Controlling Nitrate Leaching in Irrigated Agriculture

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ABSTRACT

The impact of improved irrigation and nutrient practices on ground water quality was assessed at the Nebraska Management System Evaluation Area using ground water quality data collected from 16 depths at 31 strategically located multilevel samplers three times annually from 1991 to 1996. The site was sectioned into four 13.4-ha management fields: (i) a conventional furrow-irrigated corn (*Zea mays* L.) field; (ii) a surge-irrigated corn field, which received 60% less water and 31% less N fertilizer than the conventional field; (iii) a center pivot-irrigated corn field, which received 66% less water and 37% less N fertilizer than the conventional field; and (iv) a center pivot-irrigated alfalfa (*Medicago sativa* L.) field. Dating ($^3H/^3He$) indicated that the uppermost ground water was <1 to 2 yr old and that the aquifer water was stratified with the deepest water ~20 yr old. Recharge during the wet growing season in 1993 reduced the average NO_3–N concentration in the top 3 m 20 mg L^{-1}, effectively diluting and replacing the NO_3-contaminated water. Nitrate concentrations in the shallow zone of the aquifer increased with depth to water. Beneath the conventional and surge-irrigated fields, shallow ground water concentrations returned to the initial 30 mg NO_3–N L^{-1} level by fall 1995; however, beneath the center pivot-irrigated corn field, concentrations remained at ~13 mg NO_3–N L^{-1} until fall 1996. A combination of sprinkler irrigation and N fertigation significantly reduced N leaching with only minor reductions (6%) in crop yield.

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Assessments of ground water NO_3 contamination report that many major areas of nonpoint-source contamination are located in the irrigated semiarid and arid regions of the western USA (Madison and Brunett, 1985; Anderson, 1989; Power and Schepers, 1989; Spalding and Exner, 1993). The thrust of these reports provides a clear association between nonpoint-source ground water NO_3 contamination and irrigated agriculture.

Irrigated agriculture has a major impact on the economy of several states both in the west and in the western Corn Belt. In Nebraska, 3.4 million ha of irrigated agriculture and related spin-off service industries add approximately $3 billion annually to the state's economy. Controlling leachates from irrigated crop land, especially from the 2.3 million ha of irrigated corn, requires fundamental changes in farm practices that not only lead to solutions but are acceptable to producers and regulators. Nebraska's dependence on ground water as the primary source of potable water is the major thrust for a sustained impetus to develop and implement more effective agricultural management strategies to reduce ground water NO_3 contamination.

Beginning in 1990, the USDA sponsored Management Systems Evaluation Area (MSEA) projects in five midwestern states in the corn and soybean [*Glycine max* (L.) Merr.] belt. The projects concentrated both on understanding the mechanisms involved in nonpoint-source contamination of surface and ground water by agrochemicals and on developing economically accept-

Abbreviations: MLSs, multilevel samplers; ET, evapotranspiration; MSEA, Management Systems Evaluation Area; NE-MSEA, Nebraska MSEA; CPNRD, Central Platte Natural Resources District; MCL, maximum contaminant level; DOC, dissolved organic carbon.

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able farming practices that reduce leaching. The Nebraska MSEA (NE-MSEA) project focused on the impact of irrigated agriculture on ground water quality and the development of methods to mitigate agrochemical leaching in irrigated agriculture.

This paper demonstrates that (i) seasonal responses to agricultural practices can be detected by monitoring shallow ground water quality; (ii) management can impact NO_3 loading; and, most importantly, (iii) innovative agricultural practices can maintain NO_3 concentrations at more acceptable levels without significantly compromising crop yields. The project was designed to provide regulators and irrigators with research results needed to promote environmentally sound management.

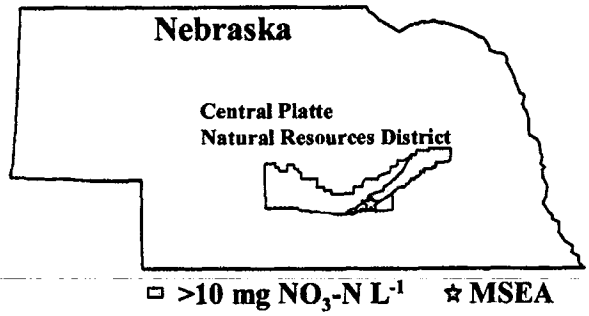

Fig. 1. Location of Central Platte Natural Resources District (NRD), shallow ground water nonpoint NO_3–N plume, and the Nebraska Management Systems Evaluation Area (NE-MSEA) research/demonstration site.

STUDY SITE

Water Quality and Agricultural Practices

The principal target area of the NE-MSEA lies within the Central Platte Natural Resources District (CPNRD) in the central Platte River Valley (Fig. 1). It is located within 202 000 contiguous hectares underlain by a shallow, NO_3-contaminated, sand and gravel aquifer (Spalding and Exner, 1993). Nitrate concentrations within this large zone vary from 10 to >50 mg NO_3–N L^{-1}. In this area dominated by furrow-irrigated corn production, most of the contamination is derived from commercial fertilizer leachates (Gormly and Spalding, 1979). While N applications in the 1960s and 1970s ranged from 250 to 300 kg ha^{-1}, recent surveys suggest that, as a result of educational programs and regulations, most applications have declined to ~150 to 180 kg ha^{-1}, although 20% of the producers continue to apply more than is recommended (Supalla et al., 1995).

In the study area, precipitation and evapotranspiration (ET) during the growing season average 420 and 690 mm, respectively, which resulted in a seasonally dependent net irrigation requirement of 0 to >450 mm during the 30 yr ending in 1996 (Martin and Watts, 1997). Although strategies for improved furrow irrigation efficiency have been introduced, the availability of abundant shallow ground water fosters inefficient irrigation practices that promote leaching (Cahoon et al., 1995). Beneath the NE-MSEA and adjacent areas, NO_3–N concentrations generally range from 30 to 40 mg L^{-1} (Spalding et al., 1993).

The NE-MSEA consists of an upgradient buffer area (~130 ha), a component research site (~32 ha), and a research/demonstration site (~54 ha). The latter is subdivided into four 13.4-ha management fields. Three are cropped to corn and the fourth to alfalfa (Fig. 2). Each spring the farmer prepared the three corn fields by shredding stalks and tilling twice with a tandem disk harrow. The corn fields received banded applications of atrazine–metolachlor mix[1] (Bicep) at planting, and 24 kg N ha^{-1} as UAN were applied with the seed. Each corn management field was subject to different irrigation and N management practices (Table 1). Applications of N fertilizer and irrigation water were controlled in the buffer to reduce recharge upgradient of the management fields.

Conventional Furrow-Irrigated Corn Management Field

The conventional field was managed by the land owner, who applied preplant NH_3 and irrigated through gated pipe into furrows using 12-h continuous sets. Irrigation was on an every-furrow basis and runoff water accumulated behind the end-of-field dike (Fig. 2). With the exception of periods of significant precipitation or very cool temperatures, weekly water applications ranged from ~160 to 200 mm. During the first 2 yr of the project, preplant NH_3 was applied without nitrification inhibitor. Subsequent CPNRD regulations required the use of an inhibitor when more than half the seasonal N application was applied preplant.

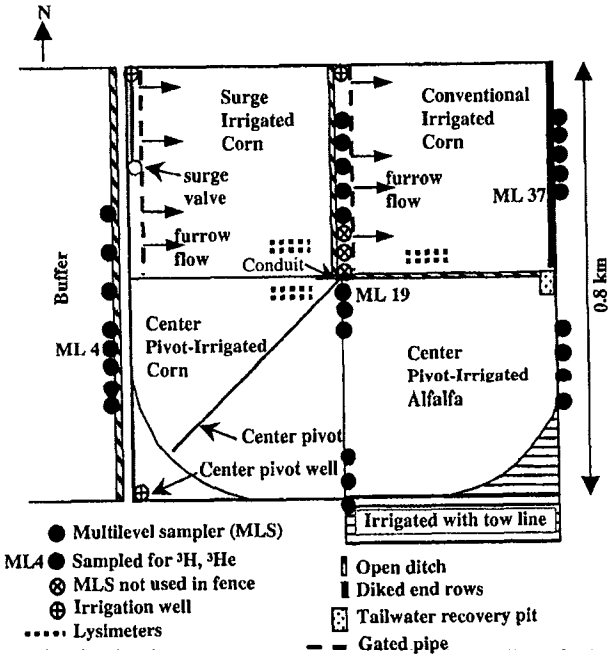

Fig. 2. Layout of research/demonstration site and sampling locations.

[1] Atrazine (2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine), metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide].

Table 1. Summary of annual precipitation, irrigation, irrigation-applied N, soil N, fertilizer N, and yield data for management fields.

Year/management field	Precipitation growing season	Irrigation water	Annual precip.	Residual N	Preplant N	Starter N	Sidedress (S) and/or fertigation (F) N	Irrigation N	Grain yield
	mm			kg ha^{-1}					Mg ha^{-1}
1991									
Conventional	297	942	468	95	180	24		288	12.51
Surge	297	455	468	150		24	101(S)	141	12.32
Center-pivot corn	297	335	468	85		24		92	12.20
Center-pivot alfalfa	297	328	468					88	
1992									
Conventional	319	744	520	108	168	24		223	13.01
Surge	319	231	520	121		24	51(S)	51	12.57
Center-pivot corn	319	208	520	70		24	22(F)	54	11.00
Center-pivot alfalfa	319	303	520					78	
1993									
Conventional	635	203	879	59	168	24		64	8.93
Surge	635	114	879	51	58	24	79(F)	39	8.05
Center-pivot corn	635	79	879	21	68	24	66(F)	24	8.17
Center-pivot alfalfa	635	84	879					25	
1994									
Conventional	385	767	542	93	187	24		253	8.00†
Surge	385	297	542	97	99	24	55(F)	99	7.98†
Center-pivot corn	385	107	542	68	98	24	38(F)	31	7.13†
Center-pivot alfalfa	385	396	542					115	
1995									
Conventional	377	582	607	106	180	24		181	11.63
Surge	377	264	607	93		24	134(S)	72	11.32
Center-pivot corn	377	307	607	83		24	164(S and F)	95	11.82
Center-pivot alfalfa	377	249	607					77	
1996									
Conventional	579	1275	684	74	167	24		356	13.45
Surge	579	241	684	60	80	24	56(S)	68	13.20
Center-pivot corn	579	152	684	74	112	24	61(S)	45	12.70
Center-pivot alfalfa	579	114	684					34	

Management field	6-yr Total applied water (mm)	6-yr Total applied N (kg ha^{-1})	5-yr Avg. grain yield (Mg ha^{-1})
Conventional	8213	3094	11.91
Surge	5302	1899	11.49
Center-pivot corn	4888	1515	11.18

† Not used in average yield calculation.

Surge-Irrigated Corn Management Field

Surge irrigation provides a more uniform water application than conventional furrow irrigation (Musick et al., 1987) and, therefore, is considered an improved technique. The field was graded using a laser-guided system in fall 1990 to obtain better water distribution on the gently sloping land. Irrigation water was delivered to the surge valve, distributed to furrows on both sides of the surge valve through gated pipe, and conveyed through the furrows with the excess discharged into a ditch at the lower end of the field and then into a lined tailwater recovery pit (Fig. 2). A combination of alternate furrow surge-flow irrigation and runoff recovery is designed to reduce deep percolation and total pumping. Irrigations were scheduled by standard water balance techniques according to ET computed from daily weather data. Typical beginning-of-season net irrigation applications (gross application minus runoff) ranged from 55 to 75 mm. Subsequent applications usually averaged ~50 mm.

During the first, second, and fifth growing seasons, NH_3 was applied as sidedress when the crop was in the 4 to 6-leaf stage. In 1993 and 1994, the N application was split between preplant NH_3 and UAN solution injected into the irrigation water (fertigation), while in 1996 the application was split between preplant and sidedress N.

Center Pivot-Irrigated Corn Management Field

Irrigations via a 379-m long center pivot followed the same scheduling technique employed on the surge-irrigated field. Typical irrigation applications were ~25 mm. After mid-July, a soil–water deficit of ~25 mm was maintained to provide storage of rainfall, thereby reducing leaching. In late summer, the deficit was gradually increased as the crop matured. This enhanced storage of off-season precipitation reduced the leaching of residual soil NO_3 the following spring.

With the exception of the first year, when only starter N was applied, N applications were split in 4 of 5 yr between either preplant or early sidedress NH_3 and incremental applications of UAN via fertigation. The latter were based on chlorophyll meter readings in the crop canopy (Schepers et al., 1995). In 1992 all the N was applied by fertigation. The approach minimized both the N application required for good production and the residual N available for leaching in the off-season.

Center Pivot-Irrigated Alfalfa Management Field

Most of the alfalfa field was watered with the same center pivot used for the pivot-irrigated corn. The corner not covered by the pivot and an additional 2.8 ha on the south were irrigated with a tow-line sprinkler system (Fig. 2). Between cuttings, water was applied

Table 2. Baseline (1990) concentrations in the water table aquifer.

Analyte	Concentration
pH	6.8 ± 0.3
Conductance, μS cm^{-1}	930 ± 170
NO_3–N, mg L^{-1}	26.1 ± 4.7
$\delta^{15}N$–NO_3, ‰	6.1 ± 0.8
NH_4–N, mg L^{-1}	0.15 ± 0.05
TKN, mg L^{-1}	0.63 ± 0.39
DOC, mg L^{-1}	3.3 ± 0.3
HCO_3^-, mg L^{-1}	315 ± 80
Cl^-, mg L^{-1}	24 ± 3
SO_4^{2-}, mg L^{-1}	211 ± 54
Na^+, mg L^{-1}	68 ± 19
K^+, mg L^{-1}	20 ± 11
Ca^{+2}, mg L^{-1}	144 ± 25
Mg^{+2}, mg L^{-1}	29 ± 5

based upon precipitation, ET, and the need to keep the field dry during hay harvest. Four cuttings of alfalfa were removed annually.

Hydrogeology

The unsaturated zone beneath the four management fields is a 1.1-m thick, well-drained, silt loam primarily of Eolian origin overlaying a 4.3-m thick zone of fine to medium-textured sands (Diffendal and Smith, 1996). The predominant soil at the site is a well-drained Hord silt loam (Pachic Hapustoll) with small areas of Hall silt loam (Typic Agriustoll). Both shallow water table and deep confined aquifers exist at the site. The water table aquifer is 14.3 to 17.3-m thick and composed of Quaternary age sand and gravel that overlie an aquitard composed of clayey silt interbedded with clay, sand, and some gravel. Deep boreholes in three corners of the research/demonstration site indicated that the clayey silt is 9 to 20-m thick and forms the upper confining bed of the Ogallala aquifer. The confining clayey silts lie uncomformably on Miocene age sandstone of the Ogallala formation, which rests on impermeable Pierre shale (Diffendal and Smith, 1996).

During the 6-yr investigation, the depth to water in the primary aquifer fluctuated from ~3 to ~6 m beneath the land surface, and the direction of horizontal ground water flow switched from east–northeast, to east, and back to east–northeast. A pump test utilizing the irrigation well in the southwest corner of the research/demonstration site indicated that the horizontal hydraulic conductivity in the primary aquifer averages 130 m d^{-1}, and the vertical conductivity is 10.4 m d^{-1} (Zlotnik et al., 1993). Using Darcy's Law, a nonretarded solute would be transported beneath the research/demonstration site at an average horizontal rate of 0.55 m d^{-1} and traverse the management fields in a little more than 4 yr. Upward leakage from the Ogallala aquifer to the primary aquifer was not detected during the pump test. Because the Ogallala formation remains NO_3 and pesticide-free, it is the domestic water supply for most homes.

Hydrochemistry

Initially a network of 11 multilevel samplers (MLSs) was installed at the research/demonstration site and in the upgradient buffer. These MLSs provided the baseline data (Table 2) (Spalding et al., 1993) for strategizing the locations of the 31 permanent MLS shown in Fig. 2. Nitrate-N concentrations exceeded the 10 mg L^{-1} maximum contaminant level (MCL) for potable water (Federal Register, 1975) and were relatively uniform throughout the primary aquifer. Ammonia-N levels were <0.1 mg L^{-1}. The N_2/Ar ratios indicated N_2 was not in excess of air-saturated water values in most of the sampled cluster wells (Martin et al., 1995), which suggests that denitrification is extremely limited in the shallow ground water. Dissolved organic carbon (DOC) concentrations are too low to be actively involved in significant levels of denitrification and were similar to those reported 20 yr ago (Spalding et al., 1978). The average $\delta^{15}N$–NO_3 value (+6.1‰) in the primary aquifer is slightly enriched relative to commercial fertilizer leachates (Gormly and Spalding, 1979). The enrichment is believed associated with manure-derived N from wintering cattle at the site. The relatively uniform NO_3–N concentrations, low DOC concentrations, uniformly low $\delta^{15}N$–NO_3 values, and the lack of excess N_2 in the sand and gravel aquifer suggest that the NO_3 is not denitrified and acts as a conservative ion.

FIELD PROCEDURES AND LABORATORY METHODS

The impact of irrigation and fertilizer management on water quality was assessed with pore-water lysimeters and MLSs. Each of the 31 MLSs permits water sampling from as many as 16 different depths throughout the water table aquifer. The MLSs act as a fence to intercept contaminant transport from each of the management fields. Most of the MLSs consist of 8 stainless steel gas-drive samplers, 16 suction sampling tubes, and 4 piezometers (Fig. 3). The suction sampling tubes were placed at the same inlet depths as the gas-drive samplers and also at eight shallower depths. The gas-drive samplers ensured that samples could be collected if the water table declined below the peristaltic pumping level of ~6.5 m. This situation, however, did not occur during the 6-yr study, and all samples were collected from the suction sampling tubes. Each of the 31 MLSs was assembled on site and placed in the borehole in a continuous string.

Two sets of five suction lysimeters (Soil Moisture Equipment model no. 1920) were installed at a depth of 1.4 m in each field. Within each corn field, the lysimeter sets were separated by 7 rows (~6.3 m). The lysimeters in each set were 60 cm apart and aligned along a corn row. Pore water was collected primarily during the irrigation season. A 250-mL side-arm flask was attached to a vacuum pump manifold, and the lysimeter was placed under a vacuum to pull the pore water from the adjacent soils into the porous cup. After about 2 h the vacuum line was closed, the sample line opened, and the soil pore water transferred from the side-arm flask to a 250-mL polypropylene bottle and acidified with H_2SO_4.

Water table measurements and sample collection occurred three times each year: during the preplant period (late March), before irrigation season (late June), and after irrigation season and harvest (early October). Normally preirrigation sampling coincided with the peak in the water table elevation, while postirrigation sampling was associated with the lowest annual water table elevations beneath the fields. Before each sampling event, depth to water was measured in the four piezometers of each MLS using an electronic tape (± 0.61 cm). The measurements were used to contour the water table to determine the direction of ground water flow. The change in direction from east–northeast to due east during the wet 1993 growing season necessitated reevaluating the effectiveness of

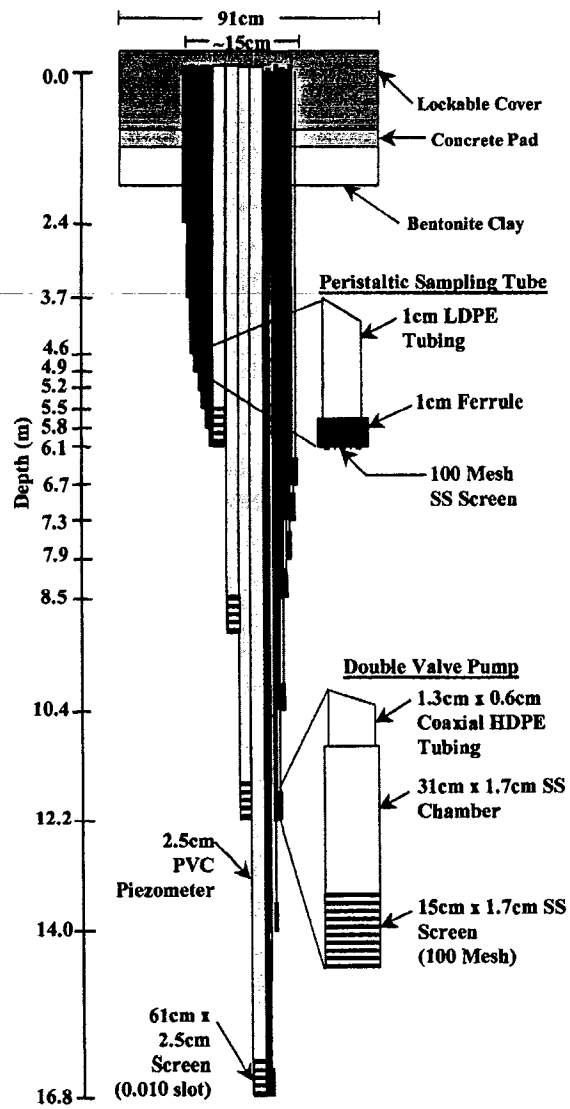

Fig. 3. Multilevel sampler construction.

the MLS locations for intercepting ground water flow downgradient from the pivot-irrigated corn field and resulted in eliminating three MLSs from the downgradient data set (Fig. 2). The change in flow direction did not compromise the locations of the MLSs downgradient from the other fields.

After three purge volumes were removed from the suction sampling tubes, conductivity and pH were measured in the field using portable meters (APHA, 1989), and bicarbonate was analyzed by potentiometric titration with standardized H_2SO_4 to pH of 4.5 using an expanded scale pH meter (APHA, 1989). Samples for Na, K, Mg, and Ca analysis were collected in 500-mL polyethylene bottles; preserved with nitric acid; and analyzed by atomic absorption spectrophotometry (APHA, 1989). Samples for NH_4 and NO_3 were collected in polyethylene bottles and acidified with H_2SO_4. Ammonium-N concentrations were determined by the automated phenate method, and NO_3–N concentrations were quantified using the cadmium reduction method (APHA, 1989). Method detection limits for NH_4–N and NO_3–N were 0.1 mg L^{-1}. Samples for chloride and sulfate analysis were collected in polyethylene bottles and analyzed by ion chromatography (APHA, 1989). Samples for total Kjeldahl N analysis were digested with H_2SO_4 (APHA, 1989).

Samples for $\delta^{15}N$–NO_3 determinations were collected in polyethylene bottles and kept on ice until they reached the laboratory where they were frozen until the time of analysis. Nitrate in the samples was converted to $(NH_4)_2SO_4$ by steam distillation (Bremner and Keeney, 1965) with a modification by Gormly and Spalding (1979). The $(NH_4)_2SO_4$ subsequently was oxidized to N_2 in a vacuum preparation system similar to that of Krietler (1975). The purified N_2 samples were analyzed with a VG Optima dual inlet isotope ratio mass spectrometer.

Samples for DOC analysis were collected in precombusted 250-mL glass bottles with ground-glass stoppers and preserved with mercuric chloride. The DOC was determined using the wet oxidation method (APHA, 1989). An aliquot of sample was filtered through a binderless, glass fiber filter; acidified; and purged to remove dissolved inorganic C. The DOC was oxidized to CO_2 using persulfate and the CO_2 was measured with a linearized detector. Each sample was analyzed in triplicate and the average DOC concentration was reported.

Samples for ^3He and tritium (^3H) measurements were collected from three MLS locations in spring 1993 (Fig. 2). For the ^3He determination, ground water was removed from the piezometers with a positive displacement pump, passed through 0.8-m copper tubes, and collected by crushing the ends of the tubes. The samples were shipped in trunks and analyzed at the Rare Gas Facility at the University of Rochester by the method of Solomon et al. (1992). Tritium samples were collected in 1-L glass bottles, shipped to the University of Rochester with the ^3He samples, electrolytically enriched, and analyzed by scintillation counting techniques.

Precipitation at the site was measured daily with a tipping bucket rain gauge.

Corn yields were determined gravimetrically using a calibrated scale. Grain from 16-row strips across each management field was harvested and weighed to provide a measure of field variability. The N content of the grain was determined by the Dumas-combustion procedure (Schepers et al., 1989).

RESULTS AND DISCUSSION

Ground Water Dating

Atmospherically derived ^3H and its stable daughter (^3He) have been used successfully to date ground water <50 yr old (Solomon and Sudicky, 1991). The method is especially applicable to shallow unconfined sand and gravel aquifers with characteristically low dispersion rates (Schlosser et al., 1989). Application of the dating technique at the NE-MSEA provides reasonably accurate dates because: (i) the layers are consistently older with depth (Fig. 4); (ii) the ages are quite consistent for water collected from the same depths across the site; and (iii) a concentrated ^3H slug indicative of the mid-1960s bomb peak is absent from this active ground water system.

Recharge to an unconfined aquifer is defined as the fluid flux normal to the water table surface and is related to the average linear fluid velocity according to

$$r = v_0\,\theta$$

where r = recharge rate (L/T); θ = effective porosity ($L^3\ L^{-3}$), and v_0 = component of the average linear velocity normal to the water table (Solomon et al., 1995).

Solomon et al. (1993, 1995) have shown that the $^3H/^3He$ age gradient in multilevel piezometer nests can ac-

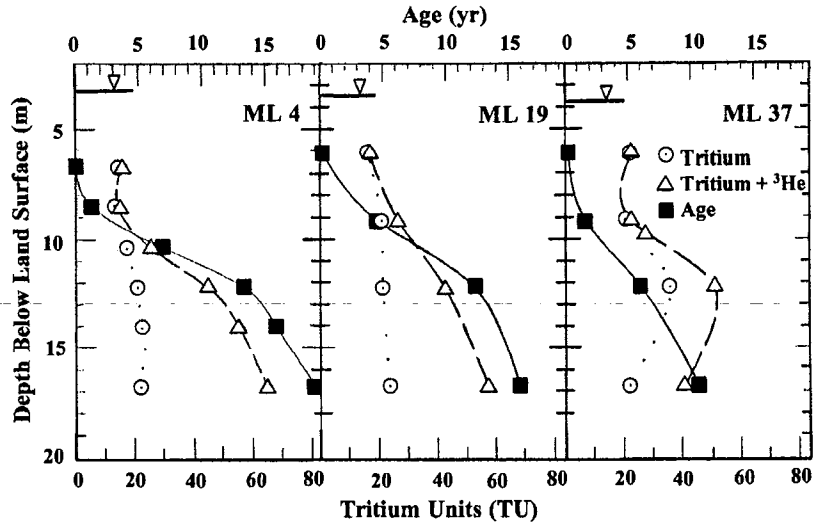

Fig. 4. Ground water age, ^{3}H, and ^{3}H + ^{3}He profiles in April 1993 from three piezometer clusters.

curately establish the average recharge to an aquifer. The slopes derived from linear regressions of the age profiles (Fig. 4) using all but the deepest piezometers in each cluster establish a recharge rate for the NE-MSEA. Data from the deepest sampling interval at the aquitard–water table aquifer interface are excluded due to mixing caused by pumping the high-capacity irrigation well, which is screened in the bottom third of the shallow aquifer. Across the site, recharge ranges from 90 mm yr^{-1} at the upgradient location (ML-4) to 250 mm yr^{-1} downgradient (ML-37) which represents 10 to 20% of the water input. The highest recharge rate occurs in the well cluster downgradient from the conventional field. It receives the greatest amounts of irrigation water (Table 1), and recharge is further enhanced by the blocked-end furrows (Fig. 2).

Investigations by Solomon et al. (1992, 1993) have shown that gas exchange at the water table, the enhanced diffusion coefficient for He, and the seasonal nature of recharge cause the ^{3}H/^{3}He *clock* to start at or near the seasonal low water table. At the NE-MSEA, the low water table normally occurs in early autumn and coincides with the harvest. Higher than normal precipitation between October 1992 and early summer 1993 caused a rise in the water table from 5.5 m to ~4 m. In spring 1993 the shallowest sample from each piezometer cluster had an ^{3}He/^{4}He ratio indistinguishable from air-saturated water. The estimated ^{3}H/^{3}He age of 0.0 ± 0.5 yr in these shallow samples supports their origins as seasonal recharge.

Nitrate-Nitrogen Profiles

Fall 1991 and 1992 NO_3–N concentration profiles of ~1000 samples collected from the 31 MLSs (Fig. 5) show that the average concentrations were consistently high (28.5 ± 5.5 mg L^{-1}) regardless of depth in the unconfined aquifer or areal location. The uniformly high concentrations with depth do not conform to profiles commonly reported in the literature, which, almost without exception, describe decreasing NO_3–N concentrations with increased depth (Hallberg, 1989; Libra et al., 1993; Spalding and Exner, 1993; Bohlke and Denver, 1995). The initial invariable NO_3 concentrations with depth appear related to a relatively homogeneous aquifer matrix, constant upgradient agricultural sources, and mixing that results from extensive pumping of large-capacity irrigation wells screened in the bottom third of the shallow aquifer (Zlotnik et al., 1995).

In response to heavy rainfall, NO_3–N concentrations in the fall 1993 profile declined ~10 to 20 mg L^{-1} and concentrations in many samples from the top 3 m of the aquifer declined below the MCL (Fig. 5). Nitrate–N concentrations (n = 85) in the uppermost 3 m averaged 11.6 ± 6.9 mg L^{-1}. The effect of the relatively low NO_3 recharge is clearly shown 3 to 6 m below the water table, where there is a linear increase (r = 0.96, n = 8) in the average concentration from approximately 12 to 25 mg NO_3–N L^{-1}. The precipitous decrease in average NO_3–N concentrations in the top 6 m of the aquifer accompanied a 2.4-m rise in the water table. Thus, infiltration of precipitation with relatively low concentrations of NO_3–N significantly improved the quality of the shallow ground water.

Improvements in NO_3 quality from the 1993 recharge were limited to the upper ground water, and NO_3–N concentrations in water deeper than 9 m did not decrease (Fig. 5). This deeper water with a ground water residence time >5 yr originated as infiltrate from upgradient fields and was laterally transported beneath the NE-MSEA at ~0.5 m d^{-1}. Thus, the first 3 yr of ground water NO_3–N data confirm that seasonal changes in water quality brought about by recent recharge can clearly be detected in shallow ground water (≤6 m) and that the depth of impact is limited by the volume of recharge. While the 1993 climatic conditions were anomalous, the NO_3–N concentrations in municipal wells in nearby Wood River and Shelton also were significantly reduced during another very wet spring in 1967 (Spalding, 1975). The data indicate that although extremely wet years and floods can cause agricultural and urban

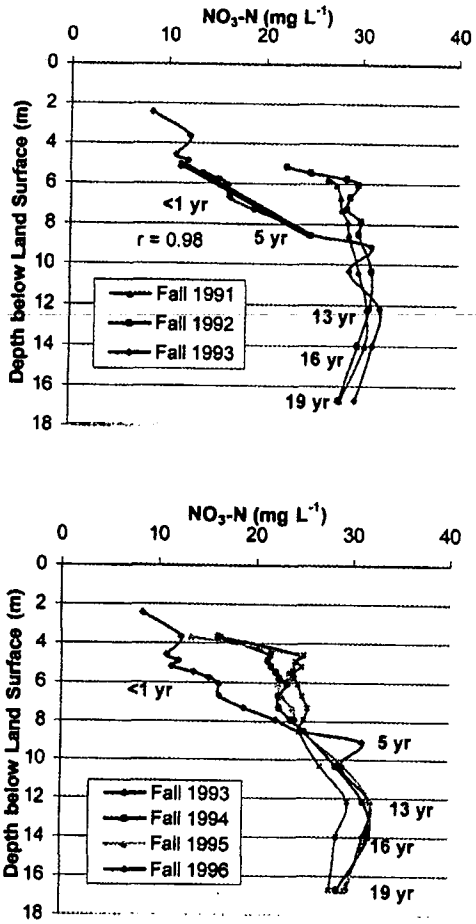

Fig. 5. Vertical profiles of ground water NO_3–N concentrations, fall 1991–1996, with regression line for NO_3–N concentration vs. depth below land surface in the mixing zone and 1993 ground water ages.

disasters, the recharge can be highly beneficial to shallow ground water quality.

For 3 successive years after 1993, average NO_3 concentrations in the shallow ground water rose (Fig. 5). Increases in the average NO_3–N concentration to approximately 25 mg L^{-1} in 1996 indicate concentrations were approaching premanagement levels of 30 mg L^{-1} under some management fields.

Each fall, NO_3 levels were lowest in the shallowest ground water sampler (Fig. 5), indicating that irrigation water had flushed most of the mobile NO_3 from the vadose zone, and that NO_3 concentrations in the most recent recharge were less than in the irrigation water. The latter is partially the result of uptake of NO_3 from irrigation water during the latter part of the irrigation season.

Shallow Ground Water Nitrate-Nitrogen Loading

An understanding of the controlling mechanisms and associations involved in long-term nonpoint-source shallow ground water loading are fundamental to the implementation of scientifically based management practices. During the 6 yr, seasonal average NO_3–N concentrations in the shallow (≤1.5 m) ground water at the fences downgradient of the management fields were correlated with water levels and generally were cyclic (Fig. 6a and b). With the exception of 1993, when above normal precipitation resulted in a rising water table, the water table usually declined between summer and fall measurements, and NO_3–N concentrations in most shallow ground water increased. The declines are caused by irrigation withdrawals, which begin in mid-June and generally continue through the first week of September. The irrigation water, which is primarily pumped from the bottom third of the water table aquifer and has a concentration of 30 mg NO_3–N L^{-1}, as well as the NO_3 in the irrigation water, are partially utilized by the crop. The returning irrigation water leaches additional nitrate from the soils and transports it to the aquifer. Consequently, irrigation returns tend to increase NO_3–N concentrations in the shallow ground water. Hotter and drier growing seasons like 1994 require the application of more irrigation water with a resultant increase in shallow ground water NO_3 loading.

Differences in N leaching beneath the management fields can be further elucidated by the pore-water NO_3 concentrations (Fig. 6a and b). Pore-water NO_3–N concentrations reflect the timely monitoring afforded by lysimeters, which make the instrumentation useful in predicting trends in shallow ground water NO_3 concentrations (Watts et al., 1997). Concentrations in the pore water, however, can be significantly more variable than in the shallow ground water where pore-water inputs are attenuated.

Shallow ground water quality downgradient of each management field was impacted by irrigation and nutrient management strategies as evidenced by discernable differences in correlation coefficients and the magnitude of the standard deviations of the NO_3–N concentrations (Fig. 6a and b). The R values for seasonally averaged NO_3–N concentrations vs. seasonally averaged water levels ranged from +0.28 for the surge-irrigated field (Fig. 6a) to +0.92 for the center pivot-irrigated corn field (Fig. 6b). Since physical characteristics of the unsaturated zone beneath the fields are similar, NO_3–N concentrations downgradient of each management field likely reflect not only the different water and nutrient practices, but also the presence of *hot spots* associated with sites of deep preferential percolation. The regression plots showed more variability in NO_3–N loading occurred at the surge-irrigated field than at the conventional furrow-irrigated field. The most uniform NO_3 fluxes occurred beneath the pivot-irrigated corn field where as much as 84% of the variability in NO_3–N concentrations was associated with water level. The higher average NO_3–N concentrations and the larger fluctuations in NO_3–N concentrations associated with both furrow irrigation practices suggest that center-pivot application of irrigation water is the vastly superior practice for controlling NO_3 leaching.

Peak concentrations in pore-water NO_3 were especially pronounced beneath both furrow-irrigated fields

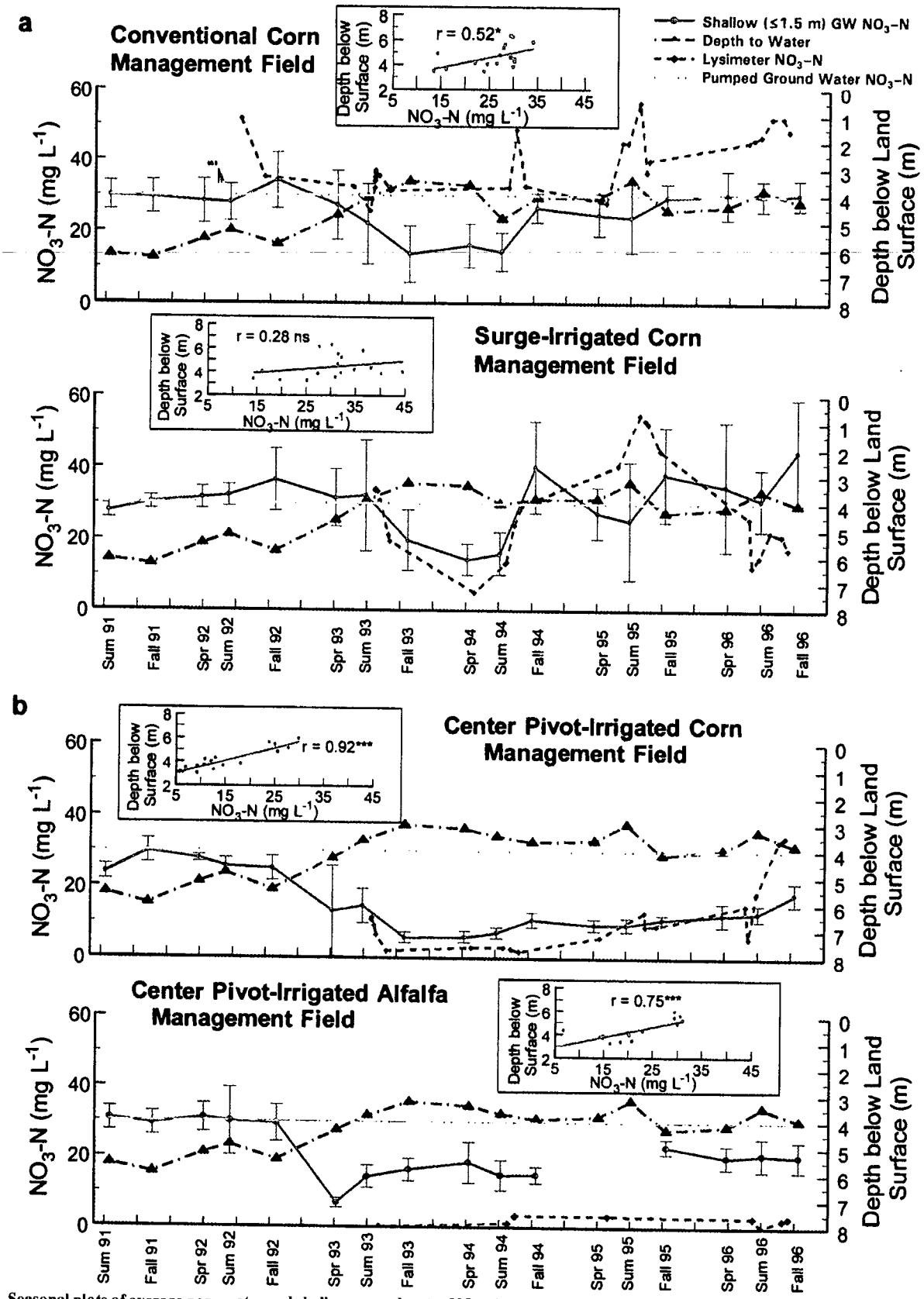

Fig. 6. Seasonal plots of average pore-water and shallow ground water NO_3–N concentrations and depth to water with inset plots of the regression line of the seasonal average shallow ground water NO_3–N concentrations vs. depth to the water table at the (*a*) furrow-irrigated and (*b*) pivot-irrigated management fields. Levels of statistical significance of *r* values are as follows: ns = not significant, * = significant at 5% level, and *** = significant at 0.1% level.

during the 1994, 1995, and 1996 growing seasons (Fig. 6a). Although Cahoon et al. (1995) documented that deep percolation occurred at the upper end of furrow-irrigated fields and also behind diked end-rows at the lower end of conventionally irrigated fields, these NO_3^- leachates were detected in the center of the fields (Fig. 2). Average pore-water NO_3–N concentrations rose approximately 20 mg L^{-1} at both fields (Fig. 6a) before the fall 1994 ground water sampling when concentrations rebounded to near or above the initial project levels of 30 mg NO_3–N L^{-1} and remained at that level for the duration of the study. At the surge-irrigated field, deep percolation of NO_3–N appeared enhanced by the preferential leaching of fertigation-applied N when the highly concentrated water ponded in furrows choked by storm-downed corn and weeds. Nitrate concentrations in ground water collected downgradient from the surge-irrigated field after the 1995 and 1996 irrigation seasons suggest that applying all or part of the N fertilizer requirement as sidedress was also detrimental to water quality (Fig. 6a). The fence downgradient of the conventional field first intercepts percolate from diked end-rows (Fig. 2) that were flooded during periods of excessive irrigation in 1996. The upgradient highly concentrated pore water appears to have been attenuated by the 30 mg NO_3–N L^{-1} recharge from excess irrigation water at the diked end-rows during ground water transport to the downgradient fence.

In contrast to the post-1993 rapid rebound in NO_3 at the fences downgradient of the furrow-irrigated fields, average shallow ground water concentrations at the pivot-irrigated corn field were considerably <10 mg NO_3–N L^{-1}, and pore-water NO_3–N concentrations remained <5 mg L^{-1} through spring 1995. Only after operator error resulted in a preplant application of an extra 22 kg N ha^{-1} before heavy spring rains in 1996 did the NO_3 levels in the pore water increase significantly (Fig. 6b). The rise in pore-water NO_3–N concentrations was accompanied by a marked increase in shallow ground water NO_3–N. Thus, a small overapplication of fertilizer N clearly was detected in the shallow ground water and caused NO_3 concentrations to rapidly exceed the MCL.

By design there were large discrepancies in total N applied to the conventional field compared with the surge and pivot-irrigated management fields (Fig. 7). On the other hand, the total amount of N applied to the surge and center pivot-irrigated management fields was quite similar. Differences in the amount of applied N were caused mostly by differences in the quantity of applied water. When irrigating corn with NO_3-contaminated water, leaching is limited by reducing fertilizer applications below recommendations, thereby causing the crop to extract N from the water. Hergert et al. (1995) suggested reducing the N recommendation for furrow-irrigated corn by the amount of N in 230 mm of irrigation water, which is less than the minimum amount of water applied by most conventional irrigators during the crop's rapid N uptake period that ends about 1 August. Irrigation applications on the conventional management field far exceeded 230 mm in all but 1993 (Table 1), the only year in which there was a reduction in shallow ground water NO_3 concentrations. Nitrogen fertilizer applications also exceeded recommendations in all but 1993. The 6-yr total fertilizer N application exceeded the amount of N removed in the grain by 438 kg ha^{-1}. Irrigation water in excess of the prescribed 230 mm was applied in 4 of 6 yr on the surge-irrigated field (Table 1); however, only in 1991 was this total exceeded before the end of the rapid N uptake period. Although N fertilizer was applied below or at recommended rates, the 6-yr total fertilizer N application exceeded the amount removed in the grain by 129 kg ha^{-1}. In theory, the expected reduction in NO_3–N leaching from the surge-irrigated field should have resulted in less adverse impact on shallow ground water than the conventional field. In practice, it did not. The surge technology was unable to adequately control leaching of N fertilizer, even when applied by split application for fertigation. In only the first year did irrigation water applied at the pivot field exceed 230 mm (Table 1). Total applied N was less than or equal to the recommended amount during the first 4 yr (Fig. 7). During the 6 yr, total applied N was only 80 kg N ha^{-1} in excess of that removed in

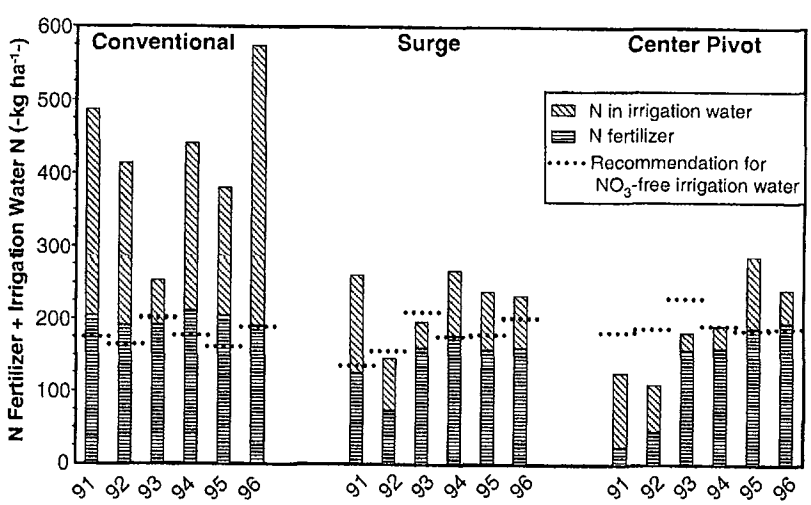

Fig. 7. Recommended N fertilizer application and N inputs from fertilizer and irrigation water for corn management fields. Recommended N for an expected yield of 12.6 Mg ha^{-1} is based upon 2% soil organic matter and residual NO_3–N in the upper 0.9 m of the root zone.

the grain, and the N application was 32% less than that on the conventional field. Thus, significant improvement in shallow ground water quality occurred only beneath the pivot-irrigated corn field.

Most year-to-year variability in grain yield was directly associated with weather (Table 2). Yields in 1992 and 1996 were outstanding while those in 1991 and 1995 were good. During the 1993 growing season, cloudy weather, excessive rainfall, and stalk breakage caused by high winds reduced corn yields to ~30% below average, while hail and high winds during the 1994 growing season stripped and knocked down the corn, reducing yields ~40%.

Even when a technology successfully reduces NO_3 leaching, farmer acceptance largely depends on yield. Yield variations ascribed to differences in management activities were not large and were sometimes misleading. The location of a tree-row partially shielded the furrow-irrigated corn, but not the center-pivot irrigated corn, from damage by wind and hail in 1994. Since the damage was preferential and not related to management differences, the yields were not used in the average yield calculations (Table 1). In 1992 the 15% reduction in yield on the pivot-irrigated field as compared to the conventional field was related to spatial variability in residual soil N and could be overcome with better knowledge of soil nuances and the use of precision fertilizer applications. An ~6% reduction in the 5-yr average yield for the pivot-irrigated management field relative to the conventional field should not adversely affect farmer acceptance, could be averted with a better understanding of the system, and was partially offset by lower fertilizer expense.

Nitrogen fertilizer was not applied to the irrigated alfalfa; however, the NO_3–N levels in the downgradient shallow ground water exceeded the MCL during all but one sampling period (Fig. 6b). The field was converted from continuous corn to a normal N_2-fixing alfalfa in 1990. Normal N_2-fixing cultivars remove about one-third less NO_3 from subsoils than do nonfixing N_2 cultivars (Blumenthal and Russelle, 1996). Reported interest in using alfalfa to remediate NO_3-contaminated soils has continued for the past 40 yr (Allos and Bartholomew, 1959; Stewart et al., 1968; Peterson and Russelle, 1991). Alfalfa can be very deep-rooted (Jodari-Karimi et al., 1983) and has been reported to remove water and N from 4-m deep capillary fringe zones (Lipps and Fox, 1964). By Fall 1992, the 3 yr old alfalfa roots probably reached the capillary fringe about 6 m beneath the surface. After the initial vadose zone inundation in Spring 1993, water table rises of >2 m during the next three successive sampling periods were accompanied by increases in average downgradient NO_3–N (Fig. 6b). The number of lysimeter samples collected beneath the alfalfa field was sparse because there was insufficient pore water for NO_3–N analysis during several sampling periods. However, when the volume of pore water was adequate, the NO_3–N concentrations did not exceed 5 mg L^{-1}. Thus, the NO_3 in the irrigation return flows appears to be removed in the shallow root zone and is not a significant contributor to the ground water contamination. This suggests that the N source must be deeper in the vadose zone, where water-logged alfalfa roots and nodules decayed and released substantial amounts of N after the water table rose. In alfalfa-dominated areas, shallow ground water NO_3 contamination has been reported by the Minnesota Pollution Control Agency (1998) and Robbins and Carter (1980), who reported significant levels of NO_3 from the mineralization of root material.

CONCLUSIONS

Well-designed and instrumented sites with MLSs give a clear indication of the impact of management changes on nonpoint-source–impacted shallow ground water quality. Nitrate concentrations in samples collected from lysimeters and MLS networks together with $^3H/^3He$ age dating of water at the Nebraska Management Site Evaluation Area indicated that weekly movement of N in the unsaturated zone was detectable, as were season-to-season changes in shallow ground water NO_3 concentrations. Fluctuations in pore-water NO_3 concentrations were more extreme than those in the more integrated shallow ground water.

The results demonstrate that the conversion from furrow to well-managed sprinkler irrigation would significantly benefit shallow ground water quality in the central Platte region and other corn-growing areas in the western USA. Uniform water application and the ability to apply supplemental N on an as-needed basis through fertigation substantially controlled NO_3 leaching beneath the pivot-irrigated management field. Farmers should be encouraged to adopt center pivot or linear spray irrigation techniques and best nutrient and water management practices to lower and maintain ground water NO_3 at or near compliance levels. It is recognized that water quality improvements will require a serious effort and probably include strategies for setting slightly lower yield goals and increasing crop use of NO_3 in irrigation water.

Surge irrigation was unable to satisfactorily limit NO_3–N leaching, negating any inherent water quality benefits of applying less water and N.

Although the sprinkler-irrigated alfalfa field did not receive N fertilizer during the 6-yr study, NO_3 concentrations in the shallow MLSs downgradient of the field showed there was significant leaching. The leaching appears to be associated with the age of the alfalfa and the timing of the rise in the water table that initiated root and nodule decay, releasing N to the shallow ground water.

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