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Nitrate in the Intermediate Vadose Zone Beneath Irrigated Cropland

by Roy F. Spalding and Lisa A. Kitchen

Abstract

More than 1000 feet of fine-textured, unsaturated zone core beneath nitrogen-fertilized and irrigated farmland was collected, leached and analyzed for nitrate-nitrogen. Fertility plots treated with 200, 300, and 400 lbs N/acre/yr accumulated significant quantities of nitrate-nitrogen in the vadose zone below the crop rooting zone. The average nitrate-nitrogen concentration approximately doubled with each 100 lbs N/acre/yr increment above the 100 lbs N/acre/yr treatment. Nitrate loading estimates for the plots treated with 400 lbs N/acre/yr indicate that over 1200 lbs N/acre was in the vadose zone beneath the crop rooting zone. In 15 years, the nitrate moved vertically at least 60 feet through these fine-textured, unsaturated sediments. As much as 600 lbs N/acre have accumulated in the vadose zone under independent corn producers' fields.

Vadose zone sampling is effective in predicting future non-point nitrate-contaminated areas.

Introduction

During the past decade, several studies have documented contamination of ground water by non-point agronomic sources of nitrate in Nebraska and in other states (Saffigna and Keeney 1977, Spalding et al. 1978, Exner and Spalding 1979, Gormly and Spalding 1979, Hallberg and Hoyer 1982, Spalding et al. 1982). Most of this contamination has occurred in cropped areas underlain by well- to excessively well-drained soils with short distances (5 to 30 feet) to ground water. In Nebraska, nitrate-nitrogen (NO_3-N) concentrations in ground water in areas such as these typically exceed and usually are well above 10 mg/L. Rates of NO_3-N increase in ground water in these areas range 0.4 to more than 1.0 mg/L/yr (Exner 1984a). In Nebraska, ground water underlying fine-textured soils and vadose zone sediments with thicknesses greater than 100 feet has experienced increases in NO_3-N of 0.1 to 0.2 mg/L/yr.

The processes involved in contaminant movement in the vadose zone beneath the crop rooting zone are poorly understood. Historically, production agriculture's interests have been in improving crop yields and not in the movement of leachate below the crop rooting zone. Consequently, almost all the research on the vertical movement of agronomic contaminants has focused on the crop rooting zone; research in the vadose zone below the crop rooting zone and above the water table has lagged (Nielsen et al. 1986). In a recent national workshop concerned with the needs for future vadose zone research, scientists referred to that portion of the vadose zone beneath the crop rooting zone as the intermediate vadose zone (IVZ) to differentiate it from the vadose zone, which contains the crop rooting zone. The workshop participants designated the IVZ as the section of the vadose zone with the greatest research needs (ARI in press).

This investigation studied NO_3-N levels in the IVZ beneath irrigated, fine-textured soils, examined the effect of a variety of N-fertilizer rates on the accumulation of NO_3-N in the IVZ, and estimated the potential impact of accumulated fertilizer in the IVZ on the underlying ground water quality.

Investigated Areas

The movement of NO_3-N through the IVZ was investigated at four sites in Nebraska. The site at the University of Nebraska's South Central Research and Extension Center (SCREC) is a 9.6-acre fertility test plot with a documented history of nitrogen treatment (Figure 1). The other three sites are near the Beatrice municipal well field in southeastern Nebraska (Figure 1). Half of the eight municipal wells in this well field have experienced large increases in nitrate concentrations with concentrations approaching or exceeding the maximum permissible level of 10 mg/L NO_3-N. Corn fields surround the well field and represent potential non-point sources of nitrate contamination to the wells.

Prior to 1969, the SCREC site was planted in a bromegrass-alfalfa mixture. Corn was grown every year from 1969 until 1986 with the exception of 1980 and 1982 when soybeans were planted. In both 1969 and 1970, an estimated 225 lbs N/acre/yr were applied to the field. In 1971, the field was segregated into 168 50-foot x 50 foot fertility plots (Figure 1). With the exception of 1980 and 1982, when N fertilizer was not applied, the numbered plots received discrete annual treatments of commercial N fertilizer from 1971 until 1986. In 1986, the fertility studies were terminated and the field was fertilized with 225 lbs N/acre.

The SCREC site is furrow-irrigated by gated pipe with an estimated 1.5 acre-ft of irrigation water annually. Precipitation averages 27.5 in/yr; 80 percent of this falls between April and September. The soils are well-drained, silty clay loams. Depth to ground water beneath two widely separated registered irrigation wells in section 17 (Figure 1) was 99 feet (NNRC 1987). The approximately 100-foot thick vadose zone is composed of 20 feet of Peoria loess, a 3-foot layer of Gilman Canyon paleosol, 35 to 45 feet of Loveland formation loess, and sands at a depth of about 60 feet. The sands encountered at approximately 60 feet could not be sampled with the available equipment. Drilling logs of nearby irrigation wells indicate the sands are continuous to the water table (NNRC 1987). Carbon-14 dating of the organic matter extracted from the Gilman Canyon horizon indicated it was deposited about 20,220 years B.P.

Fifteen cores were collected from SCREC fertility plots receiving five different N treatments. Because there are three replicate plots for each fertilizer treatment, cores were collected from at least two of the three replicates. The treatment rates were 0, 100, 200, 300, and 400 lbs N/acre/yr. In October and November 1985, three cores were obtained from the control plots and three from the plots treated with 200 lbs N/acre/yr. In January 1986, three cores were obtained from the plots treated annually with 400 lbs N/acre. In November 1986, two additional cores were obtained from the original control plots. Two cores were also obtained from the plots that had received 100 lbs N/acre/yr and two from those that had received 300 lbs N/acre/yr during the fertility study. Time constraints on the drilling rig and crew precluded obtaining all the cores at the same time.

The three irrigated cornfields on which we obtained permission to drill are within a 1.5-mile radius of the Beatrice well field and have been farmed by three independent corn producers for at least the last 20 years. Average annual precipitation within this area is about 28 inches. The amount of applied irrigation water is not known. All three producers reported applying approximately 225 lbs N/acre/yr to their fields. The soils are moderately well-drained, silty clays and the IVZ sediments generally are fine-textured clayey silts. According to the logs of registered irrigation wells, the depth to water varies from 15 feet near the boring locations in field G, to 18 feet near boring RP, to 20 feet adjacent to the boring locations in field P (NNRC 1987). The thin vadose zone is a reflection of the shallow water table in the glaciated Big Blue River Valley. Two cores were collected in each of two fields (G and P) and one core (RP) was collected from the remaining field (Figure 1).

Methods

Cores were collected using a Central Mine Equipment (CME) hollow-stem auger drilling rig equipped with a continuous coring system. The continuous coring device is comprised of a 5-foot, 3-inch O.D. split-tube stainless steel core barrel mounted within and extending an inch ahead of the 8-inch O.D. lead hollow-stem auger. Because the core, which does not rotate, is pushed into the 2.5-inch

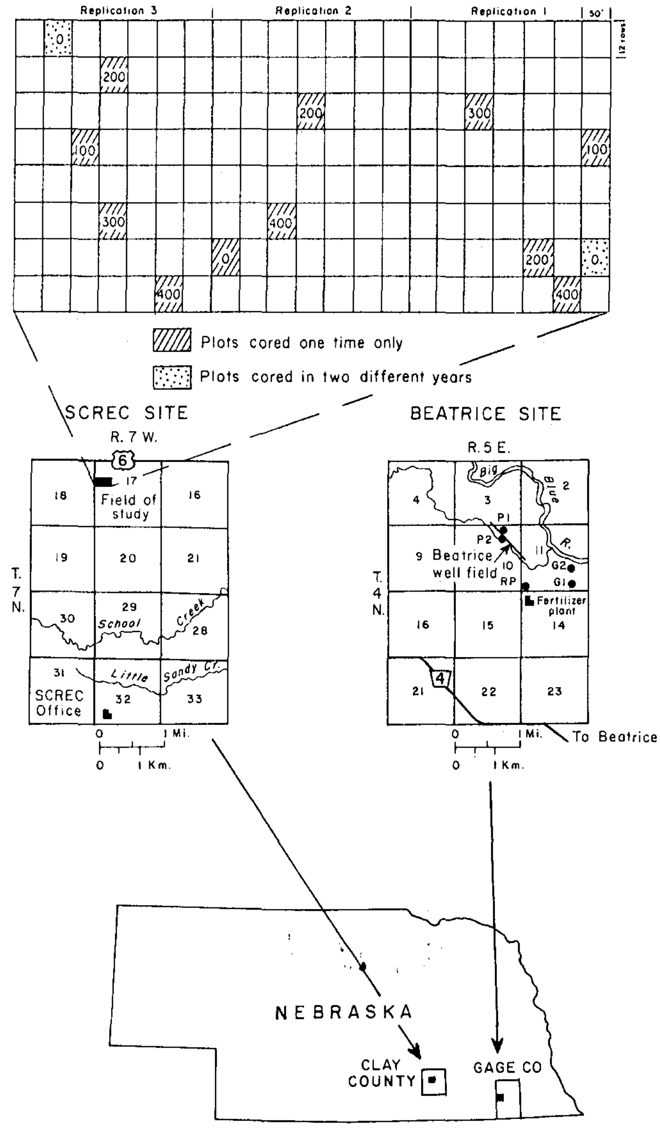

Figure 1. Study area locations. Numbers on the SCREC fertility plot grid designate fertilizer treatment rates in lbs N/acre/yr.

I.D. plastic liners within the core barrel, the cored sediments are not disturbed by the auger. Continuous sediment cores were collected in 2.5-foot plastic liners, which were labeled, capped, and immediately frozen with dry ice in a cooler for transport to the laboratory.

The thawed cores were extruded from the plastic liners in the laboratory. A 20 g aliquot was weighed, dried at 105 C for 24 hours, cooled, and reweighed to determine moisture content by weight.

The remainder of the core for chemical analysis was air-dried in the laboratory overnight. Each 2.5 feet of core was homogenized by grinding, sieving through a 10-mesh screen, and mixing. Aliquots from the composited interval were weighed, leached with 100 mL of 2N KCl in a 1:10 by weight soil to extractant ratio (Lindau and Spalding 1984). The mixture was shaken by hand for 3 minutes and with a wrist-action shaker for 1 hour (Keeney and Nelson 1982). The sample then was filtered and analyzed for NO_3-N by the automated cadmium reduction method (American Public Health Association 1975). The calculated standard deviation was

±0.3 percent for 10 preparations of a 10 μg/g soil standard. To convert the extractable nitrate on a dry weight basis to pore water nitrate concentration (mg/L), the dry sediment nitrate concentration must be multiplied by the weight of dry sediment divided by the moisture weight. Extractable NO_3-N (μg/g) is converted to lbs N/acre by multiplying the soil NO_3-N concentration (10^{-6} g/g) by 3.6 x 10^6 lbs sediment/acre-ft. The conversion assumes a soil bulk density of 1.3 g/cc. The total nitrate load present in an acre-ft column of sediment was calculated by summing the nitrate concentrations of each vertical interval beneath the crop rooting zone (6 feet).

The pipette method (USDA-SCS 1982) was used for particle size analysis.

Results

Particle size analysis of two cores collected from opposite sides of the 400-foot wide fertility field at the SCREC site indicated that the top 57 to 68 feet of the vadose layer are predominately clayey silts. Visual observations indicated that the vertical profiles of these cores were similar. The results from 44 aliquots from the two cores were weighted on a per-foot basis. Their average calculated sediment size distribution on a per-foot basis was estimated at 30±4 percent clay, 56±10 percent silt, and 14±10 percent fine sand. As evidenced by the low standard deviation, the clay content showed little variation with depth. The sand content increased in both cores between 25 and 28 feet and 45 and 48 feet, and increased in onlv one core between 34 and 35 feet.

Visual inspection indicated that the vertical sediment profiles of all 15 cores were similar. The depth to the unretrievable sands, however, varied by as much as 11 feet. This is due to a thinner layer of loess on the north side of the site and suggests that site-specific erosional cutting and filling processes could have occurred prior to the deposition of the overlying Loveland loess. With the exception of a dark black paleosol between 17 and 20 feet coloration was predominately buff to reddish-brown and indicative of oxidizing conditions.

Extractable NO_3-N concentrations in the IVZ (>6

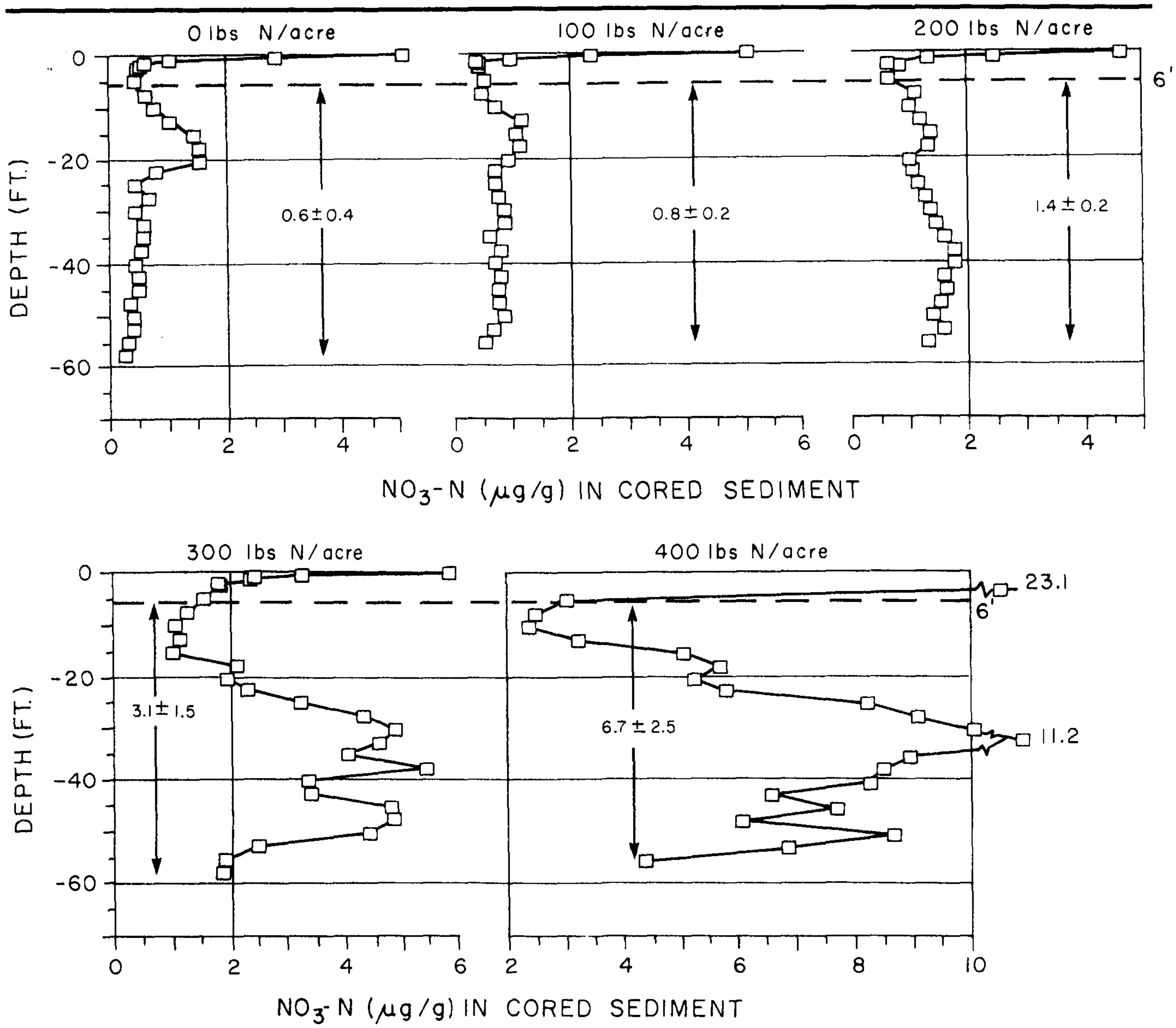

Figure 2. Average vertical nitrate-N profiles on a dry weight basis (μg/g) from fertility plots at SCREC. Number between arrows is the average NO_3-N concentration and standard deviation for the IVZ.

feet) from the fertility field at the SCREC ranged from 0.03 to 18.9 $\mu g/g$. A crop rooting zone of 6 feet was based on the maximum depth commonly ascribed to the corn rooting zone. Larger quantities of nitrate accumulated in the IVZ beneath fields receiving higher fertilizer treatments (Figure 2). Each profile (Figures 2 and 3) is an average profile for the particular fertilizer treatment. The nitrate-N concentration for each vertical interval is the average value for the same vertical interval in each of the replicate plots. Each concentration interval in the profiles from the plots receiving 0, 200 and 400 lbs N/ acre/yr is the average concentration from three replicate plots, while those in the profiles for the 100 and 300 lbs N/acre/yr treatments are an average of two replicate plots. Although averaging smooths the fluctuations in concentration in the individual replicate cores, the remaining large vertical variations in concentrations in the profiles for the plots receiving 300 and 400 lbs N/acre/yr indicate that part of the nitrate is moving vertically in concentrated slugs.

The particle size analysis of two cores collected from opposite ends of one independent corn producer's field (G) at Beatrice indicated the sediments were 22 to 38 percent clay and 5 to 22 percent sand. At site P size fractionation of one core yielded 33 percent clay and 6 percent sand. NO_3-N levels in the IVZ of three independent corn producers' fields ranged from 1.0 to 27.9 $\mu g/g$.

Discussion

Fertility Plots

In theory, the vertical movement of pore water should be relatively slow in the approximately 60 feet of fine-textured IVZ sediments at the SCREC site; consequently, transport of applied nitrate that has leached beneath the crop rooting zone should also be relatively slow. Thus, the IVZ acts like a retarding zone for downward-moving solutes. Below the loess the pore water nitrate is predicted to move rapidly through the sands with recharge to the water table.

A comparison of the average NO_3-N data from the two control plot cores obtained after the termination of the fertility study and application of the 225 lbs N/acre (unpublished data) with that from cores obtained from the control plots before the termination of the fertility study indicated that additional nitrate had not accumulated in the IVZ. In fact, the later cores averaged 0.2 $\mu g/g$ less extractable NO_3-N. Either the fertilizer had not infiltrated below the crop rooting zone by fall 1986 or, if it had, it did not significantly affect the quanity of extractable NO_3-N. Thus, the effects of applying 225 lbs N/acre

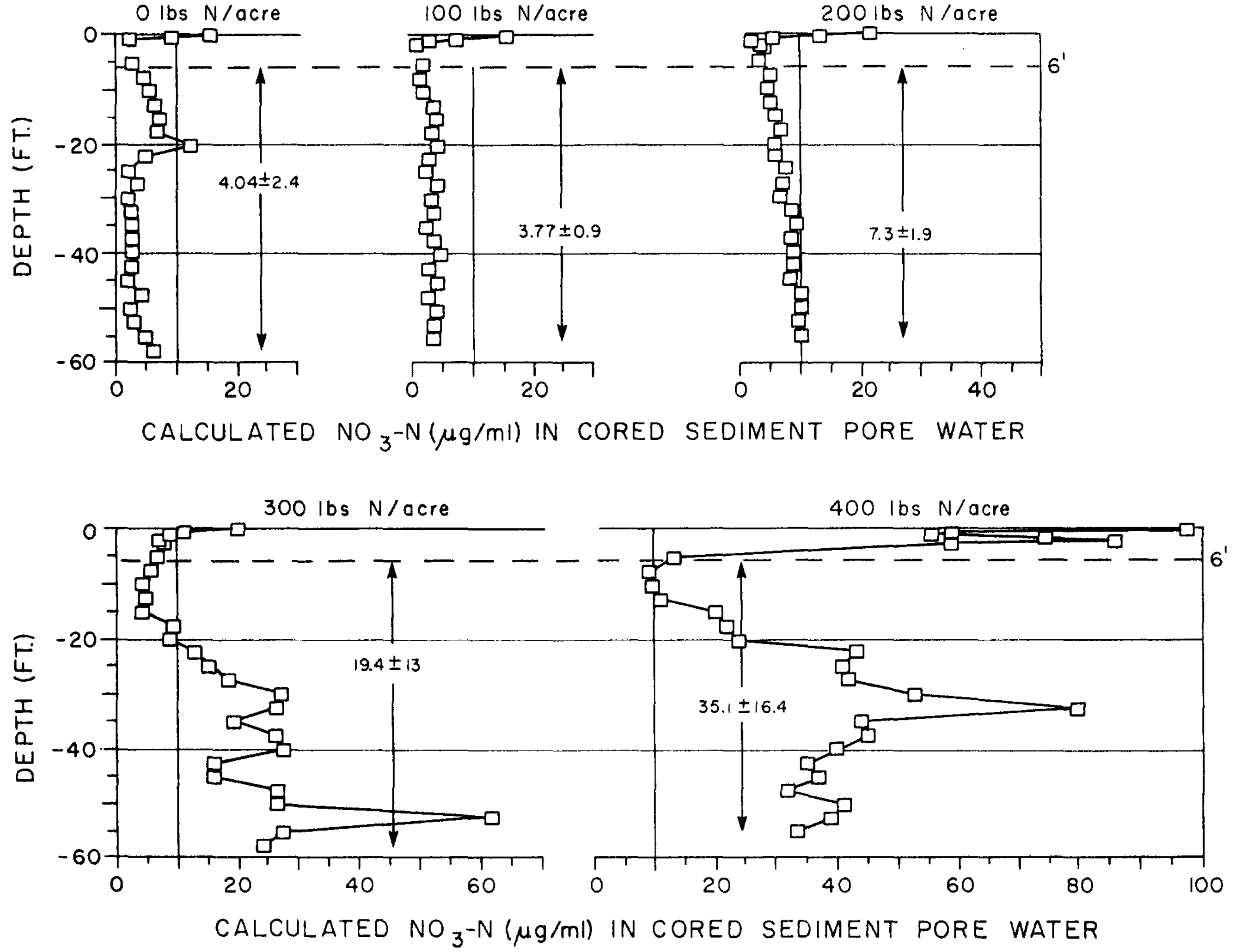

Figure 3. Calculated average vertical nitrate-N profiles in pore water ($\mu g/mL$) from fertility plots at SCREC. Number between arrows is the calculated average NO_3-N concentration and standard deviation for the IVZ.

to what formerly were the 100 and 300 lbs N/acre/yr treatment plots were minimal.

Increasingly higher concentrations of extractable NO_3-N within the IVZ were associated with increased rates of N-fertilization (Figure 2). The average difference in extractable NO_3-N beneath the control plots (0 lbs N/acre/yr) and the plots treated with 100 lbs N/acre/yr is very small (Figure 2). Whether or not the slight average increase of 0.2 μg/g NO_3-N is related to fertilizer leachate is debatable. However, corn has utilized the majority of the applied N. The effects of applying N at rates greater than 100 lbs N/acre/yr are more obvious. Average extractable NO_3-N levels approximately doubled for each additional 100 lbs N/acre/yr. The presence of elevated NO_3-N levels between 50 and 60 feet under the plots treated with 300 and 400 lbs N/acre/yr indicates that the fertilizer has moved at least 60 feet in 15 yrs.

Even beneath plots treated at a rate of 400 lbs N/acre/yr most of the measured NO_3-N concentrations in Figure 2 were below 10 μg/g (10 ppm). The data, however, are on a weight basis and should not be equated to pore water concentrations. Because nitrate is extremely soluble (> 1 kg/L), most of the nitrate in the IVZ is in the pore water. Since most recharge is from the vertical movement of pore water, the high NO_3-N in the pore water will enter the aquifer and thereby increase NO_3-N in the ground water. Continued recharge with high NO_3-N pore waters to some ground water will result in the NO_3-N levels exceeding the maximum contaminant level of 10 mg/L.

The potential loading effect of NO_3-N in the IVZ under the fertility plots on ground water NO_3-N levels was estimated. The total amount of NO_3-N in the IVZ progressively increased from 131 to 154 to 270 to 721 to 1260 lbs N/acre in the plots treated at rates of 0, 100, 200, 300, and 400 lbs N/acre/yr, respectively. If, in a worse case scenario, the entire NO_3-N load from these plots was flushed into a nitrate-free aquifer and the nitrate mixed homogeneously throughout a 25-foot saturated thickness of sands and gravels having 25 percent porosity, the concentrations of NO_3-N in the ground water would increase progressively from 7.7 to 8.9 to 16 to 42 to 74 mg/L beneath the plots treated with 0, 100, 200, 300, and 400 lbs N/acre/yr, respectively. Although such flushing would normally take several years, these calculations demonstrate why shallow wells screened in the top 6 feet of a non-point nitrate-contaminated aquifer in Nebraska contain NO_3-N levels greater than 100 mg/L (Exner 1984b).

Independent Producers' Fields

These fields were chosen to compare the amounts of nitrate in the IVZ under independent corn growers' fields with the fertility plot results. The extractable NO_3-N concentrations in the IVZ ranged from high to very high (Figure 4). When the data are compared to the fertility plot results (Figures 2 and 3), it appears that N-fertilizer must have been applied at rates of 300 to >400 lbs N/acre/yr. If reported application rates of 200 to 250 lbs N/acre/yr for 20 years are correct, then one or a combination of events could be responsible for leaching large amounts of N-fertilizer beneath the crop rooting zone. They include mineralization of large amounts of soil organic matter, fall fertilization and subsequent leaching,

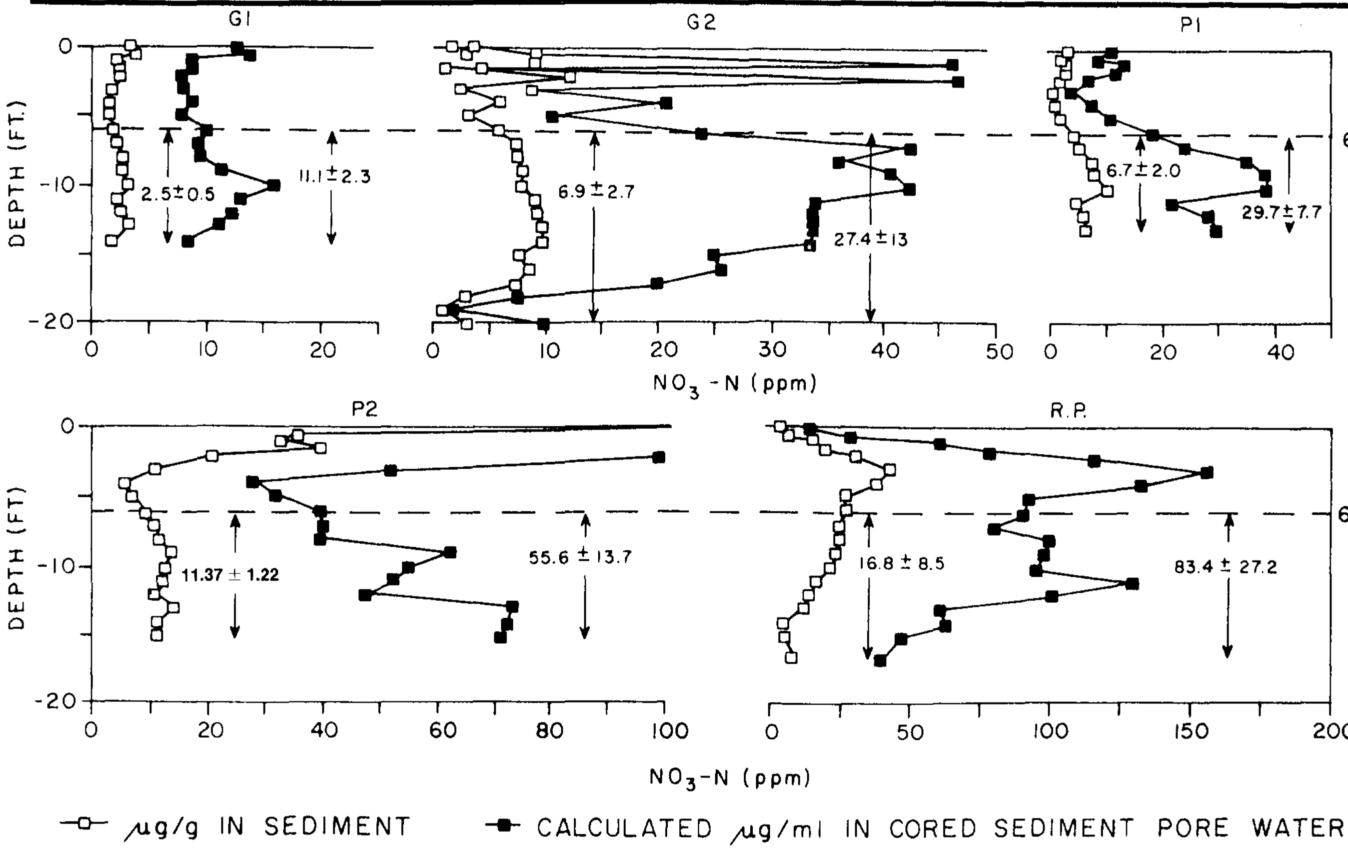

Figure 4. Vertical nitrate-N profiles from independent corn producers' fields near Beatrice, Nebraska. Number between arrows is the average NO_3-N concentration and standard deviation for the IVZ.

decreased crop nutrient uptake due to weather-related phenomena, and poor irrigation scheduling.

Intermediate vadose zone nitrate was highly variable within the same field. Some of this variability could be explained by the coring locations. The borings in both fields were 0.25 miles apart. At field P, boring P1 was in the upper end of the field while boring P2 was in the lower end. The higher NO_3-N levels in the downgradient core (P2) could reflect movement of nitrate from the upper to the lower end of the field. Ponded irrigation runoff at the lower end of the field also could increase head and cause more rapid leaching and vertical transport. At field G, core G2 was located in a furrow while G1, which had higher NO_3-N concentrations, was located in a corn row. In any case, the analysis of several cores from the same gravity-irrigated field are necessary to accurately estimate the average nitrate loading in the IVZ.

Conclusions

If there is excessive N-fertilization in irrigated areas, the potential for ground water pollution from NO_3-N exists even if those areas are underlain by fine-textured sediments. Extractable NO_3-N concentrations in the IVZ of fertility plots showed that application rates of 200 lbs N/acre/yr or more caused nitrate to accumulate in the IVZ pore water in sufficient quantities to potentially contaminate the underlying ground water. The concentration of accumulated NO_3-N approximately doubled for each additional 100 lbs N/acre/yr above 100 lbs N/acre/yr. High levels of nitrate also were present in cores from independent producers' fields. These data suggest that even in the heavy soils of southeastern Nebraska significant loss of fertilizer via leaching may be the rule and not the exception.

Vadose zone sampling in areas of potential non-point nitrate contamination should provide an effective method for forecasting future ground water quality problems. Unlike monitoring wells, which are intolerable obstructions in cornfields, vadose zone coring provides a method to sample directly beneath source areas. Although more labor intensive than ground water monitoring, this technique provides a mechanism to monitor the efficacy of different fertilizer and water management options and eliminates confusion as to where best management approaches are necessary. After coring, the boreholes should be plugged by accepted methods.

While the pollution potential from applying excessive amounts of N-fertilizer has been documented, many questions remain unanswered. They include the vertical rate of nitrate movement, the association of nitrate with textural changes, and the possibility of losses due to denitrification. Some of these questions could be answered after reexaming selected cores from the fertility plots using 1-foot rather than 2.5-foot composite intervals.

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Biographical Sketches

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