentrated. Phene et al. (1979) determined that the injection of fertilizer through a drip irrigation system increased the fertilizer use efficiency of potatoes by more than 200% over that from conventional application methods. Miller et al. (1976) reported that N nitrogen injected through a drip irrigation system was used more efficiently than when banded on tomatoes. Mohtar et al. (1989) concluded that N application for cherries with a trickle irrigation system was a viable alternative to ground application at even one-half the ground applied amount. The important pollution-reducing management element related to positional placement in the development of this BMP is that the injected UAN can be immediately absorbed by the roots which will be very active at the 40- to 45-cm dripline depth due to rapid plant growth and favorable soil water conditions.

Combined management of irrigation and anticipated rainfall has long been a necessary tool to manage fertilization on sandy soils. An untimely rain coupled with a fully recharged soil profile can mean the loss of a significant portion of the soil N. Some irrigators leave the profiles of sandy soils at soil water contents less than field capacity so that small precipitation events can be effectively stored without leaching. However, until recent years, combined management of irrigation and rainfall on other soil types has received much less attention. Lamm et al. (1995) determined that not only could significant water savings be made with SDI, but deep percolation could also be significantly reduced. In fact, the water savings were primarily attributable to reducing the non-beneficial deep percolation. The important pollution-reducing management element related to combined management of irrigation and rainfall in the development of the BMP is that a reduced irrigation level (75% of ET) will help to maximize use of seasonal rainfall and minimize deep percolation while maintaining optimum corn yields (Lamm et al., 1995).

A study was conducted from 1993 to 1996 to develop a BMP for the integrated irrigation and nitrogen fertigation management of corn using SDI. The fertigation N requirement was determined by comparing the effects of different N fertigation rates on corn yields, apparent nitrogen uptake (ANU) at harvest (amount of N in the above-ground fraction of the biomass), residual soil profile N, and the crop water use efficiency.

PROCEDURES

The project was conducted at the KSU Northwest Research-Extension Center at Colby, Kansas on a deep, well-drained, loessial Keith silt loam (Aridic Argiustoll; fine silty, mixed, mesic). This medium-textured soil, typical of many High Plains soils, is described in more detail by Bidwell et al. (1980). The 2.4-m soil profile will hold approximately 445 mm of plant available water at field capacity. This corresponds to a volumetric soil water content of approximately 0.37 cm^3/cm^3 at field capacity and a profile bulk density of approximately 1.3 g/cm^3. The experimental treatments (fertigation levels) as described below were applied during the 1993 corn growing season to develop approximately equilibrium soil profile and crop residue N levels before the 1994 season. No further discussion of the 1993 season will be made.

The continental climate can be described as semi-arid with an average annual precipitation of 474 mm and approximate annual lake evaporation of 1400 mm (Bark and Sunderman, 1990). Irrigation was scheduled on the basis of data collected from a NOAA weather station located approximately 450 m northeast of the study site. The alfalfa reference evapotranspiration (ETr) was calculated using a modified Penman combination equation similar to the procedures outlined by Kincaid and Heerman (1974). The specifics of the ETr calculations used in this study are fully described by Lamm et al. (1987). Basal crop coefficients (Kcb) were generated with equations developed by Kincaid and Heerman (1974) based on work by Jensen (1969) and Jensen et al. (1970, 1971). The basal crop coefficients were calculated for the area by assuming 70 days from emergence to full canopy for corn with physiological maturity at 130 days. This method of calculating crop evapotranspiration (ETc) as the product of Kcb and ETr has been acceptable in past studies at Colby (Lamm and Rogers, 1983, 1985). In constructing the irrigation schedules, no attempt was made to modify ETc with respect to soil evaporation losses or soil water availability as outlined by Kincaid and Heerman (1974).

The 0.81-ha study area was approximately 135 m wide and 60 m long with a land slope of approximately 0.5%. The study area accommodated 18 plots in a randomized complete block design of six whole-plot treatments with three replications. Each plot was approximately 6 m wide and 60 m long with row direction running east to west. This arrangement corresponds to eight 0.76-m corn rows. The study utilized a SDI system (Lamm et al., 1990) constructed with dual-chamber dripline (30-cm emitter spacing) installed at a depth of 40 to 45 cm in a raised bed with 1.5-m spacing between driplines. The corn was planted so that each dripline was centered between two corn rows. There was a 12-m buffer strip on the north and south edges of the study area.

A modified, ridge-till system was used in corn production with two corn rows, 0.76 m apart, grown on a 1.5-m wide bed. The stalks were flail chopped after harvest and the beds were reshaped with a disk bedder. This practice disked out the corn root clumps and heaped the residue with soil at the center of the bed allowing for some overwinter decay of the residue. In November of 1994 and 1995, a preseason broadcast application of ammonium polyphosphate was performed at the rate of 16.9 and 14.8 kg/ha of N and 57.5- and 50.2-kg/ha P_2O_5 for the respective years. No preplant fertilizer was applied during the fall of 1993. In the spring, the beds were slightly flattened to aid in planting. Corn (Pioneer 3162) was seeded at a rate of approximately 81,400 seeds/ha on 25 April 1994, 11 May 1995, and 22 April 1996. A starter fertilizer, ammonium polyphosphate (10-34-0), at the rate of 5.6 kg/ha of N and 19 kg/ha P_2O_5 was applied at planting in 1994. In 1995 and 1996, a mixture of UAN (32-0-0) and ammonium polyphosphate (10-34-0) was applied at planting at the rate of 18.3 kg/ha of N and 30.4 kg/ha P_2O_5. Nitrogen in the starter fertilizer, and the residual and mineralized N in the soil were the only sources available to the crop until the first irrigation was applied on 14 June 1994, 20 June 1995, and 26 June 1996, corresponding to 36, 27, and 42 days after crop emergence. This approach was designed to reduce potential nitrate-N leaching during periods when precipitation typically exceeds crop evapotranspiration.

Irrigation was scheduled using a water budget to calculate the root zone depletion with precipitation and irrigation water amounts as deposits and calculated daily corn water use (ETc) as a withdrawal. A previous study of subsurface drip-irrigated corn (Lamm et al., 1995) had indicated that an irrigation level reflecting a 25% reduction in calculated evapotranspiration from the fully irrigated condition will not significantly reduce corn yields. This approach should also reduce deep percolation. Modification of the irrigation schedule to reflect the 75% replacement was accomplished by multiplying the calculated ETc value by 0.75. If the root-zone depletion became negative, it was reset to zero. The study plots were irrigated to replace 100% of this modified root-zone depletion, when the depletion was within the range of 10 to 40 mm depending on the need for weekly fertigation and the availability of labor. The root zone depletion was assumed to be zero at crop emergence, which is a relatively realistic assumption in normal years. However, the entire 2.4-m soil profile would rarely be at field capacity. Irrigation was metered separately onto each plot with commercial, municipal-grade, flow accumulators with an accuracy of ±1.5%. SDI systems give much better control of water application than can be obtained under surface or sprinkler irrigation systems.

All N in the study was applied as an experimental variable except for small amounts supplied in the spring starter fertilizer application, and the naturally occurring nitrate-N in the irrigation water. Six seasonal amounts of injected N totaling 0, 90, 135, 180, 225, and 270 kg/ha were evaluated. The N source, urea-ammonium-nitrate (UAN, 32-0-0) was injected at a depth of 40 to 45 cm with the SDI system on an approximately weekly basis beginning about 30 to 40 days after emergence. Weekly fractional amounts to be applied were estimated from a nitrogen-use curve developed at Iowa State University (Ritchie et al., 1989). Although more complex models could be used for determining the amount of N to be applied, this model was used for simplicity and applicability by irrigators. Injections were made at the plot level with a commercial, industrial-grade, diaphragm-type injector within a 15- to 30-min cycle during a multi-hour irrigation event. The period of irrigation before and after the injection period was always greater than 2 h. The irrigation system applies approximately 1.2 mm/h. Fertilizer injections were applied weekly, even if the irrigation schedule required more or less frequent irrigation.

Soil water amounts were monitored for each plot in 0.3-m increments to a depth of 2.4 m on an approximately weekly basis during the cropping season with a neutron probe. Water use was calculated as the sum of seasonal changes in soil water between the first and last sampling dates, irrigation and total rainfall. Runoff was restricted to the plot areas by the modified ridge tillage system.

Available soil N was determined for each plot in the spring (9 May 1994, 15 May 1995, and 20 May 1996) near the date of crop emergence and after harvest (3 October 1994, 27 October 1995, and 14 October 1996). Samples were taken in the corn row (38-cm horizontal distance from the dripline). Typically in Kansas, soil samples for soil N determination are only taken for the top 60 cm of the soil profile. However, in this case, the N application point is 40 to 45 cm below the soil surface, so it was necessary to sample more extensively. It was also necessary to sample to the bottom of the soil root zone, to meet the study objectives related to plant uptake and leaching. Soil samples were taken in 0.15-m increments in the top 0.6 m and in 0.3-m increments between the 0.6- and 2.4-m soil profile depths. Soil samples were dried in a forced-air oven at 50°C and finely ground before shipping to the Kansas State University (KSU) Soils Laboratory for ammonium- and nitrate-N determination.

Five whole plants (above-ground) were randomly selected from each of the 18 plots at physiological maturity for plant tissue analysis. Whole plant samples were coarsely chopped, weighed, dried in a forced-air oven at 50°C, and weighed again for dry matter determination. Field biomass was calculated from the aboveground dry weight of the five plants and the plant populations for each of the plots. The samples were finely ground after drying and a subsample was sent to the KSU Soils Laboratory for determination of the whole-plant N content. The apparent nitrogen uptake (ANU) was calculated from the field biomass levels and the whole-plant N content for each plot. These data were used to estimate and track the amount of N used by the corn plant as opposed to the previously mentioned measurements to track the N in the soil.

A representative plant sample (6 m from a center row near the center of the plot) from each plot was hand harvested at physiological maturity (9 September 1994, 26 September 1995, and 2 October 1996) for yield determination. Grain yields were corrected to 15.5% wet-basis moisture content.

Irrigation water samples were analyzed for the amount of nitrate-N near the end of each pumping season to determine the contribution of the irrigation water to the N budget of each crop. An earlier study by Lamm et al. (2001) reported nitrate-N concentrations in the water were near typical background levels, averaging 3.37 mg/kg.

Crop grain yields, apparent nitrogen uptake, water use, water use efficiency and after-harvest profile soil nitrogen levels were analyzed using a single-factor analysis of variance and means were separated with least significant difference at $P < 0.05$. Linear regression equations were also determined for yield, apparent nitrogen uptake, and water use efficiency as a function of N fertigation rate.

RESULTS AND DISCUSSION

WEATHER CONDITIONS

Seasonal precipitation (120 day period beginning at crop emergence) varied from near normal levels of 277 and 280 mm in 1994 and 1995 to an extremely high level of 518 mm in 1996 (fig. 1). The 25-year seasonal mean is 315 mm. In both 1994 and 1995, July and August precipitation was low. The corn emerged on 10 May, 25 May, and 15 May for the three respective years.

The cumulative calculated crop evapotranspiration (fig. 1) was slightly above the 25-year mean of 577 mm in 1994 (628 mm) and 1995 (590 mm) but substantially below the mean in 1996 (494 mm).

The normal net irrigation requirement for corn is 391 mm based on an 80% chance precipitation. In this study, seasonal irrigation amounts of 277, 305, and 152 mm were required in 1994, 1995, and 1996, respectively (fig. 1). Since the irrigation level was limited to replace only 75% of ET_c by design, irrigation amounts for 1994 and 1995 were near normal, but for 1996 the amount was below normal. Fertigation was generally applied weekly beginning about the second to third week of June (fig. 1). The final fractional amount of N (usually around 20%) was applied in mid to late August.

The 1994 crop year was extremely good, in spite of the dry July-August period, with plant growth and development 7 to 14 days ahead of schedule by the time the dry period began. In contrast, extremely cool climatic conditions in 1995 resulted in late planting and poor growth during the early vegetative period. An early frost resulted in a very short growing season and consequently low corn yields. Abundant rainfall, low ETc, and an extremely long and mild grain filling period resulted in high yields in 1996.

Although the climatic conditions for the three years were varied, they do represent an adequate range of conditions for the results of this fertigation study.

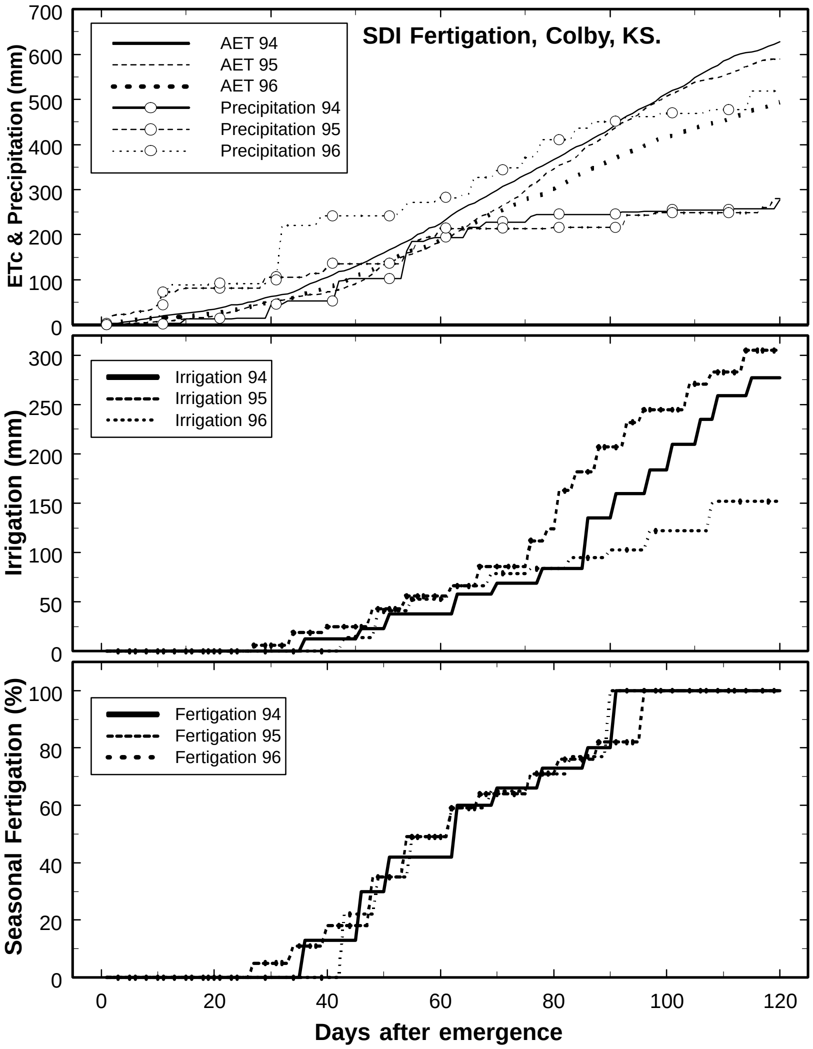

Figure 1. Cumulative actual evapotranspiration (Etc), precipitation, irrigation and fertigation for three cropping seasons (1994-1996) in a SDI fertigation study for corn.

Residual Nitrate-N in the Soil Profile

Ammonium-N does not move appreciably with soil water distribution but nitrate-N moves readily in solution. After four years of continuous application (1993-1996, with 1993 not included in analysis) of the fertigation treatments, nitrate-N concentrations in the soil were increasing and moving downward when the fertigation rate exceeded 180 kg/ha (fig. 2). The preseason ammonium polyphosphate, starter fertilizer at planting and the irrigation water would supply a small amount of additional N. As a result, the threshold 180-kg/ha rate of injected N would have resulted in a total applied N of 194, 225, and 217 kg/ha for 1994, 1995, and 1996, respectively (table 1). The higher fertigation rates of 225 and 270 kg/ha resulted in soil nitrate concentrations for some depth increments exceeding 10 mg/kg. In contrast, the lower fertigation rates had nitrate-N concentrations lower than 3 mg/kg for all depths except the surface 0.15 m, which was still less than 5 mg/kg (fig. 2).

The soil profiles for the 180, 225, and 270-kg/ha fertigation rates for the six different sampling periods are shown in figure 3. Erratic changes in the nitrate-N concentrations in the soil profile with time for the 225- and 270-kg/ha fertigation rates suggest leaching of nitrate-N. In several cases, the spike in nitrate-N measured in the fall was gone following the dormant winter period. Many researchers have suggested that the winter dormant period is the time of highest nitrate leaching susceptibility.

The preplant ammonium polyphosphate and the starter fertilizer are part of an overall production scheme to maintain proper levels of phosphorus in the soil and encourage early plant development, so it makes good sense to continue these practices as needed. Schlegel et al. (1995, 1996) determined application of phosphorus rates beneficial to N management both in terms of higher net returns and decreased environmental risks. The soil profile data would suggest a BMP of approximately 180 kg/ha of N applied through in-season fertigation will result in minimal leaching potential.

Total Ammonium- and Nitrate-N in the Soil Profile

Some producers might wish to apply extra N fertilizer with the idea that N transformations in the soil might build higher long-term fertility levels. Nitrogen concentrations in the soil profile were relatively stable at around 100 kg/ha as long as the fertigation rate was at or below 180 kg/ha with the exception of the high level measured for the 135-kg/ha rate during the first spring (fig. 4). This point is believed to be an anomaly caused by the soil not yet being at relative equilibrium even though the same fertigation treatments

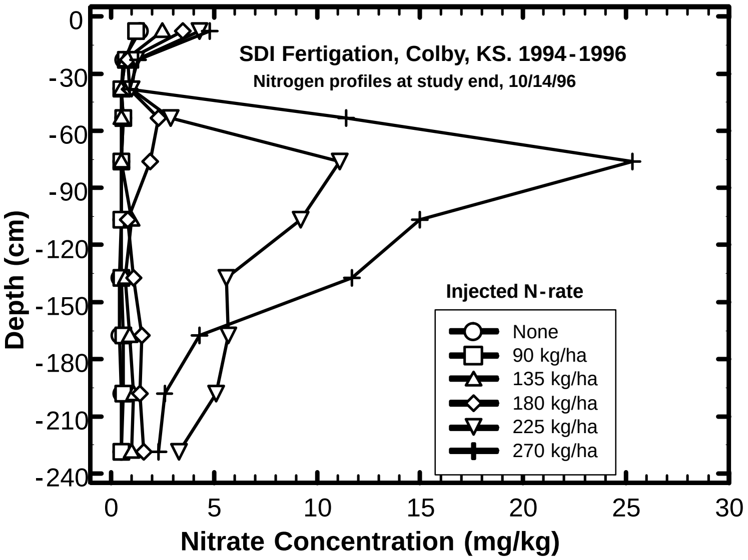

Figure 2. Nitrate-N concentrations in the soil profile for various N fertigation levels at the conclusion (10/14-96) of a SDI fertigation study for corn, KSU Northwest Research-Extension Center, Colby, Kansas.

were applied in 1993. The higher 225- and 270-kg/ha rates were generally between two and three times higher in total profile ammonium-N and nitrate-N. Their instability with time suggests these fertigation rates were not in equilibrium and that the instability was indicative of movement (leaching) or transformations. High N applications above a maintenance level required to maintain adequate soil fertility will not establish a higher equilibrium. There was a trend toward higher residual levels of N in the soil profile during the after-harvest period in all three years for the 225- and 270-kg/ha fertigation rate but it was only statistically significant ($P < 0.05$) in 1995 (table 1). Thus, these data also suggest a BMP of approximately 180 kg/ha of in-season nitrogen fertigation would avoid a large buildup of N in the soil profile.

CORN YIELDS

Fertigation rate significantly affected ($P < 0.05$ significance level) corn yield in all three years of the study (table 1). However, there were no statistically significant differences in yield above the 180 kg/ha N rate. In 1995 and 1996, there were no significant differences in yield above the 135 kg/ha N rate. Maximum yield in 1995 were approximately 5 Mg/ha lower than in the other two years due to a short growing season and poor growing conditions. Yields were high in 1996 but not as high as in 1994. The presence of Gibberella corn ear rot lowered 1996 plot yields by approximately 2 Mg/ha as compared to unaffected areas nearby. The presence of ear rot was not related to the study treatments and rather is related to climatic conditions and previous crop history. Averaged over the three year period there was no significant yield increase for fertigation rates above 135 kg/ha. However, there was a more uniform plateauing of yields at the 180 kg/ha N fertigation rate (fig. 5) and corn production economics would suggest the added N would be justified. Linear regression of yield and nitrogen rate indicated a very strong relationship (table 2) with the coefficients on both N-rate and its square term being highly significant. It is concluded that yield data also supports a BMP of 180 kg/ha of in-season N fertigation to optimize corn yields.

APPARENT NITROGEN UPTAKE

The quantity of N in the aboveground biomass was significantly different ($P < 0.05$) among fertigation levels in all three years. There was a tendency for ANU to plateau at

Table 1. Summary of corn yield, nutrient uptake, and water use data from a SDI nitrogen fertigation study, KSU Northwest Research-Extension Center from 1994-1996.

Fertigation N Rate (kg/ha)	Total Applied N (kg/ha)				Yield (Mg/ha)				Apparent Nitrogen Uptake (kg/ha)				Water Use[a] (mm)				Water Use Efficiency[b] (Mg/ha-mm)				Profile Nitrogen[c] (kg/ha in 2.4 m)			
	’94	’95	’96	Mean	’94	’95	’96	Mean	’94	’95	’96	Mean	’94	’95	’96	Mean	’94	’95	’96	Mean	’94	’95	’96	Mean
0	14	46	38	33	4.6	4.3	3.9	4.3	61	53	66	60	538	650	651	613	0.008	0.007	0.006	0.007	90	96	79	88
90	104	135	128	122	11.2	8.6	9.8	9.9	138	98	141	126	638	711	646	665	0.018	0.012	0.015	0.015	123	103	93	107
135	149	180	173	167	13.6	9.4	13.3	12.1	204	174	234	204	627	744	663	678	0.022	0.013	0.020	0.018	118	88	92	100
180	194	225	217	212	15.9	10.2	14.0	13.4	308	187	253	249	678	716	652	682	0.023	0.014	0.021	0.020	91	99	105	98
225	238	270	262	257	15.8	10.4	13.3	13.2	294	238	265	265	686	734	668	696	0.023	0.014	0.020	0.019	143	259	240	214
270	283	315	307	302	16.1	10.4	14.9	13.8	279	203	231	238	699	777	660	712	0.023	0.013	0.023	0.020	268	156	342	255
Mean					12.9	8.9	11.5	11.1	214	159	198	191	645	721	657	674	0.020	0.012	0.018	0.016	139	133	158	144
Least significant difference 0.05					1.4	1.3	2.6	1.8	48	40	69	53	30	64	34	43	0.003	0.002	0.004	0.003	NS	53	NS	91

[a] Water use is defined as sum of irrigation, rainfall, and change in soil water in the 2.4-m soil profile between 12 May to 14 September 1994; 1 June to 18 September 1995; and 21 May to 1 October 1996.

[b] Water use efficiency is defined as yield divided by water use.

[c] Total ammonium- and nitrate-N in the 2.4-m soil profile in the fall after harvest (3 October 1994; 27 October 1995; and 13 October 1996).

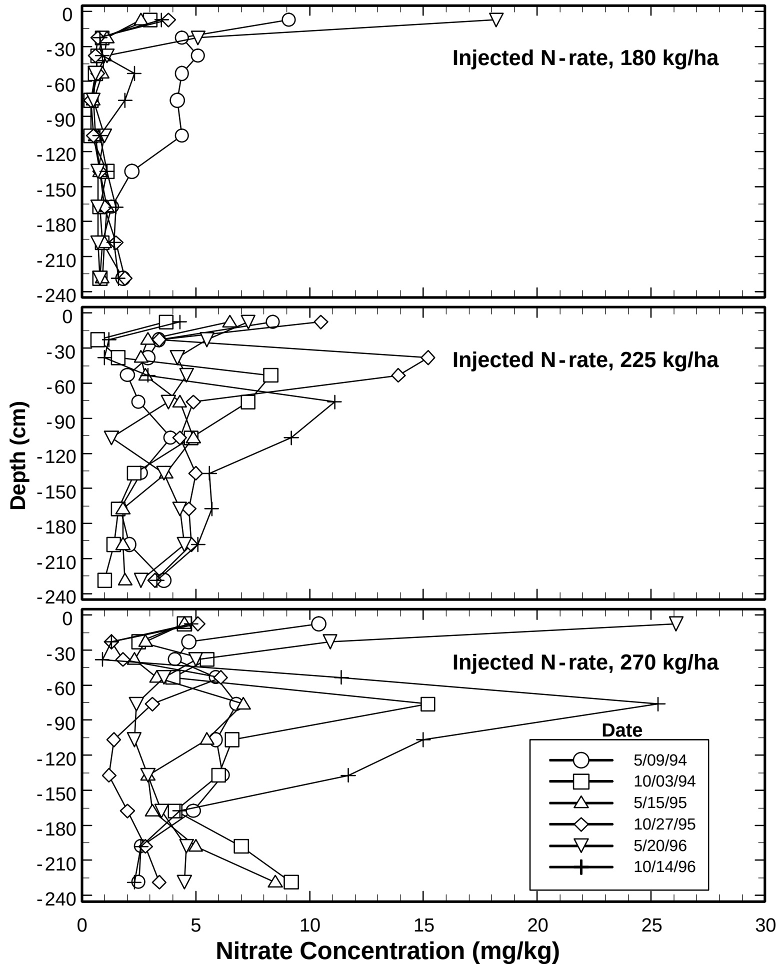

Figure 3. Nitrate-N concentrations as a function of depth for six sampling dates for the 180-, 225-, and 270-kg/ha N fertigation rates.

the 180-kg/ha N fertigation rate in all three years (table 1 and fig. 5). In 1995 and 1996, the lower 135-kg/ha N fertigation rate was not significantly different from the 180-kg/ha rate. However, there was much higher ANU for the 180-kg/ha rate in 1994. The three-year average ANU exceeded the total quantity of applied N for all N fertigation rates up to 225 kg/ha indicating good use of the applied N (fig. 5). The slope of ANU as related to the applied N rate is nearly

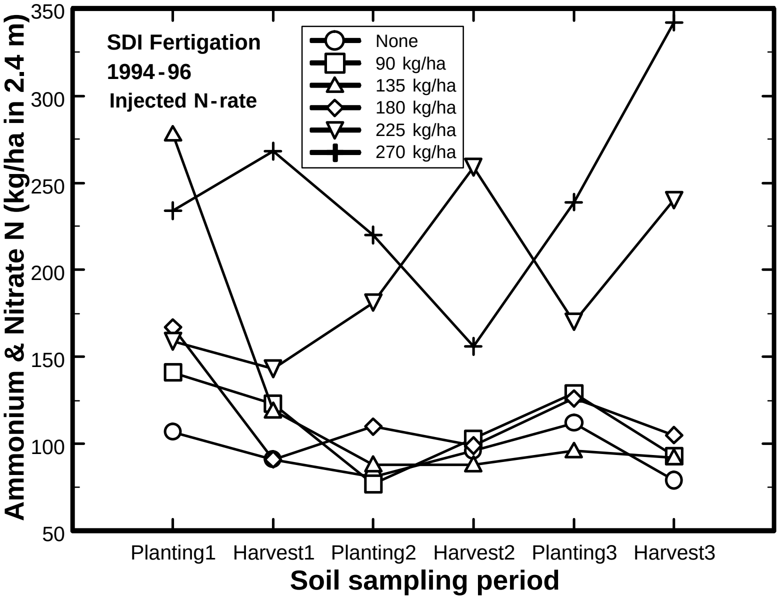

Figure 4. Total ammonium- and nitrate-N in the 2.4-m soil profile for the six N fertigation levels for the six sampling dates in the study.

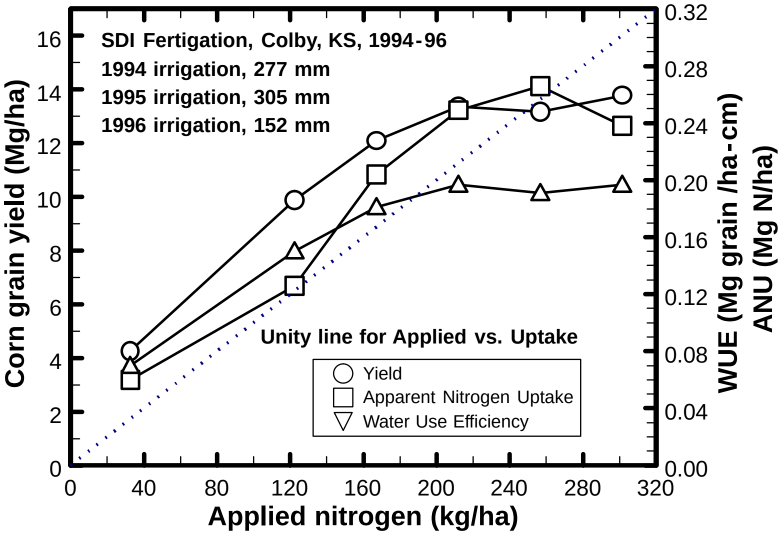

Figure 5. Average (1994-96) corn yield, apparent nitrogen uptake in the above-ground biomass, and water use efficiency as related to the total applied N (preseason amount, starter fertilizer, fertigation, and the naturally occurring N in the irrigation water). Total applied N exceeded fertigation applied nitrogen by 35 kg/ha.

Table 2. Linear regression equations and associated statistics for corn grain yield, apparent nitrogen uptake (ANU) and water use efficiency (WUE) as related to N fertigation rate.[a]

$\text{Yield} = 4.2 + 0.0738\ \text{Nrate} - 0.000143\ \text{Nrate}^2$
R Square = 0.987 Standard Error (SE) of Estimate = 0.41
SE of Intercept = 0.41 Different than Zero at $P < 0.0019$
SE of Nrate Coefficient = 0.0062 Different than Zero at $P < 0.0013$
SE of Nrate^2 Coefficient = 0.00002 Different than Zero at $P < 0.0075$
Yield in Mg/ha, Applied Nrate in kg/ha

$\text{ANU} = 48.6 + 1.351\ \text{Nrate} - 0.00212\ \text{Nrate}^2$
R Square = 0.844 Standard Error (SE) of Estimate = 32.0
SE of Intercept = 31.3 Different than Zero at $P < 0.218$
SE of Nrate Coefficient = 0.479 Different than Zero at $P < 0.067$
SE of Nrate^2 Coefficient = 0.0017 Different than Zero at $P < 0.302$
ANU in kg/ha, Applied Nrate in kg/ha

$\text{WUE} = 0.0069 + 0.00011\ \text{Nrate} - 0.00000023\ \text{Nrate}^2$
R Square = 0.984 Standard Error (SE) of Estimate = 0.0006
SE of Intercept = 0.00061 Different than Zero at $P < 0.0015$
SE of Nrate Coefficient = 0.00001 Different than Zero at $P < 0.0014$
SE of Nrate^2 Coefficient = 0.00000 Different than Zero at $P < 0.0067$
WUE in Mg/ha-mm, Applied Nrate in kg/ha

[a] Average response from 1994-1996.

identical for all N-rates up through the 180-kg/ha rate thus reflecting that there would be little differences in leaching. This fact is further evidenced by the linear regression statistics for ANU as related to N fertigation rate (table 2). The effect of the N-rate square term only becomes appreciable at the highest N-rate that was examined in the study. Averaged over the three years of the study, the data continue to support a BMP of 180 kg/ha of in-season N fertigation. The 180-kg/ha N fertigation rate resulted in a N use efficiency of 53 kg grain/kg N, which is considerably higher than the older regional guideline of approximately 45 kg grain/kg N.

WATER USE AND WATER USE EFFICIENCY

Water use differed significantly ($P < 0.05$) among fertigation treatments in all three years with the higher fertigation rates generally utilizing more water (table 1). Irrigation amounts were identical among treatments so it can be concluded that adequate levels of fertigation can help better utilize available soil water. Water use efficiency (WUE) in all three years was significantly different ($P < 0.05$) among treatments (table 1) with a trend toward maximization of WUE at a nitrogen fertigation rate of 180 kg/ha (fig. 5). Linear regression of WUE and N fertigation rate indicated a very strong relationship with the coefficients for both N-rate and its square term being highly significant at $P < 0.007$ (table 2). The plateauing of water use efficiency (fig. 5) coincided with plateauing of corn yield and ANU at approximately 180 kg/ha of in-season N fertigation (approximately 210 kg/ha of total applied N). This emphasizes that high-yielding corn production also can be efficient in nutrient and water use.

DISCUSSION OF THE BMP

The purpose of a Best Management Practice (BMP) is to protect water quality while still providing producers a way to remain economically viable. Some of the evidence presented in the previous sections indicated from a statistical standpoint that the 135-kg/ha nitrogen fertigation rate was not significantly different ($P < 0.05$) from the higher N fertigation rates. However, nothing in statistics requires producers to accept a 95% certainty level before they adopt a new practice. Indeed, they must also weigh the consequences of their adoption of the practice. If the probability and magnitude of the economic benefits (crop yields) exceed the costs of the practice (higher nitrogen costs and also environmental risks) then the producer will likely adopt the practice. Nitrogen fertilizer solution in the form of UAN (32-0-0) costs approximately US$0.306/kg of N, so increasing the N fertigation rate from 135 to 180 kg/ha increased costs about US$13.77/ha. As shown in earlier sections, the 180-kg/ha N fertigation rate does not appreciably affect the environmental risks. The 3-year mean corn yield was increased from 12.1 to 13.4 Mg/ha by increasing the N fertigation rate from 135 to 180 kg/ha. At a corn price of US$98.42/Mg, the yield increase translates to a US$127.95/ha increase in gross revenues, which is over nine times the cost of the additional fertilizer. There is little environmental cost with this higher 180-kg/ha N fertilizer rate as indicated by lack of additional soil N increase at the deeper depths. As a result this N rate is a good economically viable BMP with minimal environmental risk.

The addition of a phosphorus management program in this study plus the N in the irrigation water increased the total applied N rate to approximately 212 kg/ha. This N rate compares favorably with the results of Schlegel et al. (1995, 1996), which showed that a 180-kg/ha applied N rate optimized yields and net returns over a 30-year corn production period. Overall yields during that 30-year period were lower than the yields obtained with this production system and as a result would require a slightly smaller quantity of N. Additionally the 30-year study optimal N-rate did not include the N in the irrigation water, although they did estimate it as less than 10 to 12 kg/ha on an annual basis.

FORMALIZED STATEMENT OF THE BMP

A properly stated BMP will not only list the practice that is to be promoted, but also the assumptions and/or constraints under which it is to be used. While the establishment of BMPs is a function of regulatory agencies, the authors will suggest the essential elements and supporting data for a BMP for fertigation of corn using SDI that is applicable to western Kansas.

The BMP is weekly injections of nitrogen fertilizer solutions that can be applied by SDI systems for well-managed irrigated corn production on deep silt loam soils. Irrigation shall be scheduled to replace approximately 75% of the calculated soil water deficit attributable to evapotranspiration. The fertilizer injections should not begin sooner than 20 days after crop emergence or later than 30 days after crop emergence and should end not later than 30 days prior to physiological maturity. It is recommended that the cumulative in-season nitrogen fertigation amount should not exceed 180 kg/ha and the total applied nitrogen (fertigation, preseason applications, starter fertilizer, and naturally-occurring amounts in the irrigation water) should not exceed 210 kg/ha. An adequate overall nutrient management program including applications of phosphorus should also be utilized to help ensure that the N amounts are utilized within the corn production systems. Annual or bi-annual soil testing is recommended to a depth of 1.5 m to quantify residual soil nutrient levels. Large increases in soil nitrate-N concentrations over time indicate reductions in fertilization may be warranted. State-approved backflow prevention devices and proper chemigation procedures shall be used at all times. When applicable by state law, a certified chemigation operator shall monitor and control the fertigation applications.

Key assumptions and constraints were utilized in development of the BMP. Therefore the applicability and success of the BMP may be affected by variations from the following list of constraints:

- deep well drained silt loam soils,
- semi-arid climate with summer precipitation pattern,
- nitrogen solution in the form of urea-ammonium-nitrate (UAN),
- high yielding corn production with mean yields above 12.5 Mg/ha,
- 1.52-m drip-line spacing between alternate pairs of 0.76-m spaced corn rows,
- fall disk-bedding tillage management to enhance residue recycling,
- uniform and accurate chemigation equipment, and
- proper design, maintenance and operation of the SDI system.

CONCLUSIONS

In-season N fertigation for corn using SDI is a highly efficient production practice. The optimum in-season N fertigation level was 180 kg/ha. This level resulted in average corn yields of 13.4 Mg/ha and did not significantly affect the levels of residual N in the soil.

A recommended BMP is to use weekly injections of N fertigation for corn such that seasonal total N fertigation does not exceed 180 kg/ha. This BMP was not only very sound from an environmental standpoint, but also provided a 9-to-1 net return advantage over the next lowest fertigation level (135 kg/ha).

A SDI-based N-fertigation BMP was formally stated. Further evaluations in other regions may reveal what constraints may be relaxed and which constraints may need tightening.

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