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Long-Term Observations of Vadose Zone and Groundwater Nitrate Concentrations under Irrigated Agriculture

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Proper N management for agricultural production is critical to minimize groundwater contamination with NO_3. For 18 yr, research was conducted to observe NO_3–N concentrations in the vadose zone, groundwater, and subsurface drainage under sprinkler-irrigated, primarily corn (*Zea mays* L.) production. Potato (*Solanum tuberosum* L.) and soybean [*Glycine max* (L.) Merr.] were also grown intermittently on the site. The lysimeter leachate NO_3–N concentration increased to 156 mg L^{-1} under corn production within 1 yr after the initiation of irrigation (at the onset of the study), then decreased to <10 mg L^{-1} during a 6-yr period of best-management N fertility management for corn. The average yearly lysimeter NO_3–N concentration fluctuated between 8 and 117 mg L^{-1} during the study. Nitrate concentrations in the shallow groundwater followed a similar time series trend as leachate concentrations, but with lower concentrations and lagging about 1 yr. Subsurface drainage NO_3–N concentrations were much lower but followed the same trend as the shallow groundwater. An N balance indicated higher net N mineralization after the initiation of irrigation and the years after potato production. Fertilizer N application rates and yearly weather conditions, which affected crop vigor and N uptake, combined to affect the fall residual soil NO_3. Fall soil NO_3 from 0- to 1.8-m depth was the most significant factor influencing the leachate NO_3–N concentration each year during the study (r^2 = 0.76).

Abbreviations: GDD, growing degree days; NBAL, nitrogen balance.

The continued demand for higher crop yields and the relatively low cost of N fertilizer per unit of yield increase has resulted in increased NO_3–N concentrations in the groundwater, especially in areas with coarse-textured soils and shallow groundwater. An increased level of NO_3–N in the groundwater is not a locally confined problem, however, as NO_3–N from agricultural sources in the Midwest has been linked to problems as far reaching as the hypoxic zone in the Gulf of Mexico (Burkart and James, 1999). Excess NO_3–N entering the groundwater and surface water from agricultural areas is the result of a number of factors. In the most basic sense, NO_3–N concentration increases in the vadose zone and groundwater because there is more N in the system than can be utilized by an actively growing crop or otherwise immobilized. Numerous studies have reported higher NO_3–N leaching and higher soil test N with higher N fertilizer application rates compared with reduced input management.

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Andraski et al. (2000) reported suction cup lysimeter NO_3–N concentrations <10 mg L^{-1} when N application was below the economic optimum N rate (EONR) but >20 mg L^{-1} when N application was above the EONR. Angle et al. (1993) measured soil N levels of 8.7 mg kg^{-1} when 260 kg ha^{-1} was applied compared with only 2.5 mg kg^{-1} with no fertilizer applied. Martin et al. (1994) found 106 kg ha^{-1} less NO_3 leaching when using a split application of 126 kg ha^{-1} compared with a 232 kg ha^{-1} preplant application.

Several studies have found that higher than optimum irrigation rates or excessive rainfall after irrigation caused an increase in NO_3–N leaching on sandy soils. Errebhi et al. (1998) reported that NO_3–N leaching increased by 35% when the fertility rate was increased from 0 to 135 kg N ha^{-1} in a normal year, compared with an increase of 157% in a year with heavy rains in the growing season. Gehl et al. (2005) found that an irrigation rate of 1.25 times the optimum resulted in 64 kg N ha^{-1} more leaching than the optimum irrigation rate. Gentry et al. (1998) reported higher tile drain NO_3–N losses (64 vs. 38 kg N ha^{-1}) when soil NO_3–N was high after a poor corn-growing season, emphasizing the influence of the weather on NO_3–N leaching.

High soil NO_3–N levels, leading to increased N losses in subsurface drainage and groundwater, have been shown to result from increased mineralization of soil organic N during periods of favorable soil temperature and moisture conditions. Albus and Knighton (1998) indicated an increase in shallow groundwater NO_3–N concentration from 13 to 40 mg L^{-1} 29 mo after irrigation was initiated on a previously unirrigated site, and Cambardella et al. (1999) reported soil NO_3–N values of

100 kg ha^{-1} in an autumn with soil moisture and temperature conditions favorable for mineralization, compared with <50 kg N ha^{-1} when fall conditions were unfavorable. In addition, different crops vary in their effectiveness at utilizing the available soil N, which increases the risk of leaching. Errebhi et al. (1998) indicated that NO_3–N leaching is very prevalent under potato, and Stites and Kraft (2001) found that an amount of NO_3–N equivalent to 70% of the fertilizer N leached to the groundwater in their study under potato. Row crops such as corn and soybean have been shown to result in higher tile drain NO_3–N concentrations (32 and 24 mg N L^{-1}, respectively) than alfalfa and alfalfa–grass mixtures (2 mg N L^{-1}) (Randell et al., 1997). Also, Klocke et al. (1999) showed higher NO_3–N concentrations under a corn–soybean rotation (42 mg L^{-1}) than under continuous corn (24 mg L^{-1}).

A number of methods have been used to monitor NO_3 in the soil, soil water, and groundwater. Angle et al. (1993) took deep soil cores to quantify the amount of NO_3–N leached beyond the corn root zone. Andraski et al. (2000) and Gehl et al. (2005) used porous cup solution samplers to obtain point measurements of soil water NO_3–N concentrations. Lysimeters, which encompass a larger area than solution samplers, provide a means to directly measure water flux as well as NO_3–N concentrations in the vadose zone to accurately quantify the NO_3–N mass lost beyond the crop root zone (Klocke et al., 1999; Martin et al., 1994; Rasse et al., 1999). Wells installed to extract water from the saturated zone have been used to monitor NO_3–N concentrations at various depths in a shallow aquifer (Spalding et al., 2001). Others have utilized subsurface or "tile" drains to characterize the NO_3–N loading to groundwater on a field or watershed scale (Gentry et al., 1998; Kladivko et al., 2004). The vast majority of previous studies were conducted during a relatively short time span (2–6 yr) and usually determined NO_3–N leaching with only one type of measurement, e.g., soil cores, soil solution samplers, or tile drains.

The purpose of this study was to summarize multiple long-term data series of NO_3–N concentrations in the vadose zone, shallow groundwater, and subsurface drainage under irrigated row crop production to determine the major factors influencing NO_3 leaching across multiple management practice periods and to evaluate a multiyear N balance.

Materials and Methods

Site Description

The study site was located in southeastern North Dakota (46.05° N, 98.11° W) on a 64-ha field, of which 43 ha were irrigated with a center pivot irrigation system since 1989. The Order 1 soil survey indicated that the soil at the site was predominantly Hecla loamy fine sand (sandy, mixed, frigid Oxyaquic Hapludoll) on the south portion of the field and Wyndmere fine sandy loam (coarse-loamy, mixed, superactive, frigid Aeric Calciaquoll) and Stirum fine sandy loam (coarse-loamy, mixed, superactive, frigid Typic Natraquolls) on the north portion of the field. The slightly saline–sodic soil conditions on the north side of the field resulted in reduced crop vigor in nearly every season. Limited samples taken at the beginning of the study indicated total soil C of 15.8 g kg^{-1} and 18.7 g kg^{-1} organic matter in the plow layer.

Water Quality Monitoring

Instruments to monitor the water quality of the vadose zone and saturated zone were installed along two transects dividing the north and south halves of the field (Fig. 1). The instrumentation included 16 large soil core lysimeters (Derby et al., 2002), four reconstructed profile lysimeters, 18 shallow groundwater-monitoring wells, and two subsurface drains. The soil core lysimeters were 0.6-m-diameter polyvinyl chloride (PVC) cylinders containing intact soil cores and extending to a depth of 1.8 m. They were instrumented to collect a combination of vacuum extractor and free drainage. The disturbed profile lysimeters were rectangular steel boxes with a cross-sectional area of 1.86 m^2 filled with repacked soil layers and extending to a depth of 1.8 m. They were instrumented to collect free drainage. Both types of lysimeters were buried such that the tops were 0.36 m below the soil surface and the drainage collection lines came to the surface 7.6 m away at an access trail to allow normal farming practices to continue. Two lysimeters in the northwest part of the field were not sampled after 1992 and 1993 due to possible leaks allowing groundwater to enter the drainage collection reservoirs directly. The other two lysimeters in the same part of the field were not sampled after 2004, also due to possible leaks. Because of changes in the research and budgetary constraints, the two reconstructed lysimeters on the south side of the field were not sampled from 1998 through 2002 or after 2004.

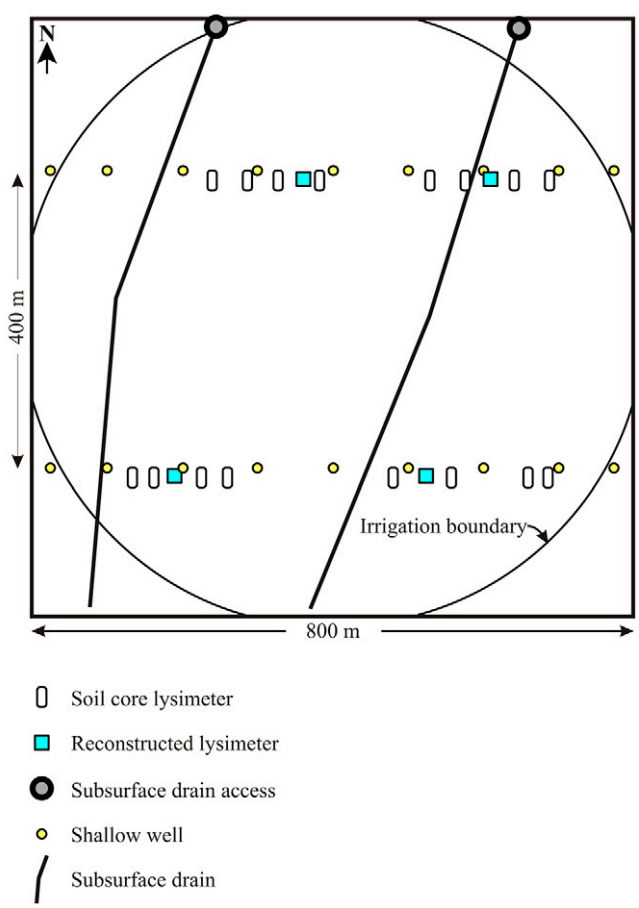

Fig. 1. Map of research field showing location of lysimeters and groundwater monitoring wells.

The wells were 5-cm-diameter PVC pipe with a 0.9-m slotted section of well screen at the bottom to collect water samples from the upper layer of the groundwater. The well screens were placed at a depth to allow samples to be drawn from the upper 0.3 m of the groundwater; however, fluctuations in water table during the study resulted in samples being drawn from the entire 0.9-m screened interval at times. The average depth of the top of the well screens below the soil surface was 2.4 m. The subsurface drains (Fig. 1) did not extend up gradient (south) past the boundary of the research field and only collected water from the site. A detailed description of the instrumentation is provided by Casey et al. (2002) and Derby et al. (1997).

Water samples were taken weekly or bimonthly from the lysimeters during the non-winter months (April–October) for most of the study period. Water table elevation was recorded and water samples were taken from the wells monthly during the non-winter months and periodically during the winter from 1990 to 1995, then less frequently after 1995. All water samples were acidified in the field with H_2SO_4 and refrigerated or frozen until NO_3– plus NO_2–N analysis by Cd reduction (USEPA, 1983) could be performed. Nitrite-N was only measured in very low concentrations so NO_3– plus NO_2–N is included in total NO_3–N values.

Soil and Plant Sampling

Soil cores for NO_3–N were taken immediately adjacent to the lysimeters. Samples were taken between rows with a hydraulic probe to a depth of 0.9 m in the spring before sidedress N application and to 1.8 m after harvest from 1990 to 1995. After 1995, samples were only taken after harvest to a depth of 1.8 m. The soil samples were placed in plastic bags and frozen until analysis could be performed. From 1990 to 1995, the field-moist samples were extracted with 2 mol L^{-1} KCl, which was then analyzed by the U.S. Bureau of Reclamation water lab in Bismarck, ND, for NO_3–N colorimetrically by automated Cd reduction (USEPA, 1983). After 1995, the soil samples were air dried, extracted with water containing a small amount of $CaSO_4$ to promote flocculation, and analyzed for NO_3–N by the North Dakota State University Soil Testing Lab in Fargo, using an ion-specific electrode. The fact that different methods of soil NO_3 determination were used should not be a concern. Gelderman and Beegle (1998) stated that any variations in soil NO_3–N due to laboratory method are of little importance compared with variations due to other factors, such as field sampling techniques.

In most years, the entire area over the lysimeters (one 61-cm row over the soil core lysimeters and four 122-cm rows over the reconstructed lysimeters) were hand harvested and crop yield as well as total plant N uptake was determined. Plant samples were oven dried and ground in a Wiley mill to pass a 2-mm sieve. Total N was determined using the H_2SO_4–salicylic acid Kjeldahl method to include NO_3–N (Bremner and Mulvaney, 1982). For 3 yr when hand harvesting was not done (1999 on the north and 1999, 2001, and 2002 on the south), an average yield was determined from mechanically harvested adjacent areas and N uptake was estimated from linear regression of yield and N uptake data from other years (data not shown). The linear regressions of yield and crop N uptake had r^2 = 0.87, 0.80, and 0.73 for corn, soybean, and potato, respectively.

Agronomic Practices

Before 1989, the field was primarily in a dryland corn–fallow rotation. Starting in 1989, center-pivot sprinkler irrigation was begun and corn was grown on the field until 1996. After 1996, potato or soybean was grown some years instead of corn. A detailed cropping and fertilizer history is included in Table 1.

From 1990 to 1995, research personnel directed fertilizer and irrigation application as part of a best management practices project for improved irrigation and N use efficiency. The research goals of the project emphasized reduced N fertilization and careful irrigation scheduling based on real-time soil matric potential measurements, water balance, and estimates of plant-extractable soil water (Steele et al., 2000). Nitrogen fertility was based on modified North Dakota State University (NDSU) extension recommendations (Dahnke et al., 1992) of supplying approximately 1.12 kg N ha^{-1} for every 62.8 kg ha^{-1} of expected yield and subtracting the spring 0- to 0.9-m soil test N from the amount to be applied. Yield goals between 9416 and 10,044 kg ha^{-1} and preplant or presidedress soil test values were used. A small amount (13 kg ha^{-1}) of N as monoammonium phosphate was applied during planting and the remainder of the recommendation was applied as either urea or urea–NH_4NO_3 at the six- to eight-leaf stage of the corn. Urea–NH_4NO_3 was applied to the 12-row buffer areas between the lysimeters for the entire length of the field. Fertilizer was applied either by hand or with small plot equipment directly over the lysimeters to maximize application accuracy. The farmer fertilized the majority of the field with anhydrous NH_3 at approximately the same rate as the application to the lysimeter area, also at the six- to eight-leaf stage.

After 1995, all decisions regarding fertilizer management, irrigation scheduling, and crop rotation were returned to the farmer cooperator, except in 2001 to 2004 on the north side of the field, where variable-rate N application for precision agriculture was used (Derby et al., 2007). The variable N rates were delineated by zones determined by historical yield, topography, and apparent soil electrical conductivity, and urea was broadcast applied preplant.

The fertilizer rates used by the farmer were generally higher than those recommended for best management practices (Table 1), either because he did not follow the NDSU extension recommendations or used a higher yield goal. Fertilizer N was applied in a number of forms including broadcast or banding of various dry formulations, injection of anhydrous NH_3, and fertigation with urea–NH_4NO_3 through the irrigation system. The bulk of the fertilizer was applied at the six- to eight-leaf stage for corn and in multiple split applications coordinated with the hilling operations for potato. Application of fertilizer over the lysimeters was done as part of the normal field operations after 1995.

Nitrogen Balance Calculations

An accounting of N in the plant–soil–leachate system was done by calculating N inputs and outputs. Inputs were spring soil NO_3–N and fertilizer N. Outputs were plant N, leachate N, and fall residual soil NO_3–N. Applied N was the total of all fertilizer N applied. Nitrogen balance (NBAL) was the difference between N inputs and N outputs. The spring soil NO_3–N totals to the 1.8-m depth (Table 1) were either (i) the spring 0- to 0.9-m soil N values plus the 0.9- to 1.8-m soil N values from after harvest the previous year (1990–1995) or (ii) the total NO_3–N in the

Table 1. Cropping history of research area and N fertilizer application history of north and south lysimeter areas.

Year	Crop	Soil NO_3–N†	Preplant or starter N	Sidedress or broadcast N	Fertigation N	Total N application	Formulation‡	Yield
		kg ha^{-1}						kg ha^{-1}
				North lysimeters				
1990	corn	277	13	56	0	69	urea	6,280
1991	corn	129	13	112	0	125	urea	9,440
1992	corn	153	13	90	0	103	urea	8,180
1993	corn	75	13	135	0	148	urea	6,310
1994	corn	65	48	73	0	121	UAN	6,350
1995	corn	36	11	168	0	179	UAN	10,750
1996	potato	34	53	199	0	252	urea	31,540
1997	corn	127	18	168	67	253	AA	12,610
1998	corn	245	24	134	45	203	AA	8,700
1999	potato	118	71	0	135	206	UAN	39,240
2000	soybean	75	11	0	0	11	starter	2,050
2001	corn	74	11	105	56	172	urea	12,620
2002	corn	52	11	122	84	207	urea	10,140
2003	corn	50	12	161	84	257	urea	10,260
2004	corn	170	10	147	67	224	urea	8,120
2005	potato	157	0	331	38	369	urea	45,680
2006	corn	131	95	0	25	120	urea	9,800
				South lysimeters				
1990	corn	484	13	56	0	69	urea	8,720
1991	corn	309	13	112	0	125	urea	12,570
1992	corn	144	13	90	0	103	urea	10,330
1993	corn	87	13	135	0	148	urea	7,720
1994	corn	121	48	73	0	121	UAN	10,920
1995	corn	67	11	168	0	179	UAN	12,470
1996	potato	52	53	199	0	252	urea	37,440
1997	corn	88	10	168	67	248	AA	12,230
1998	corn	192	24	134	45	203	AA	12,020
1999	potato	338	71	0	135	206	UAN	39,240
2000	corn	97	11	157	84	252	AA	12,760
2001	soybean	263	11	0	0	11	starter	3,970
2002	corn	151	11	140	84	235	AA	11,740
2003	corn	151	12	135	84	231	AA	11,670
2004	corn	249	10	140	67	217	AA	10,690
2005	potato	187	0	331	38	369	urea	46,210
2006	soybean	141	5	0	0	5	starter	4,000

† Soil NO_3–N from 0- to 1.8-m depth. Soil NO_3–N for 0.9- to 1.8-m depth from the previous fall was added to the spring 0- to 0.9-m depth soil NO_3–N for 1990–1995. After 1995, the 0- to 1.8-m depth soil NO_3–N is from the previous fall soil sample.

‡ The formulation of the majority of fertilizer applied to the lysimeter areas. Urea is urea or another dry formulation broadcast; UAN is urea–NH_4NO_3 injected beside the row in 1994 and 1995 or by fertigation in 1999; AA is anhydrous NH_3 knifed between rows; Starter is only starter fertilizer applied during seeding of soybean.

0- to 1.8-m depth sampled after harvest the previous year plus 20 kg ha^{-1} (1996–2006). Twenty kilograms NO_3–N per hectare was added because that was the average change in soil NO_3–N in the upper 0.9 m from the after-harvest soil sampling the previous year to the spring soil sampling in years 1990 to 1995. It was assumed that very little change in soil NO_3–N occurred during the winter at 0.9 to 1.8 m. Swenson (1975) measured minimal change in 0.9- to 1.8-m soil NO_3–N concentrations from fall to spring at six North Dakota locations. Minimal drainage was measured from the lysimeters during the winter months, implying that NO_3–N leaching was not occurring. Plant N removal was the total N of all aboveground plant material for corn and soybean, and vines and tubers for potato. Leachate N loss was calculated by multiplying the NO_3–N concentration in the lysimeter leachate by the drainage volume. Fall soil N was the sum of NO_3–N in the 0- to 1.8-m soil depth measured after harvest.

Statistical Analysis

Statistical analysis was performed with JMP IN software (SAS Institute, 2005). Mean NO_3–N concentrations for each sampling date within years and mean yearly drainage, precipitation plus irrigation, and NO_3–N concentrations were compared using Student's *t*-test to determine if changes in concentration with time were significant ($\alpha = 0.05$).

Individual linear regression and one-way ANOVA were used to determine the relationship of yearly lysimeter NO_3–N concentration and NBAL to a number of variables. The variables tested in the analysis with lysimeter NO_3–N concentration were yearly precipitation and irrigation amounts, seasonal cumulative growing degree days (GDD), GDD for April to May and September to October, April to May and September to October average temperature, April to May and September to October rainfall, spring and fall soil NO_3–N (0–1.8 m), applied fertilizer N, fertigation N, fertilizer formulation, crop, crop N uptake, and yield. The variables included for analysis with NBAL were GDD, crop, precipitation and irrigation, fertilizer formulation, fertigation, and

yield. The soil N, applied N, and crop N were not included in these analyses because they were used in the calculation of NBAL. The analysis was also performed using the previous year's values to ascertain if there was a significant lag effect of the variables on NO_3 concentration or NBAL the following year. Bivariate and ANOVA results were interpreted to indicate factors significant at the $\alpha = 0.05$ level in the determination of leachate NO_3–N concentration and NBAL.

Results and Discussion

Lysimeter Drainage

Yearly rainfall, rainfall plus irrigation, and drainage totals are shown in Fig. 2. During the study, the average amount of water supplied by rainfall plus irrigation fluctuated between 370 and 806 mm. Cool, wet growing seasons resulted in low amounts of irrigation (1992 and 1993). The lysimeter drainage was consistently higher by an average of 127 mm on the north side of the field than the south side, even though the amount of total water input was usually not significantly different. A possible explanation is that the soil conditions on the north side, i.e., salinity and sodicity, gave rise to lower crop vigor, resulting in lower yields and lower water use efficiency. The only exception was 2000, when drainage was lower on the north than on the south. In 2000, soybean was grown on the north side of the field and the farmer cooperator scheduled significantly less irrigation for the soybean than for corn, resulting in lower drainage amounts. During the study, drainage on the north and south sides of the field averaged 53 and 31% of total water input, respectively.

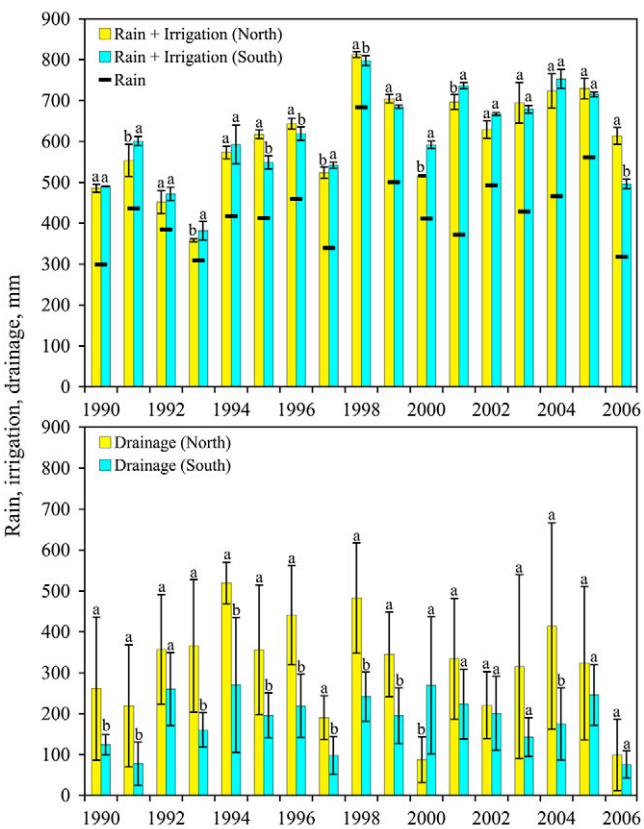

FIG. 2. Rainfall, irrigation, and lysimeter drainage totals for each year on the north and south sides of the field. The error bars indicate ±1 standard deviation. Values within each year with the same letter are not statistically different at $\alpha = 0.05$.

Vadose Zone Leachate Nitrate

Nitrate concentration measured in the leachate from the lysimeters on the north and south sides of the field is shown in Fig. 3. The between-year and within-year trends discussed here are statistically significant at $\alpha = 0.05$.

Lysimeter sampling was started in September 1989, nearly an entire growing season after irrigation was started. The initially high NO_3–N concentration in the leachate leaving the corn root zone was attributed to mobilization of high residual soil N from dryland agriculture and increased N mineralization due to favorable soil moisture conditions (Casey et al., 2002) and was reflected in the high spring soil test N (Table 1). The high concentration results were unexpected given the very conservative N application rates used based on best management practices. In 1991, the concentration started to drop to what appeared to be a sustainable level in 1993 to 1995, approaching the USEPA's drinking water maximum contamination level (MCL) of 10 mg L^{-1}. This suggests that the low N rates (Table 1) used during this time period were successful in reducing N losses

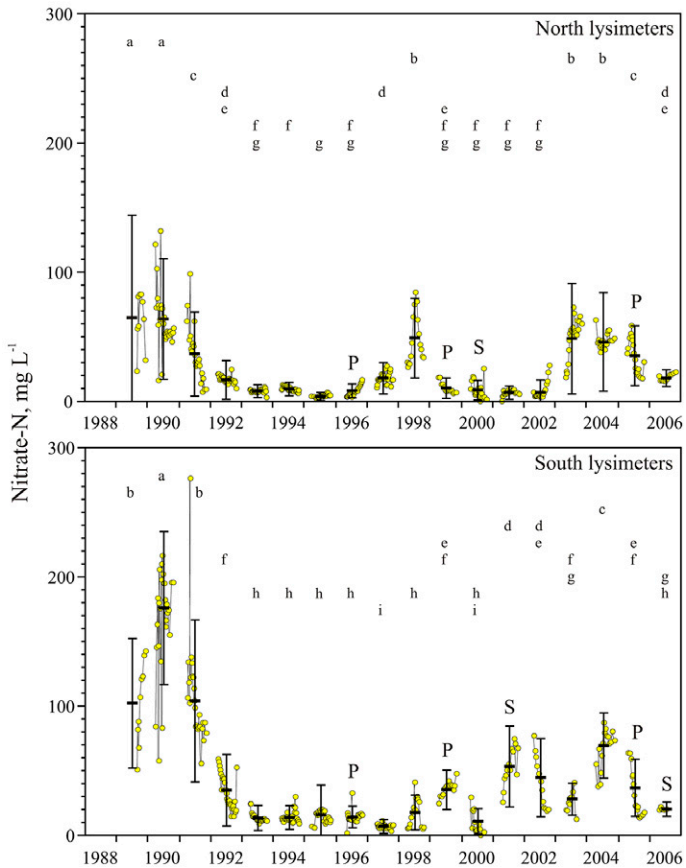

FIG. 3. Nitrate-N concentration in the vadose zone measured in soil core lysimeters and reconstructed lysimeters on the north and south sides of the field. Circles indicate mean NO_3–N concentrations for all lysimeters sampled on a given date. Heavy black lines indicate yearly mean concentrations. The error bars indicate ±1 standard deviation. Yearly mean concentrations with different lowercase letters for each side of the field are significantly different ($P < 0.05$). The large bold letters indicate the crop that was grown that year: P, potato; S, soybean; no letter, corn.

to the groundwater, regardless of differences in soil type from the north to the south parts of the field, even though corn yields were consistently higher on the south half of the field (Table 1) due to more favorable soil conditions.

Very little change in average NO_3–N concentration was seen in 1996 when management was turned back over to the farmer and potato was planted for the first time. The concentrations started to increase slightly midway through the year on the north side, however, presumably indicating the leaching of the fertilizer that was applied in 1996. Based on other studies that indicate that NO_3–N leaching can increase under potato production depending on N rates and the intensity of rainfall (Errebhi et al., 1998; Prunty and Greenland, 1997), it was surprising to observe very little change in lysimeter NO_3–N concentrations in 1996, the first year of potato production, when 252 kg N ha^{-1} was applied. For that matter, lysimeter NO_3–N did not increase from the previous year for any year when potato was grown, except for 1999 on the south side of the field. Also, NO_3–N did not increase in the years following potato production, except for 1997 on the north.

Nitrate concentrations were again near the MCL under the potato and soybean cropping practices on the north side in 1999 and 2000, as well as during the first 2 yr (2001–2002) of a precision agriculture project. In 2001 to 2004, variable-rate N application based on management zones took place only on the north side of the field and low yearly average concentrations were maintained during 2001 to 2002. Concentrations increased between 29 July and 15 Oct. 2002, however, indicating that the 207 kg ha^{-1} of applied N (Table 1) was in excess of crop demand and was starting to leach past the root zone. The concentrations for 2001 and 2002 were dramatically higher where zone-managed N application was not used (the south side of the field). Even though only 11 kg ha^{-1} of starter N was applied to the south soybean crop in 2001, the NO_3–N concentration of the leachate was steadily increasing throughout 2001 and was steadily decreasing throughout 2002. This indicated that the NO_3–N leaching in 2001 on the south side was probably from N applications to the corn in 2000. Past lysimeter studies conducted within 2.5 km of this site with the same soil type indicated that it took about 1 yr for NO_3–N to pass through the soil to a depth of 2.3 m (Prunty and Greenland, 1997; Prunty and Montgomery, 1991). That was corroborated by an accidental application of a high rate of N to one of the reconstructed lysimeters on this site on 14 June 1994, after which a substantial spike in NO_3–N was observed on 11 May 1995. Average NO_3–N concentrations were high (nearly 50 mg L^{-1}) again in 2003 and 2004 on the north side, as higher N rates approaching 260 kg ha^{-1} resulted in NO_3–N leaching. Also, the weather conditions in 2003 and 2004 were not ideal for crop growth, as a windstorm in 2003 broke off as many as 50% of the plants in certain areas of the field and crop growth was affected by below-normal growing season temperatures in 2004 (Derby et al., 2007). This resulted in poor fertilizer N utilization and high residual soil N levels. Nitrate-N concentrations decreased during 2005 and then did not change significantly during 2006 on both sides of the field. The decrease observed in 2005 and the low concentrations in 2006 were surprising, considering that 369 kg N ha^{-1} was applied to the potato crop in 2005.

Statistical analysis was performed to determine the relationship of the yearly average lysimeter NO_3–N concentration to the parameters listed above. For this analysis, the north and south sides were not analyzed separately since there was no significant difference between the sides with respect to mean NO_3–N concentration ($P = 0.16$). Only soil N and late-season precipitation values were found to be significant at the $\alpha = 0.05$ level. The P values for these relationships are included in Table 2. Since the spring soil N values were essentially the same as the previous fall soil N values, fall soil N was used along with the previous September to October precipitation values and the fall soil N × previous September to October precipitation interaction to develop a linear model to predict the lysimeter NO_3–N concentrations during the study period. A plot of yearly average lysimeter NO_3–N concentrations vs. the concentrations predicted from the linear model is shown in Fig. 4. Interestingly, the slope of the relationship between NO_3–N concentration and the previous September to October precipitation was negative, indicating that the wetter it was in the fall, the lower the average NO_3–N concentration measured in the lysimeters the following year. This relationship may be due to denitrification losses resultant from wet soil conditions in the fall. This analysis indicated that the residual soil NO_3–N was the most important factor in controlling the NO_3–N concentration in the soil water leaving the crop root zone ($r^2 = 0.76$). The mass of NO_3–N lost through the leachate was also linearly related only to the previous fall soil NO_3–N ($r^2 = 0.32$, $P = 0.0005$).

Bivariate analysis was also performed to determine the relationship of fall soil N to the many factors listed above, the significant results of which are also included in Table 2. Factors found to be significant were related to early- and late-season temperature, crop N uptake, applied N, and the formulation of the fertilizer. The general linear model containing all of the factors related to fall soil N listed in Table 2 resulted in an r^2 of 0.82 with a P value of <0.0001. The estimates for the previous

Table 2. Selected bivariate analysis results for average annual NO_3–N concentrations and fall soil N.

	Bivariate fit of	df	*P* value
Lysimeter NO_3–N by	spring soil N	33	<0.0001
	previous spring soil N	31	0.0023
	previous fall soil N	33	<0.0001
	previous Sept.–Oct. precipitation	33	0.0483
Well NO_3–N by	lysimeter NO_3–N	33	0.4263
	previous lysimeter NO_3–N	31	0.0155
	tile drain NO_3–N	33	0.0014
Tile drain NO_3–N by	lysimeter NO_3–N	33	0.8214
	previous lysimeter NO_3–N	31	0.0058
	2 yr previous lysimeter NO_3–N	29	0.0006
	previous well NO_3–N	31	0.0351
Fall soil N by	previous early growing degree days	31	0.0022
	previous avg. temperature	33	0.0312
	previous Apr.–May temperature	33	0.0034
	Sept.–Oct. temperature	33	0.0331
	crop N uptake	33	0.0328
	previous crop N uptake	31	0.0055
	previous applied N	33	0.0470
	fertilizer formulation	33	<0.0001
	fertigation-applied N	33	0.0251
	previous fertigation-applied N	31	0.0229

season temperature factors had negative slopes, while the remaining factor estimates had positive slopes. Within the formulation factor, the fall soil N estimates were 231, 112, 99, and 67 kg N ha^{-1} for anhydrous NH_3, urea, starter, and urea–NH_4NO_3, respectively.

The lack of direct correlation between leachate NO_3–N concentrations or N loss and the variables other than the previous fall soil N was surprising. Obviously, factors such as crop N uptake, fertilization, temperature, seasonal precipitation and irrigation amounts, and soil type have an effect on NO_3–N leaching. At this site, however, these factors had very little direct, statistically significant influence on yearly leachate NO_3–N concentration during the 18-yr study, but did combine to affect the soil residual N.

Groundwater Nitrate

Nitrate concentration in the upper 0.3 to 0.9 m of the groundwater on the north and south sides of the field is shown in Fig. 5. Samples from the wells in the winter of 1988 indicated an average background level concentration before initiation of irrigation of about 10 mg L^{-1} on the north and <2 mg L^{-1} on the south. After the onset of irrigation in 1989, the concentration began to increase on both sides of the field until 1991 and 1992. The concentration time-series profile was very similar to that measured in the lysimeters (Fig. 3) but the peak in concentration was lower, about 1 yr later, and more spread out than that measured in the lysimeters. The 1-yr lag was verified statistically by the significant relationship of the average annual groundwater (well) NO_3–N concentrations to the previous year's lysimeter NO_3–N concentrations, while the well and lysimeter concentrations within the same year were not related significantly (Table 2). Casey et al. (2002) attributed the lag and spreading of the peak to hydrodynamic dispersion and the lower concentrations to NO_3–N reduction.

The within-year increases were significant at $\alpha = 0.05$ for 1989 on the north and 1989 and 1990 on the south. The increase from 26 to 51 mg L^{-1} on the south in 1991 was significant, as was the decrease from 39 to 21 mg L^{-1} on the north in 1993. All other within-year changes in concentration were not statistically significant. The effects of the conservative N rates applied during 1990 to 1995 (average of 124 kg ha^{-1}) were also evident in the shallow groundwater, as NO_3–N concentrations began to drop in 1993 to 1995, after the initial flush of excess NO_3–N from the soil profile. Concentrations fell below 10 mg L^{-1} in 1997 and then started to increase again in response to higher N application rates (Table 1). The 1-yr lag between the lysimeters and wells was again evident in 1999 in the north side NO_3–N concentration peaks, corresponding to the peak in 1998 for the lysimeters.

On the north side, mean concentrations of about 5 mg L^{-1} were observed during the first 2 yr of zone N management when N application was reduced (Table 1). When N rates on the north side were increased again in 2003 to 2005, the NO_3–N concentration in the shallow groundwater increased yearly to an average of 22 mg L^{-1} in 2005. The fluctuations in NO_3–N concentrations between 1998 and 2006 on the south side were not significant ($\alpha = 0.05$).

Water table depths were also measured at the time of sample collection (data not shown). During the study, the water table

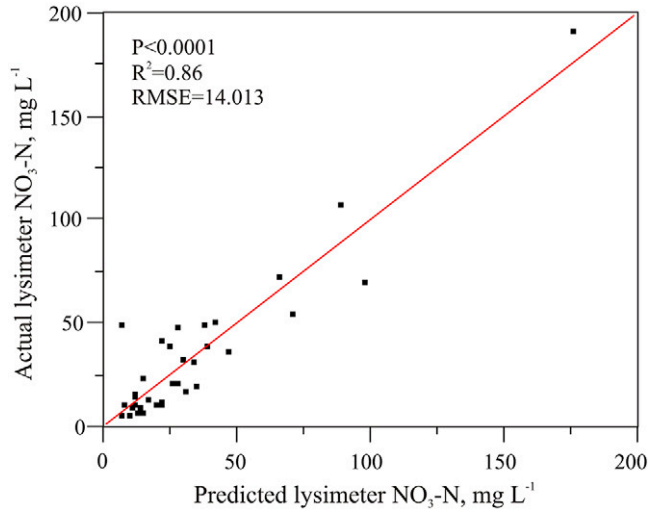

FIG. 4. Plot of actual vs. predicted lysimeter NO_3–N concentration from regression model including previous fall residual soil NO_3–N from 0- to 1.8-m depth, previous September and October precipitation, and their interaction.

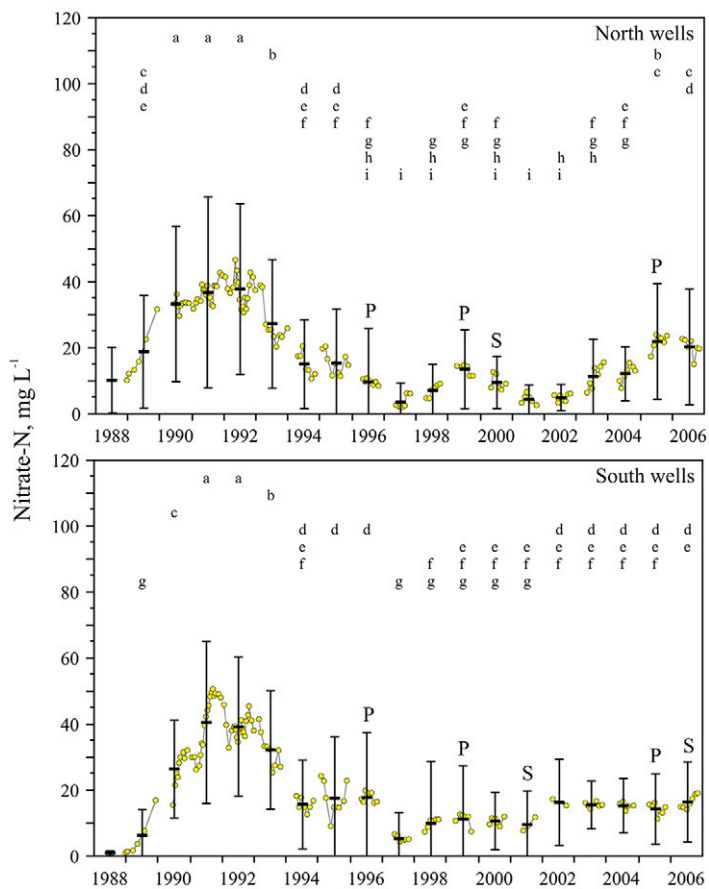

FIG. 5. Nitrate-N concentration in the groundwater measured at shallow wells on the north and south sides of the field. Circles indicate mean NO_3–N concentrations for all wells sampled on a given date. Heavy black lines indicate yearly mean concentrations. The error bars indicate ±1 standard deviation. Yearly mean concentrations with different lowercase letters for each side of the field are significantly different ($P < 0.05$). The large bold letters indicate the crop that was grown that year: P, potato; S, soybean; no letter, corn.

elevation increased an average of 0.3 m, from 395.2 to 395.5 m above mean sea level (r^2 = 0.12, n = 124, P < 0.0001). Overall, there was a slightly negative trend in groundwater NO_3–N concentrations as the water table increased (r^2 = 0.18, n = 124, P < 0.0001). This phenomenon can be explained by the fact that there was stratification of NO_3–N near the surface of the groundwater at this site. Olson (1992) measured NO_3–N with multilevel samplers at this site and reported higher NO_3–N concentrations near the water table and decreasing with depth. Furthermore, other wells at this site that were screened to sample a lower depth in the aquifer had very low concentrations relative to the wells reported here that were screened to sample near the water table (Casey et al., 2002). Schuh et al. (1997) and Mayer (1992) also reported stratified NO_3–N profiles in confined and unconfined aquifers, respectively. Research has indicated that a major cause of NO_3–N stratification in these systems is denitrification. Hence, as the water table rose, the portion of the aquifer being sampled (the screened portion of the well) was deeper relative to the surface of the water table and the measured NO_3–N concentration was slightly lower; however, this relationship alone does not adequately explain the time series trend of NO_3 in the shallow groundwater.

Subsurface Drainage Nitrate

Since the drain lines and wells sampled roughly the same portion of the groundwater, the concentrations in the wells and drains should have been very similar. However, the NO_3–N concentration in the subsurface drainage (Fig. 6) was much lower than the concentration observed in the shallow wells, with the study period average drain NO_3–N concentration being only 20% of the average shallow well concentration. Knighton (1997) and Casey et al. (2002) attributed the difference to a combination of biotic and abiotic NO_3–N reduction. A biofilm containing bacteria capable of NO_3–N reduction (*Brevibacter* spp. and *Arthrobacter* spp.) and a C source was present in the drain lines as well as the gravel envelope surrounding the drains in this field. Ferrous Fe present in the drainage water also could have reduced the NO_3–N.

Similar to the shallow wells, the mean NO_3–N concentration measured in the subsurface drainage increased after the onset of irrigation. Differences between the north and south sides of the field cannot be discussed for the subsurface drainage since the drain lines run under both sides, integrating the groundwater NO_3–N concentration on a field scale. The center of the peak in concentration after the initiation of irrigation was not seen until 1992, about 2 yr after it was observed in the lysimeters, and the return to low concentrations was not observed until 1997, when the yearly mean was only 2.6 mg L^{-1}. Although the overall NO_3–N concentration trend for the drains is about 2 yr behind that of the lysimeters, it could be argued that the higher concentrations in the drains in 1998 may have been directly correlated with the marked increase in the north lysimeters in 1998 (Fig. 3). The concentrations had been increasing in the north lysimeters since mid-1996, however, which would again indicate a 2-yr lag. Bivariate analysis indicated that the average annual drain NO_3–N concentrations were most significantly related to the lysimeter concentrations from 2 yr previous and to the groundwater NO_3–N concentration within the same year (Table 2). The drain NO_3–N concentrations were not significantly related to the lysimeter concentrations within the same year but were significantly related to the previous year's lysimeter concentrations. These results indicate a 1- to 2-yr lag between the lysimeters and the tile drains and that the drains and wells were sampling essentially the same water. The general upward trend in the concentrations between 2001 and 2006 appears to be the combined result of high leachate concentrations on the north in some years and the south in other years.

The infrequent spikes in NO_3–N in the drains, which were significantly different (P < 0.05) than the surrounding observations, were observed when drain sampling occurred very soon after a large rainfall event. The increased drain flow as well as preferential flow under depressional areas of the field after fertilizer application and large rainfall events may have been responsible for the short-lived NO_3–N spikes. Derby and Knighton (2001) showed that depression-focused recharge does occur on this field, carrying solutes rapidly to the groundwater, and observed similar spikes in an applied Cl^- tracer after recharge events.

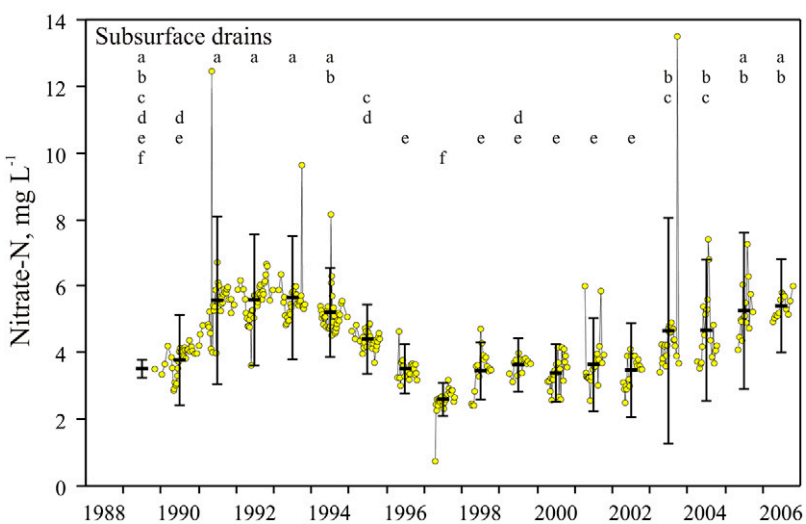

FIG. 6. Nitrate-N concentration in the subsurface drains measured at the north edge of the field. Circles indicate mean NO_3–N concentrations for all wells sampled on a given date. Heavy black lines indicate yearly mean concentrations. The error bars indicate ±1 standard deviation. Yearly mean concentrations with different lowercase letters for each side of the field are significantly different (P < 0.05). The large bold letters indicate the crop that was grown that year: P, potato; S, soybean; no letter, corn.

Nitrogen Balance

An accounting of N in the plant–soil–leachate system is depicted in Fig. 7. Initial soil N and additions of N are indicated by positive values, while residual soil N and removal of N from the system (leachate and plant uptake) are indicated by negative values. The difference between N outputs and N inputs for each year are shown in Fig. 7 as an N balance term (NBAL). The NBAL value indicates the amount of N required to equate N inputs to N outputs and includes unmeasured parameters such as mineralization, N fixation, immobilization, denitrification, and gaseous N emissions. The departure of NBAL from zero indicates gains or losses of N during the year that were not accounted for. A positive NBAL value for a given year indicates that additional N that was unaccounted for must have

been available for leaching, crop uptake, or fall soil residual during the year to balance the N inputs and outputs, presumably from N mineralization. Conversely, if the NBAL was negative, N not accounted for in an amount greater than mineralization was either lost via denitrification or volatilization or immobilized. The range for NBAL during the study period was −71 to 194 kg N ha^{-1} on the north and −201 to 202 kg N ha^{-1} on the south, with averages of 34 and 27 kg N ha^{-1} yr^{-1} for the north and south, respectively.

The NBAL was within about ±50 kg ha^{-1} for 15 side-years, which means that the majority of the N was accounted for in the measured inputs and outputs. The NBAL indicated net mineralization early in the study resulting from the initiation of irrigation, as discussed above related to the lysimeter leachate NO_3–N concentrations. The NBAL was usually negative or lower than the previous year when potato was grown, possibly indicating immobilization during crop residue decomposition. Also, NBAL increased in the years following potato production. That indicates that the potato vines decomposed rapidly and the mineralized N was available for the crop the following year. In 1996 on the north side of the field, however, the NBAL showed that more N was lost from the system than was added, suggesting a large contribution from mineralization necessary to balance the N input and outputs. The N removed by the potato crop on the north side, however, was much greater than crop N removal on the south side. The N content of the vines harvested from the north was more than two times greater than that of the vines harvested from the south side. In addition, the total vine dry matter harvested on the north was also more than twice that of the south side of the field, leading to a large crop N removal value. It was unclear what caused this difference.

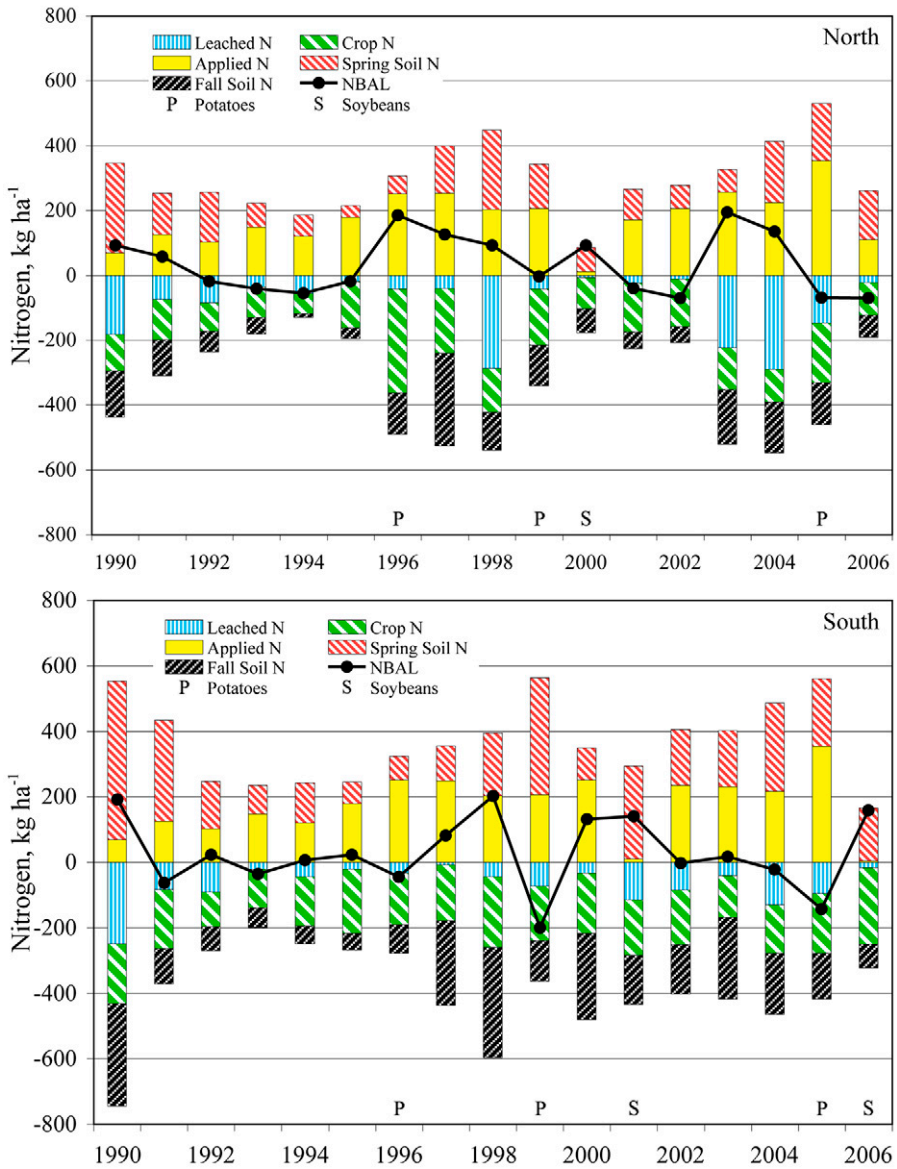

FIG. 7. Nitrogen inputs and outputs for each year. The N balance (NBAL) is the difference between outputs and inputs. The large bold letters indicate the crop that was grown that year: P, potato; S, soybean; no letter, corn.

High NBAL values were observed in 2003 and 2004 on the north side of the field. Large leachate N losses occurred both of these years due to poor crop growth caused by adverse weather conditions; however, these trends were not observed on the south side of the field. Soil salinity and sodicity problems of the north side but not the south side (discussed above) probably exacerbated the negative effects of the weather on crop growth in 2003 and 2004. As a result, the corn on the south side of the field was able to maintain relatively efficient water use, resulting in lower N leaching losses. A positive NBAL was observed in the soybean cropping years, presumably due to biological N_2 fixation.

The values for the unaccounted-for N represented by the NBAL term were reasonable based on values of mineralization and immobilization reported by others. For control plots located on this field as part of a concurrent N fertility study from 1990 to 1995 (Derby et al., 2005), calculated net mineralization rates ranged from 17 to 229 with an average of 75 kg ha^{-1} on the north and from −24 to 92 with an average of 63 kg ha^{-1} on the south, using the method described by Errebhi et al. (1998). Gentry et al. (1998) measured as much as 156 kg N ha^{-1} immobilized in the microbial biomass and estimated N mineralization as high as 133 kg N ha^{-1} in the upper 50 cm of soil under a corn–soybean rotation. Green and Blackmer (1995) measured rapid decreases in soil NO_3 due to immobilization during corn residue decomposition, but after 300 d, the soil NO_3 was higher than initial levels, indicating net mineralization. By applying labeled NO_3 to the soil, they were able to conclude that the NO_3 in the soil was immobilized by the decomposition of residues while N was mineralized from soil organic matter (SOM) and residues, with the result being a net increase in soil NO_3 of about 67 kg N ha^{-1} in 15 cm of soil. Alva et al. (2002) measured cumulative mineralized N of 172 and 72 kg ha^{-1} for corn and potato from January to September in 30-cm-deep field incubation columns.

Schindler and Knighton (1999) hypothesized that denitrification was responsible for the N deficit observed in their N balance study on this site, especially in 1993 when the growing season was cooler and wetter than normal. In general, the SOM and crop residue pool is in a constant state of flux with regard to immobilization, mineralization, and decomposition. The status of that pool and its contribution to the NBAL value depends on factors such as the soil moisture status, soil temperature, and time of year. For example, if soil samples taken in the fall happen to coincide with a period of high residue decomposition, soil NO_3 levels might be low due to immobilization. The result would be a negative NBAL value. The study period averages of 34 and 27 kg ha^{-1} of N added each year are well within the range of published net mineralization values.

Bivariate analysis and one-way ANOVA were performed to determine the relationship between NBAL and the factors listed above. The factors found to be significant on the north were the previous year's April to May cumulative GDD (P = 0.015) and the previous year's April to May average temperature (P = 0.008), both of which were negative correlations. The only factor that was significant on the south side was crop (P = 0.004). This analysis indicated that the north side of the field, which has soil-related productivity problems, was more susceptible to early-season temperature in regard to mineralization, immobilization, and denitrification. Conversely, the NBAL on the south side of the field was generally a factor of the crop grown that year, with average NBAL values of −135, 46, and 148 kg ha^{-1} for potato, corn, and soybean, respectively. When both sides were included in the analysis, the NBAL averages were −52, 37, and 130 kg ha^{-1} for potato, corn, and soybean (P = 0.03), respectively, while the average NBAL values were 84, 20, and −22 kg ha^{-1} when the previous year's crops were potato, corn, and soybean (not significant at α = 0.05). This implied that there was losses not accounted for (by immobilization, denitrification, and volatilization) during potato and after soybean, unmeasured gains (mineralization) during soybean and after potato, and net mineralization during and after corn.

Conclusions

This research indicated that high NO_3–N concentrations in the vadose zone and shallow groundwater occurred after the initiation of irrigation on sandy soils, even when very conservative N rates were used. It was also shown that proper N management with careful attention to soil N and reasonable yield goals (best management practices) resulted in a decrease in leachate and groundwater NO_3–N concentrations to near preirrigation concentrations. A return to the fertility management practices used by local producers, which usually meant higher N application rates, resulted in higher leachate and groundwater NO_3–N concentrations. Nitrate-N concentrations in the leachate responded to surface applications either later in the year of application or early in the following year. Concentrations in the shallow groundwater lagged about 1 yr behind the leachate concentration time series and were lower. Subsurface drainage NO_3–N concentrations were much lower than the shallow groundwater concentrations measured in the wells due to biotic or abiotic NO_3 reduction. Although apparent net mineralization was higher during soybean and the year following potato production and there were unmeasured net N losses during potato and 1 yr after soybean production, different crops did not directly affect the leached NO_3–N concentrations. The single most important factor leading to increased NO_3–N leaching past the crop root zone and to the groundwater was the amount of fall residual NO_3–N in the soil profile. In turn, fall soil N was influenced significantly by factors related to temperature, N application, and crop N uptake.

The results also indicate the importance of long-term field studies to the more complete interpretation of NO_3–N fate. For example, if only 3 yr of research had been conducted at the onset of the study, the interpretation would have been that the conservative N rates were unsuccessful in reducing leachate and groundwater contamination. Similarly, if the zone management project had been stopped after the 2001 to 2002 seasons, the high leachate concentrations in 2003 to 2004, presumably due to adverse weather, would not have been observed. The importance of measuring NO_3 in the soil, leachate, groundwater, and subsurface drainage is also emphasized by this study. Obviously, if only the drainage leaving the field in the subsurface drainage had been measured, we would have had a false sense of the actual N loading to the groundwater.

This research indicated that careful N fertility management is very important to minimize NO_3–N losses from the root zone, regardless of the crop. Some potential management practices to reduce the soil NO_3–N level and subsequent leachate and groundwater NO_3–N concentrations indicated by this research include (i) reducing N application during the first years after the initiation of irrigation, (ii) reducing N applications by having reasonable yield goals and giving proper credit for fall residual soil NO_3–N, and (iii) adjusting N applications based on adverse weather conditions or poor soil properties that may affect crop growth. Field-scale studies of this nature, which include measurements at the soil, vadose zone, and groundwater levels across multiple management practice periods, are necessary to adequately understand vadose zone and groundwater quality under irrigated agriculture.

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