Paper No. 972174
An ASAE Meeting Presentation

NITROGEN FERTIGATION FOR CORN USING SDI: A BMP

Freddie R. Lamm
Research Agricultural Engineer
KSU Northwest Research-Extension Center
Colby, Kansas, USA

Alan J. Schlegel
Research Soil Scientist
KSU Southwest Research-Extension Center
Tribune, Kansas, USA

Gary A. Clark
Research and Teaching Agricultural Engineer
KSU Dept. of Biological and Agricultural Engineering
Manhattan, Kansas, USA

Written for Presentation at the
1997 ASAE Annual International Meeting
Sponsored by ASAE
Minneapolis Convention Center
Minneapolis, Minnesota
August 10-14, 1997

Summary:
A BMP was developed for the use of fertigation on corn using subsurface drip irrigation. Briefly the BMP is to use the integrated management of irrigation to replace 75% of ET and weekly fertigation injections beginning 20-30 days after crop emergence with the total injected amount not to exceed 180 kg/ha. This BMP should be applicable to silt loam soils common in the US Great Plains with semi-arid, continental-type climates.

Keywords:
Subsurface drip irrigation, Microirrigation, Chemigation, Water quality, Nitrate

ASAE, 2950 Niles Rd., St. Joseph, MI 49085-9659 USA
Voice: 616.429.0300 FAX: 616.429.3852 E-Mail:<hq@asae.org>

NITROGEN FERTIGATION FOR CORN USING SDI : A BMP

Freddie R. Lamm   Alan J. Schlegel   Gary. A. Clark [1]

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 fertigation for corn using subsurface drip irrigation (SDI).

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

Corn yield, ANU, and WUE all plateaued at the same level of total applied nitrogen which corresponded to the 180 kg/ha nitrogen fertigation rate. Average yields for the 180 kg/ha nitrogen fertigation rate was 13.4 Mg/ha. Corn yield to ANU ratio for the 180 kg/ha nitrogen fertigation rate was a high 53:1. The results emphasize that high-yielding corn production also can be efficient in nutrient and water use.

[1] The authors are Freddie R. Lamm, Associate Professor, Northwest Research-Extension Center, Kansas State University, Colby, KS., Email: flamm@oznet.ksu.edu, Phone: 785-462-6281, Fax: 785-462-2315; Alan J. Schlegel, Associate Professor, Southwest Research-Extension Center, Kansas State University, Tribune, KS., and Gary A. Clark, Professor, Biological and Agricultural Engineering, Kansas State University, Manhattan, KS.

This is contribution no. 98-44-A from the Kansas Agricultural Experiment Station. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of Kansas State University or the US Department of Agriculture. This research constitutes part of a plan of work for the USDA-CSREES Western Regional Research Project W-128 and was also partially funded by the Kansas Fertilizer Research Fund.

[2] The mention of trade names or commercial products does not constitute their endorsement or recommendation by the authors, the Kansas Agricultural Experiment Station, or by the U.S. Department of Agriculture.

INTRODUCTION

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

Technological improvements in agricultural production systems which 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 overirrigation 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 nitrogen needs throughout the season reduces the potential for groundwater contamination from nitrates and may also enhance crop yields (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 can compare favorably to corn irrigated with center pivot sprinklers. These comparisons do not include possible reductions in fertilizer usage or possible environmental savings associated with SDI.

Corn is a high resource user in terms of both water and nitrogen 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 over $185.00/ha. Combining the potential benefits from these two technologies (water and fertilizer savings, yield enhancement or greater in-field yield uniformity, and protection of groundwater quality) could result in a setting which is cost comparative to the more traditional forms of irrigation and fertilization.

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 show up 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 paper 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 nitrogen management in crop production. Some of these approaches include:

1. Sourcing of the nitrogen;
2. Temporary immobilization;
3. Split and/or multiple applications;
4. Precision placement;
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 have been considered in the development of this BMP.

Plants are capable of direct uptake of both ammonium and nitrate nitrogen. 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 and ammonium-N is less likely than nitrate-N to be leached deeper into the soil away from the roots. Also 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 nitrogen used by the seedling corn plant 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 dominate 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 nitrogen sourcing in the development of this BMP are; 1) N form of starter fertilizer [Mixture of Urea Ammonium Nitrate (UAN 32-0-0) and Ammoniated Superphosphate (10-34-0) in this study] 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 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 the nitrogen is usually accomplished by the addition of a nitrification inhibitor to keep the nitrogen in the ammonium-N form. This is often used on sandy soils where leaching is a problem. However, Ferguson et al., (1991) point out that this can be detrimental when applied with late side-dressed anhydrous ammonia on silt loam soils. Temporarily immobilizing the nitrogen at this time can reduce plant uptake. This would seem to indicate more nitrogen 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 <u>not</u> use nitrification inhibitors that may reduce plant uptake and thus leave more nitrogen in the soil. The advantages and disadvantages of temporary immobilization will instead be addressed by the multiple injections of the 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 <u>readily available form in the presence of the root system</u>. In some cases, this means the nitrogen has to be applied well in advance of plant uptake. For example, surface-applied nitrogen 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 and Manges (1991), in a two year study in northwest Kansas, found no statistically significant differences in corn yields between weekly injections of nitrogen with a subsurface drip irrigation system as compared to the surface-applied preplant nitrogen banded in the furrow. However, they postulated that delaying the nitrogen 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 Ammoniated Superphosphate10-34-0 in this study) reduces the pool of nitrogen available for leaching during periods when crop ET exceeds precipitation, 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 nitrogen available for leaching.

Precision placement is an effective means of increasing nitrogen use efficiency. Concentrations of nitrogen necessary for optimum plant growth can be precisely placed in a limited soil volume thus reducing the total pool of nitrogen available for leaching. Nakayama and Bucks (1986) point 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) found 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) found nitrogen injected through a drip irrigation system was used more efficiently than when banded on tomatoes. Mohtar et al., (1989) concluded that nitrogen application for cherries with a trickle irrigation system was a viable alternative to ground application at even 1/2 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 40-45 cm dripline depth due to rapid plant growth and favorable soil water conditions.

Combined management of irrigation and 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 nitrogen. 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) found 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 1993-1996 to develop a BMP for the integrated irrigation and nitrogen fertigation management of corn using SDI. The fertigation nitrogen requirement was determined by comparing the effects of different nitrogen fertigation rates on corn yields, apparent nitrogen uptake (ANU) at harvest (amount of nitrogen 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 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 nitrogen 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 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 AET 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 AET 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 6 whole-plot treatments with 3 replications. Each plot was approximately 6 m wide and 60 m long with row direction running east to west. This corresponds to eight 76-cm corn rows with driplines spaced every 1.5 m between 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, 76 cm apart, grown on a 1.5 m wide bed. The stalks were flail chopped after harvest and the beds were be 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 application of ammoniated superphosphate was broadcast applied at the rate of 16.9 and 14.8 kg/ha of nitrogen 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)[2] was seeded at a rate of approximately 81,400 seeds/ha April 25, 1994, May, 11, 1995 and April 22, 1996. A starter fertilizer, ammoniated superphosphate (10-34-0), at the rate of 5.6 kg/ha of nitrogen 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 ammoniated superphosphate (10-34-0) was applied at planting at the rate of 18.3 kg/ha of nitrogen and 30.4 kg/ha P_2O_5. Nitrogen in the starter fertilizer, and the residual and mineralized nitrogen in the soil were the only sources available to the crop until the first irrigation was applied on June 14, 1994, June 20, 1995 and June 26, 1996 which corresponds to 36, 27 and 42 days after crop emergence. This approach can reduce potential nitrate-N leaching during a period when precipitation typically exceeds evapotranspiration.

The study utilized a SDI system (Lamm et al., 1990) constructed with dual-chamber drip tape (30-cm emitter spacing) installed at a depth of 40-45 cm with a 1.5 m spacing between dripline laterals. The corn was planted so that each dripline lateral was centered between two corn rows.

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 (AET) as a withdrawal. A previous study of subsurface drip-irrigated corn (Lamm et al., 1995) had indicated 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 AET 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 the calculated 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. 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 nitrogen in the study was applied as an experimental variable except for the small amounts supplied by the spring starter fertilizer application, and the naturally occurring nitrate-N in the irrigation water. Six seasonal amounts of injected nitrogen total, 0, 90, 135, 180, 225, and 270 kg/ha were evaluated. The nitrogen source, urea-ammonium-nitrate (UAN, 32-0-0) was injected at a depth of 40-45 cm with the SDI system on an approximately weekly basis beginning about 30-40 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 nitrogen 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 as an approximately 0.25-0.5 hour part of a multi-hour irrigation event. The period of irrigation before and after the injection period was always greater than 2 hours. The irrigation system applies approximately 1.2 mm/hour. Weekly fertilizer injections were generally used, even if the irrigation schedule required more 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 each 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 rainfall. Runoff was restricted to the plot areas by the modified ridge tillage system.

Available soil nitrogen was determined for each plot in the spring (May 9, 1994; May 15, 1995 and May 20, 1996) near the date of crop emergence and after harvest (October, 3, 1994; October 27,1995 and October 14, 1996). Samples were taken in the corn row (38 cm horizontal distance from the dripline). Typically in Kansas, soil samples for soil nitrogen determination are only taken for the top 60 cm of the soil profile. However, in this case, the nitrogen application point is 40-45 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 m and 2.4 m soil profile depth. 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. 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 above-ground 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 nitrogen content. The apparent nitrogen uptake (ANU) was calculated from the field biomass levels and the whole-plant nitrogen content for each plot. These data were used to estimate and track the amount of nitrogen used by the corn plant as opposed to the previously mentioned measurements to track the nitrogen 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 (September 9, 1994; September 26, 1995 and October 2, 1996) for yield determination.

Irrigation water samples were analyzed for the amount of nitrate nitrogen near the end of each pumping season to determine the contribution of the irrigation water to the nitrogen budget of each crop. An earlier study by Lamm and Manges (1991) found nitrate levels in the water were near typical background levels, averaging 3.37 mg/kg.

RESULTS AND DISCUSSION

Climatic Conditions

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

The cumulative calculated evapotranspiration (Figure 1) was slightly above the 25-year mean of 577 mm in 1994 (628 mm) and 1995 (590 mm) but significantly 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 (Figure 1). Since the irrigation level by design was limited to replace on 75% of AET, the years 1994 and 1995 were near normal, but 1996 was much below normal. Fertigation was generally applied weekly beginning about the second to third week of June (Figure 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 7-14 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 AET, and an extremely long and mild grain filling period resulted in high yields in 1996.

Although the climatic conditions for the 3 years were varied they do represent a good range of conditions for the results of this fertigation study.

Residual Nitrate-N in the Soil Profile

Ammonium-N does not move significantly 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 levels in the soil were increasing and moving downward when the fertigation rate exceeded 180 kg/ha (Figure 2). The preseason ammoniated superphosphate, 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 nitrogen would have resulted in a total applied nitrogen of 194, 225, and 217 kg/ha for 1994, 1995, and 1996, respectively (Table 1). The higher fertigation levels of 225 and 270 kg/ha resulted in nitrate concentrations for some depth increments exceeding the 10 mg/kg maximum contaminant level specified for drinking water. In contrast, the lower fertigation rates had lower than 5 mg/kg nitrate-N for all depths and lower than 3 mg/kg for all depths except the surface 0.15 m.

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, a spike in nitrate-N as measured in the fall is 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 ammoniated superphosphate and the starter fertilizer are part of an overall production scheme to maintain proper levels of phosphorus in the soil and to encourage early plant development, so it makes good sense to continue these practices as needed. Schlegel et al., (1995, 1996) found application of Phosphorus levels beneficial to nitrogen management both in terms of higher net returns and decreased environmental risks. In terms of in-season fertigation examination of the nitrate-N levels in the soil profile would suggest a BMP of approximately 180 kg/ha.

Total Ammonium- and Nitrate-N in the Soil Profile

Some producers might wish to apply extra nitrogen fertilizer with the idea that nitrogen transformations in the soil might build higher long term fertility levels. Figure 4 shows the total ammonium- and nitrate-N levels for the 2.4 m soil profile for the six sampling dates. Nitrogen levels 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. It is believed this point is an anomaly caused by the soil not yet being at relative equilibrium even though the same fertigation treatments were applied in 1993. The higher 225 and 270 kg/ha rates were generally between two and three times higher in total profile ammonium- and nitrate-N. Their instability with time suggests that the 225 and 275 kg/ha fertigation rates were not in equilibrium and that the instability was indicative of movement (leaching) or transformations. High nitrogen applications above a maintenance level required to maintain adequate soil fertility will not establish a higher equilibrium. There was a trend towards higher residual levels of nitrogen 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). These data suggest a BMP of approximately 180 kg/ha of in-season nitrogen fertigation would avoid a large buildup of nitrogen in the soil profile.

Corn Yields

Corn yields were significantly (P=0.05 significance level) different among fertigation levels in all three years of the study. In all three years there were no statistically significant differences in yields above the 180 kg/ha nitrogen rate. In 1995 and 1996, there were no significant differences above the 135 kg/ha nitrogen rate. Maximum yields 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 in the study area of Gibberella corn ear rot lowered 1996 yields approximately 2 Mg/ha as compared to unaffected areas nearby. The presence of ear rot is not related to the study. It is related to climatic conditions and previous crop history. Mean corn yields (1994-96) were not significantly different down through the 135 kg/ha nitrogen fertigation rate (Table 1). However, there was a more uniform plateauing of yields at the 180 kg/ha nitrogen fertigation rate (Figure 5) and corn production economics would suggest the added nitrogen would be justified. Corn yield data would continue to support a BMP of 180 kg/ha of in-season fertigation to optimize corn yields.

Apparent Nitrogen Uptake

The amount of nitrogen in the above-ground biomass was significantly different (P=0.05) among fertigation levels in all three years. There was a tendency for ANU to plateau at the 180 kg/ha nitrogen fertigation rate in all three years (Table 1 and Figure 5). In 1995 and 1996, the lower 135 kg/ha nitrogen fertigation rate was not significantly different from the 180 kg/ha rate, but there was much higher ANU for the 180 kg/ha rate in 1994. The three year average ANU exceeded the total amount of applied nitrogen for all nitrogen fertigation rates up to 225 kg/ha indicating good use of the applied nitrogen (Figure 5). Averaged over the three years of the study, the data would continue to suggest a BMP of 180 kg/ha of in-season nitrogen fertigation. The 180 kg/ha nitrogen fertigation rate resulted in a nitrogen use efficiency of 53 kg grain/kg N which is considerably higher than the old rule-of-thumb ratio 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 (Figure 5). The plateauing of water use efficiency (Figure 5) coincided with plateauing of corn yield and ANU at approximately 180 kg/ha of in-season nitrogen fertigation (approximately 210 kg/ha of total applied nitrogen). 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). 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, so increasing the nitrogen fertigation rate from 135 to 180 kg/ha increased costs about US$13.77/ha. As shown in earlier sections, the 180 kg/ha nitrogen 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 nitrogen 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 9 times the cost of the additional fertilizer. As a result this is a good economically viable BMP with minimal environmental risk.

The addition of a phosphorus management program in this study plus the nitrogen in the irrigation water increased the total applied nitrogen rate to approximately 212 kg/ha. This compares favorably with the results of Schlegel et al. (1995, 1996) which showed that a 180 kg/ha applied nitrogen 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 amount of nitrogen. Additionally the 30-year study optimal N-rate did not include the nitrogen in the irrigation water, although they did estimate it as less than 10-12 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.

The BMP is:

> *Weekly injections (or more frequently) of nitrogen fertilizer solutions 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 irrigation deficit attributable to evapotranspiration. The fertilizer injections should begin not 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 nitrogen 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 levels 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 dripline spacing between two 0.76 m-spaced corn rows
Fall disk-bedding tillage management to enhance residue recycling
Uniform and accurate chemigation equipment
Proper design, maintenance and operation of the SDI system.

CONCLUSIONS

In-season nitrogen fertigation for corn using SDI is a highly efficient production practice. The optimum in-season nitrogen 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 nitrogen in the soil.

Using weekly injections of nitrogen fertigation for corn not to exceed a seasonal total of 180 kg/ha is a BMP. The BMP of 180 kg/ha was not only very sound from an environmental standpoint, but had a 9 to 1 net returns advantage over the next lowest fertigation level (135 kg/ha).

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

REFERENCES

Bidwell, O. W., E. E. Banbury, W. L. Barker, and G. E. Muilenburg. 1980. The Colby Branch Experiment Station and agriculture in northwest Kansas with special mention of soils. KAES Bulletin 635. Kansas State Univ., Manhattan Ks. 44 pp.

Bark, L. D., and H. D. Sunderman. 1990. Climate of Northwestern Kansas. Report of Progress 594. Kansas State University, Manhattan Ks. 54 pp.

Batie, S. S. and P. L. Deibel. 1991. State strategies for managing agricultural contamination of groundwater. Pages 34-35 in proceedings of the 8th annual Water and the Future of Kansas Conference, Manhattan, Kansas, March 4-5, 1991. Kansas State University, Kansas Water Resources Institute. 47 pp.

Blair, G. J., C. P. Mamaril, and M. H. Miller 1971. Influence of nitrogen source on phosphorus uptake by corn from soils differing in pH. Soil Sci. Soc. Am. Proc. 63:235-238.

Bucks, D.A., and S. Davis. 1986. Chapter 1 in Trickle Irrigation for Crop Production. Edited by F. S. Nakayama, and D. A. Bucks. Elsevier Publications, Netherlands. 383 pp.

Duke, H. R., D. F. Heerman and L. J. Dawson. 1991. Selection of appropriate applied depth from center pivots. Presented at the 1991 international summer meeting of the American Society of Agricultural Engineers, Albuquerque, New Mexico, June 23-26, 1991. Paper No. 912052 from ASAE, St. Joseph MI. 18 pp.

Dhuyvetter, K. C., F. R. Lamm, and D. H. Rogers. 1995. Subsurface drip irrigation (SDI) for field corn -- An economic analysis. In Proceedings of the Fifth International Microirrigation Congress, April 2-6, 1995, Orlando Florida. ASAE, St Joseph, MI. 986 pp.

Ferguson, R. B., J. S. Schepers, G. W. Hergert and R. D. Lohry. 1991. Corn uptake and soil accumulation of nitrogen: Management and hybrid effects. Soil Sci. Soc. Am. J. 55:875-880.

Jensen, M. E. 1969. Scheduling irrigation using computers. J. of Soil and Water Conservation 24(8):193-195.

Jensen, M. E., C. E. Franzoy, and D. C. N. Robb. 1970. Scheduling irrigations using climate-crop-soil data. ASCE, J. of Irrigation and Drainage 96(IRI):25-38.

Jensen, M. E., B. J. Pratt and J. L. Wright. 1971. Estimating soil and moisture depletion from climate, crop and soil data. Transactions of ASAE, 14(5):954-959.

Kincaid, D. E. and D. F. Heerman. 1974. Scheduling irrigation using a programmable calculator. USDA Publication ARS-NC-12, February, 1974. 55 pp.

Lamm, F. R., and D. H. Rogers. 1983. Scheduling irrigation using computed evapotranspiration. Presented at the 1983 Mid-central regional meeting of the American Society of Agricultural Engineers. Available as ASAE Paper No. MCR 83-109 ASAE, St. Joseph, Michigan. 22 pp.

Lamm, F. R. and D. H. Rogers. 1985. Corn yield response to different irrigation regimes. Presented at the 1985 Mid-central regional meeting of the American Society of Agricultural Engineers. Available as ASAE Paper No. MCR 85-131, ASAE, St. Joseph, Michigan. 12 pp.

Lamm, F. R., D. A. Pacey, and H. L. Manges. 1987. Spreadsheet templates for the calculation of Penman reference evapotranspiration. Presented at the 1987 Mid-central regional meeting of the American Society of Agricultural Engineers. Available as ASAE Paper No. MCR 87-106, ASAE, St. Joseph, Michigan. 21 pp.

Lamm, F. R., H. L. Manges, D. H. Rogers, W. E. Spurgeon, and M. H. Farmer. 1990. Design and installation of a drip irrigation system for research purposes. Presented at the 1990 international winter meeting of the American Society of Agricultural Engineers, Chicago, Il., December 18-21, 1990. Paper No. 902530 from ASAE, St. Joseph MI. 21 pp.

Lamm, F. R., and H. L. Manges. 1991. Nitrogen fertilization for drip-irrigated corn in northwest Kansas. Presented at the 1991 international winter meeting of the American Society of Agricultural Engineers, Chicago, Illinois, December 17-20, 1991. Paper No. 912596 from ASAE, St. Joseph Michigan. 17 pp.

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 northwest Kansas. Transactions of the ASAE, 38(2)441-448.

Langemeier, R. N. 1991. National survey of pesticides in drinking water wells--Phase 1 report summary. Pages 28-29 in proceedings of the 8th annual Water and the Future of Kansas Conference, Manhattan, Kansas, March 4-5, 1991. Kansas State University, Kansas Water Resources Institute. 47 pp.

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

Mohtar, R. H., V. F. Bralts, C. D. Kesner, and B. R. Hahn. 1989. Comparative nitrogen application methods for tart cherry trees. Presented at the 1989 international winter meeting of the American Society of Agricultural Engineers, New Orleans, Louisiana, December 12-15, 1989. Paper No. 89-1643 from ASAE, St. Joseph, Michigan. 23 pp.

Nakayama, F. S. and D. A. Bucks. 1986. Trickle Irrigation for Crop Production. Edited by F. S. Nakayama, and D. A. Bucks. Elsevier Publications, Netherlands. 383 pp.

O'Brien, D. M., D. H. Rogers, F. R. Lamm, and G. A. Clark. 1997. Economics of SDI for corn in western Kansas. Presented at the 1997 international meeting of the American Society of Agricultural Engineers, Minneapolis, MN., August 10-14, 1997. Paper No. 972072 from ASAE, St. Joseph, Michigan. 15 pp.

Olson, R. A. and L. T. Kurtz. 1982. Crop nitrogen requirements , utilization and fertigation. Chapter 15 in Nitrogen in Agricultural Soils. Edited by F. J. Stevenson. Agronomy Monograph No. 22, American Society of Agronomy, Madison, Wisconsin. 940 pp.

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

Ritchie, S. W., J. J. Hanway, and G. O. Benson. 1989. How a corn plant develops? Iowa State University, Cooperative Extension Service, Ames, Iowa. Special Report No. 48. 21 pp.

Schlegel, A. J., and J. L. Havlin. 1995. Corn response to long-term nitrogen and phosphorus fertilization. J. Prod. Agric. 8:181-185.

Schlegel, A. J., K. C. Dhuyvetter, and J. L. Havlin. 1996. Economic and environmental impacts of long-term nitrogen and phosphorus fertilization. J. Prod. Agric. 9:114-118.

van Schilfgaarde, J. 1990. Irrigation in the USA: Musings on a rapidly changing scene. Pages 1-7 in proceedings of the 3rd National Irrigation Symposium, "Visions of the Future", Phoenix, Arizona, October 28- November 1, 1990. American Society of Agricultural Engineers, St Joseph, Michigan. 761 pp.

Table 1. Summary of corn yield, nutrient uptake, and water use data from a SDI nitrogen fertigation study, KSU Northwest Research-Extension Center from 1994-96.

Fertigation N rate kg/ha	Total Applied N kg/ha				Yield Mg/ha				Apparent nitrogen uptake kg/ha				Water use[1] mm				Water use efficiency[2] Mg/ha-mm				Profile nitrogen[3] kg/ha in 2.4 m			
	1994	1995	1996	Mean	1994	1995	1996	Mean	1994	1995	1996	Mean	1994	1995	1996	Mean	1994	1995	1996	Mean	1994	1995	1996	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	14.8	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

[1] Water use is defined as sum of irrigation, rainfall, and change in soil water in the 8-ft. soil profile between May 12 to Sept 14, 1994; June 1 to Sept 18, 1995; and May 21 to Oct 1, 1996.

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

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

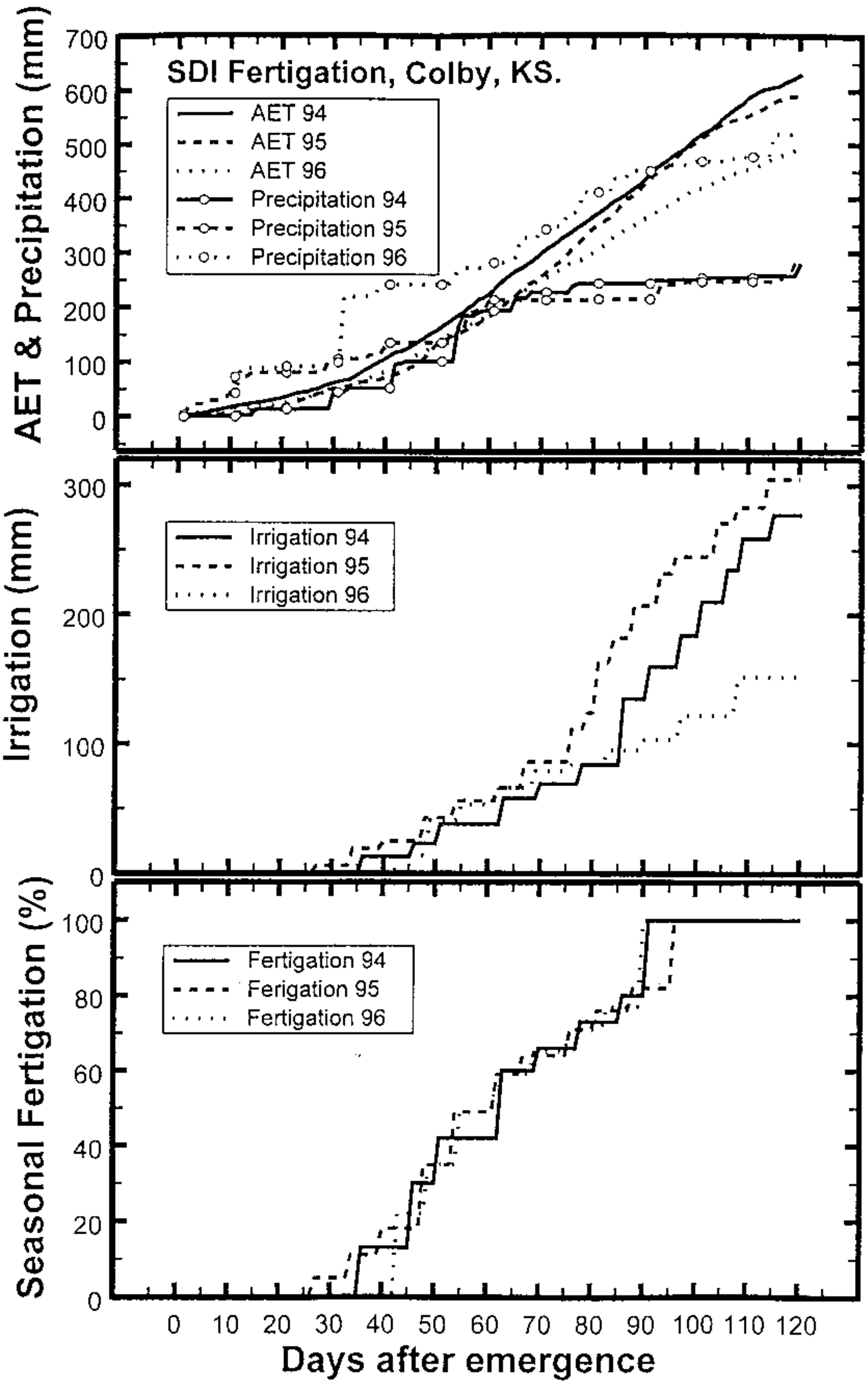

Figure 1. Cumulative actual evapotranspiration, precipitation, irrigation and fertigation for three cropping seasons (1994-96) in a SDI fertigation study for corn.

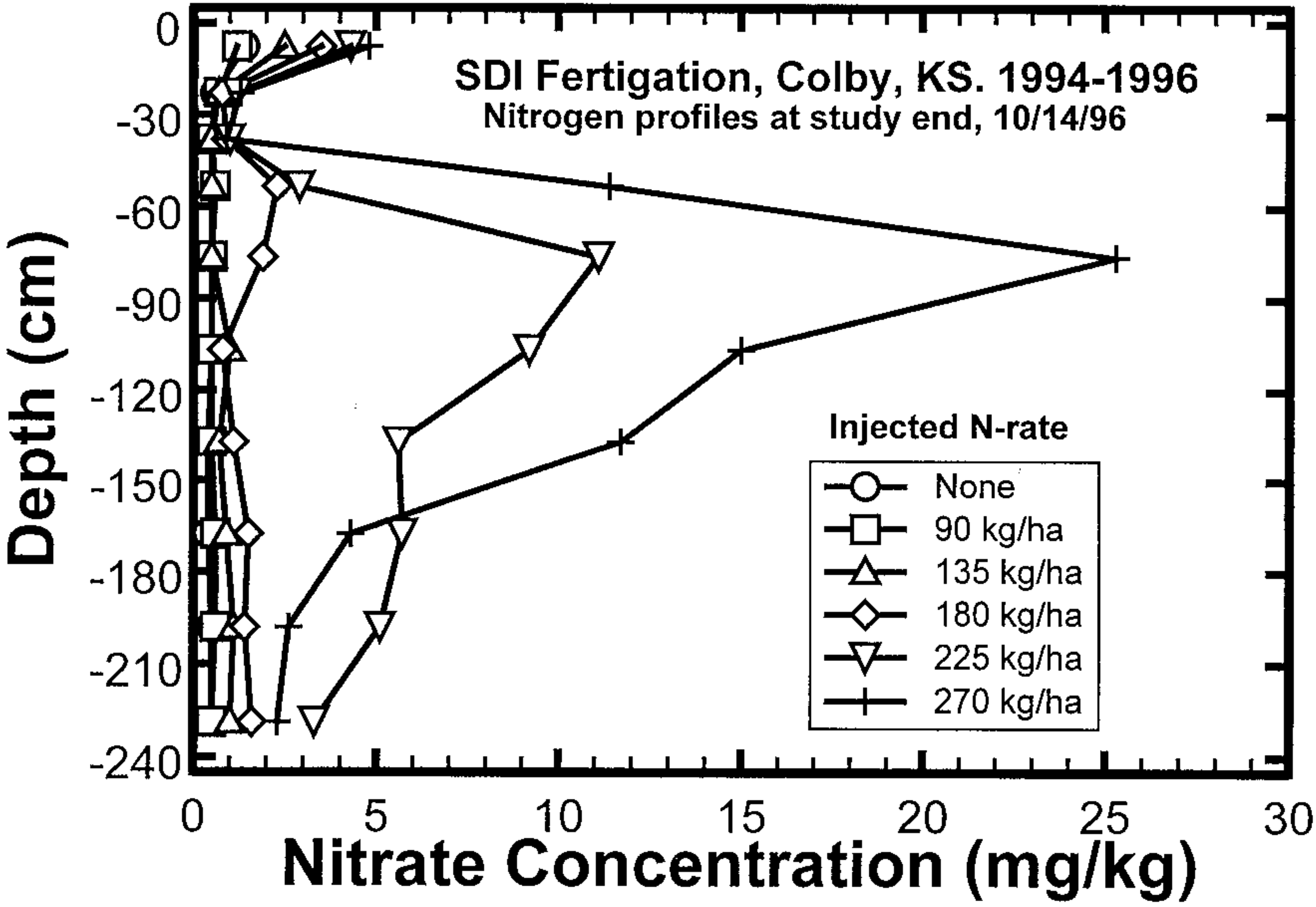

Figure 2. Nitrate-nitrogen concentrations in the soil profile for various nitrogen fertigation levels at the conclusion (10/14-96) of a SDI fertigation study in corn, KSU Northwest Research-Extension Center.

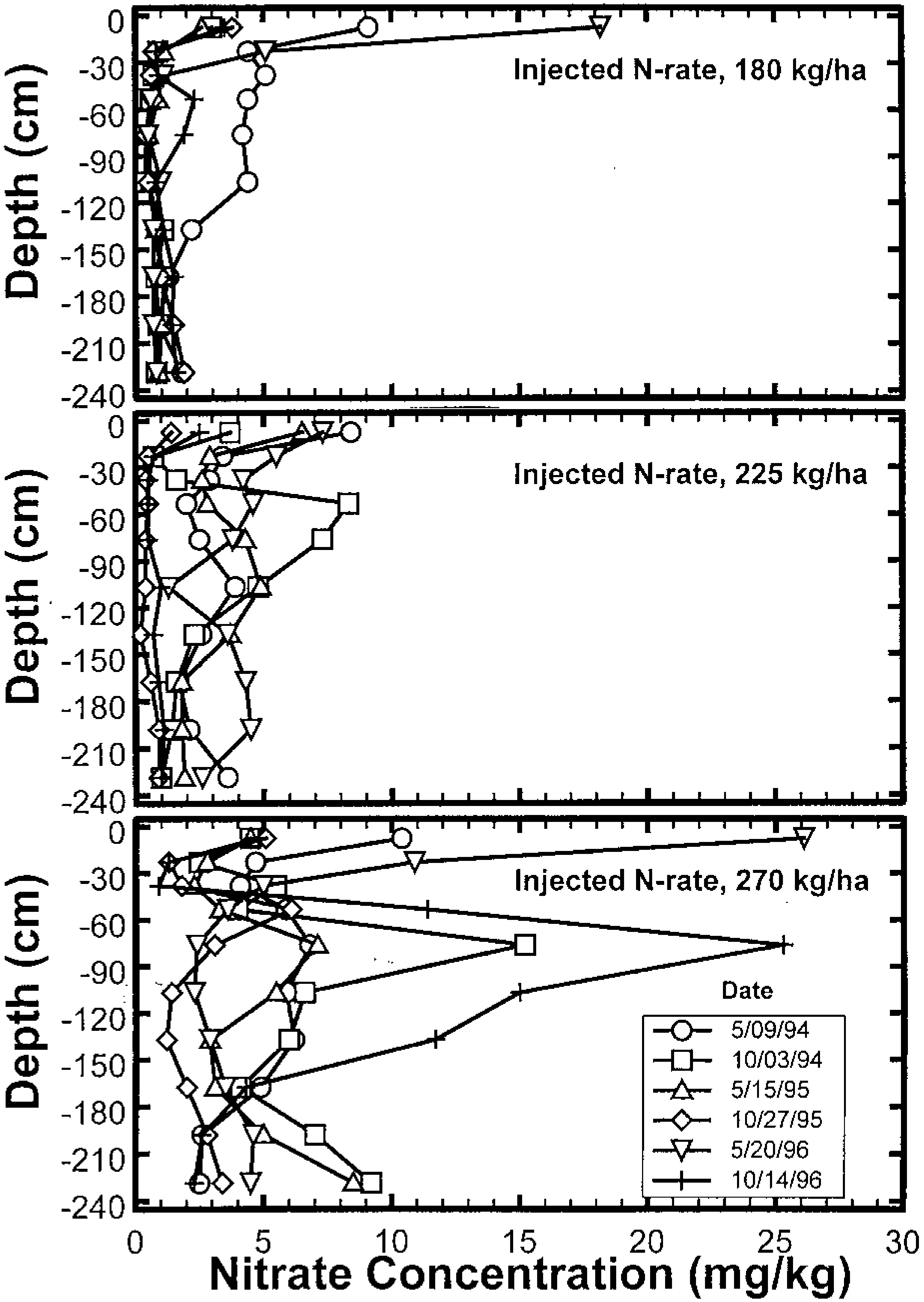

Figure 3. Nitrate-nitrogen concentrations as a function of depth for six sampling dates for the 180, 225, and 270 kg/ha nitrogen fertigation rates.

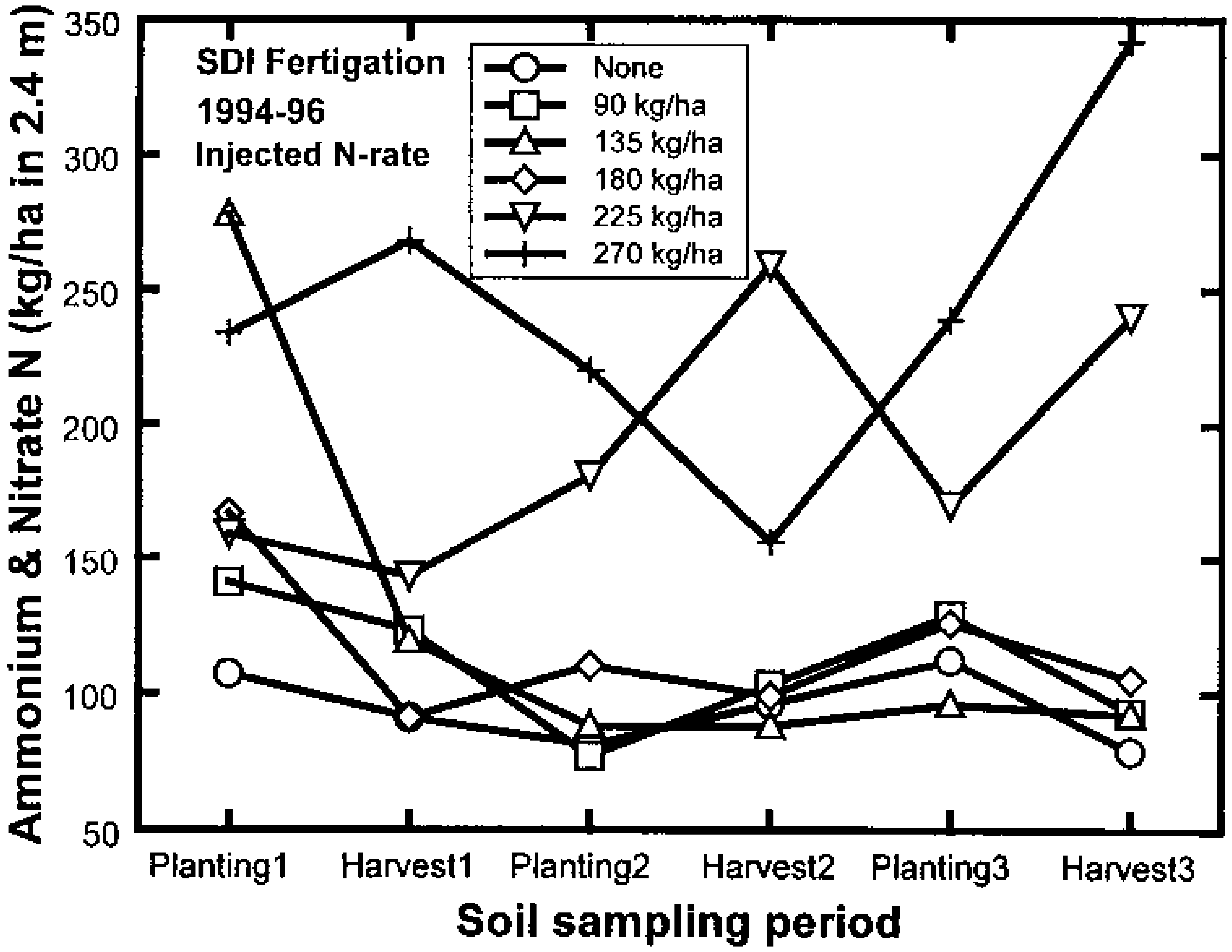

Figure 4. Total ammonium- and nitrate-nitrogen in the 2.4 m soil profile for the six nitrogen fertigation levels for the six sampling dates in the study.

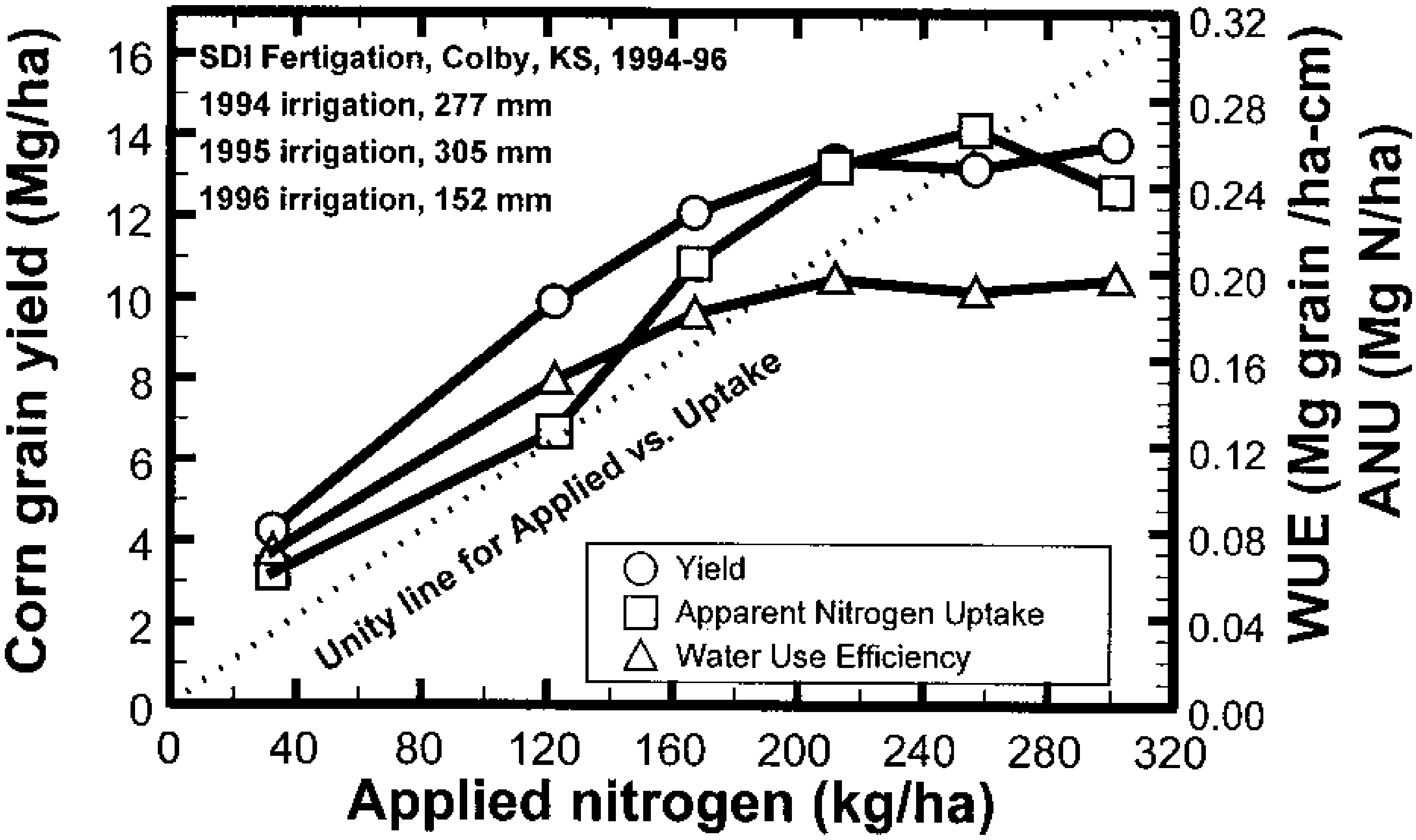

Figure 5. Average (1994-96) corn yield, apparent nitrogen uptake in the above-ground biomass, and water use efficiency as related to the total applied nitrogen (preseason amount, starter fertilizer, fertigation, and the naturally occurring N in the irrigation water). Total applied nitrogen exceeded fertigation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