

Post-Harvest Soil Nitrate in Irrigated Corn: Variability Among Eight Field Sites and Multiple Nitrogen Rates

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ABSTRACT

Elevated post-harvest soil NO_3 is an indicator that N fertilizer was applied in excess of the amount required to obtain maximum corn (*Zea mays* L.) yield, and represents a quantifiable environmental risk if water percolates through the soil profile during the fallow season. The reliability of using post-harvest soil NO_3 as an indicator of NO_3 leaching potential was considered for various field sites with similar soil characteristics and slightly variable rainfall conditions. Six N treatments (surface broadcast) included: (i) 300 and (ii) 250 kg N ha^{-1} applied at planting; (iii) 250 kg N ha^{-1} split-applied at planting (1/2) and sidedress (1/2); (iv) 185 kg N ha^{-1} split-applied at planting (1/3) and sidedress (2/3); (v) 125 kg N ha^{-1} split-applied at planting (1/5) and sidedress (2/5, 2/5); and (vi) 0 kg N ha^{-1} . At one site, N treatments were represented in each of two irrigation treatments: 1.0 \times (optimal) and 1.25 \times (125% optimal). Soil samples were collected in 30-cm increments at preplant and post-harvest to a 240-cm depth. Sand content exceeded 0.8 g g^{-1} within the 240-cm soil profile at every site except one; and distinct textural transitions were present within the soil profile at four sites. Maximum grain yield was obtained with <185 kg N ha^{-1} at every site in both years. When less than average water was received at those sites with distinct textural transition (silt and clay to sand) in the upper soil profile, post-harvest soil NO_3 for N rates > 180 kg N ha^{-1} often exceeded 60 kg N ha^{-1} within a 30-cm sampling depth. When these same sites received additional rainfall, post-harvest results indicated that NO_3 had moved down the soil profile, past the textural transition, and perhaps beyond the 240-cm depth. For those sites with uniformly high sand content (0–240 cm), few differences in post-harvest NO_3 could be attributed to the N treatments exceeding 185 kg N ha^{-1} . Nitrate had probably moved beyond 240 cm by the end of the growing season. Slight differences in site characteristics (e.g., textural boundaries) can greatly influence conclusions derived from post-harvest soil sampling regarding the risk of NO_3 leaching.

NITRATE CONTAMINATION of surface and groundwater from overuse of N fertilizers is a continuing concern for crop production regions of the USA, particularly where corn is grown. The sandy soils of the Central Great Plains, where irrigated corn is commonly grown, are highly susceptible to NO_3 leaching due to the continuous availability

of water (through irrigation) and low water holding capacities. The importance of N fertilizer to achieving positive economic returns with high corn yield is widely recognized, and research has focused on N management practices that reduce negative environmental risks associated with N fertilizer applications.

Accumulation and redistribution of NO_3 within the soil varies depending on management practices, soil characteristics, and growing season precipitation. Elevated post-harvest soil NO_3 content is usually provided as evidence that N fertilizer was applied in excess of corn uptake (Ferguson et al., 1991; Karlen et al., 1998; Andraski et al., 2000). Jolley and Pierre (1977) observed an increase of greater than 1130 $\text{kg NO}_3\text{-N ha}^{-1}$ in fertilized plots (compared with unfertilized plots) in a 4.2-m profile after 17 yr of fertilization with 168 $\text{kg N ha}^{-1} \text{ yr}^{-1}$ applied to corn. A large amount of N had accumulated between 60 and 210 cm, with the greatest accumulation observed between 120 and 150 cm. After 10 yr of continuous corn fertilization with 196 $\text{kg N ha}^{-1} \text{ yr}^{-1}$ on a loam soil, Nelson and MacGregor (1973) reported a total soil NO_3 content of 241 kg N ha^{-1} (0- to 5.5-m depth). During most years of their study, the N rate (106 kg N ha^{-1}) corresponding to maximum corn yield resulted in a soil NO_3 content of only 122 kg N ha^{-1} (0- to 5.5-m depth). Nitrate concentration was not increased below the 200-cm depth. Smika et al. (1977) showed that for a loamy fine sand in Colorado, total soil NO_3 remaining in the 180-cm profile after harvest was highly correlated ($r = 0.95$) to the amount of water percolating to the 150-cm depth. Total NO_3 in the profile changed little from spring to fall sampling, although redistribution within the profile occurred during the growing season. Fields that were managed so that <5% of the growing season water percolated to the 150-cm depth had greater than 250 $\text{kg NO}_3\text{-N ha}^{-1}$ to a depth of 180 cm, compared with only 20 kg ha^{-1} for fields managed for 10% water percolation. Their results indicate that substantial NO_3 movement can occur during the growing season when excess water percolation occurs.

Nitrate remaining in the post-harvest soil profile, representing a potential risk for leaching during the fallow period, has been shown to be closely related to N fertilizer rate (above the yield maximizing rate), seasonal precipitation, and soil texture. Ferguson et al. (1991) found NO_3 concentrations at the 180-cm depth in a silt loam Nebraska soil were about 21 kg N ha^{-1} greater at N rates of 150 and 300 kg N ha^{-1} compared with 75 kg N ha^{-1} or unfertilized rates. Distribution of NO_3 in the 180-cm profile and differences in NO_3 between low (0 and 75 kg N ha^{-1}) and high (150 and 300 kg N ha^{-1})

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Abbreviations: EONR, economic optimum nitrogen rate; IS, irrigation schedule or irrigation treatment; RCBD, randomized complete block design; SOM, soil organic matter.

N rates suggests that movement of NO_3 below 180 cm occurred at the two highest N rates. Andraski et al. (2000) found a strong relationship ($r^2 = 0.88$) between excess N fertilizer applied and end-of-season soil NO_3 content (0–90 cm) in a Wisconsin silt loam under continuous corn management. The soil profile $\text{NO}_3\text{-N}$ content at the economic optimum nitrogen rate (EONR) was 108 kg ha^{-1} , compared with 25 to 50 kg ha^{-1} where N rates were 80 to 150 kg ha^{-1} below the EONR, and from 150 to 375 kg N ha^{-1} where N rates were 50 to 200 kg ha^{-1} greater than the EONR. Bundy and Andraski (1996) also found a strong relationship ($r^2 = 0.73$) between end-of-season soil NO_3 content in a 60-cm profile and the amount of excess N applied in a four-year study on high yield potential soils in Wisconsin. On a loamy sand planted to corn in New York, Sogbedji et al. (2000) found elevated residual NO_3 levels for a N treatment (134 kg N ha^{-1}) that exceeded that required for maximum yield (100 kg N ha^{-1}). Over three growing seasons, the soil $\text{NO}_3\text{-N}$ content in the 120-cm profile was 51 kg N ha^{-1} for the 134 kg N ha^{-1} rate compared to 23 kg N ha^{-1} for the 100 kg N ha^{-1} rate.

Lund et al. (1974) found that soil texture within the root zone (0–1.8 m) explained 86% of the variability in NO_3 concentration below the root zone (1.8–8.0 m). At 15 study locations within a 30-ha field that had been managed uniformly with manure (76 Mg $\text{ha}^{-1} \text{yr}^{-1}$ for 4 yr), the NO_3 concentration below the 1.8-m depth decreased linearly ($r^2 = 0.68$) as the clay content in the root zone increased. In a three-year study in Quebec, Canada, Liang and MacKenzie (1994) evaluated the changes in soil NO_3 concentration due to N fertilizer rate for a clay and a sandy clay loam soil. They reported a quadratic increase ($r^2 = 0.99$) in soil NO_3 concentration (0 to 0.8 m) in the clay soil as N fertilizer rate increased above the optimum (170 kg N ha^{-1}). A significant, linear relationship ($r^2 = 0.97$) was observed in only one of the three years for the sandy clay loam (0 to 0.6 m). The lack of treatment effect was attributed to leaching losses in the coarse soil. Similarly, Hahne et al. (1977) showed that less NO_3 accumulated and greater quantities of NO_3 were lost in a fine sandy loam compared with that lost from clay loam and silt loam soils. Data from their study showed that proper irrigation of soils with rapid internal drainage can markedly reduce NO_3 loss through leaching. Additionally, N treatments above 140 kg N ha^{-1} resulted in substantial increases in NO_3 accumulation at a depth of 60 to 90 cm. An absence of NO_3 accumulation below 105 cm in the sandy loam indicated that NO_3 had moved rapidly below 3 m, once reaching the 105-cm depth.

A considerable amount of research has been conducted on NO_3 redistribution in soils under various N and crop management strategies, illustrating the adverse impact of excess N and excess water applications. Generally, the evidence presented to verify the occurrence of NO_3 leaching is the presence of elevated NO_3 concentration in the lower part of a soil profile, for example, below the root zone and after the growing season. If elevated NO_3 is not observed in the lower part of the soil profile, the conclusion might be inferred that NO_3

leaching has not occurred, and the specific N management practice considered adequate for minimizing NO_3 leaching. The objective of this study was to evaluate post-harvest soil NO_3 content and distribution for sandy soils under irrigated corn production, considering the potential variability in NO_3 redistribution within the soil profile for multiple field sites receiving similar N applications within a similar geographic area (i.e., sandy textured soils along Kansas rivers).

MATERIALS AND METHODS

A total of 15 (year, site, irrigation combinations) N response trials were conducted in Kansas in 2001 and 2002. Locations included Scandia (97°47'19" W, 39°46'23" N), Manhattan (96°37'09" W, 39°08'02" N), Rossville (95°55'40" W, 39°06'59" N), St. John (98°55'50" W, 38°08'02" N), Pretty Prairie (two sites, 98°04'17" W, 37°48'04" N), and Ellinwood (two sites, 98°37'18" W, 38°15'01" N). Scandia, St. John, Pretty Prairie, and Ellinwood were conducted in fields of cooperating producers, and Manhattan and Rossville were located on Kansas State University research farms. Criteria for selecting sites included irrigated corn production on sandy textured soils with relatively shallow groundwater depths (3–50 m). Soils at the sites were primarily well-drained sandy loams, except at St. John, which was poorly drained (Table 1). Cultivation, planting, and weed control were performed by the producer or research station manager. Typical tillage included chisel plow and a seedbed preparation pass. Weed control included preplant or pre-emergence herbicides. Specific descriptions of experimental sites and soil characteristics were presented by Gehl et al. (2005a). General soil characteristics are provided in Table 1.

Plots were arranged in a randomized complete block design (RCBD) with four blocks at each site. Each plot was 6 m (eight rows, 0.76-m row width) wide and 9.1 m long at all sites except Manhattan, where plots were 4.6 m (six rows, 0.76-m row width) wide and 9.1 m long. Annual N treatments were surface broadcast as NH_4NO_3 , including 300 kg N ha^{-1} applied at planting; 250 kg N ha^{-1} applied at planting; 250 kg N ha^{-1} applied at planting (1/2) and sidedress (1/2); 185 kg N ha^{-1} applied at planting (1/3) and sidedress (2/3); 125 kg N ha^{-1} applied at planting (1/5) and sidedress (2/5, 2/5); and 0 kg N ha^{-1} . Sidedress applications were made at the six- to eight-leaf stage (leaf stage is defined according to the number of leaves having a visible leaf collar, including the first short rounded-tip leaf) for the first application, and at the 10-leaf stage for the second application. Treatments were adjusted at St. John to accommodate producer management practices (35 kg N ha^{-1} applied as a starter at planting; see Table 2), so that total N applied was similar to intended rates. In 2001, Pretty Prairie East and West received 16 kg N ha^{-1} applied as starter, as well as 52 and 121 kg N ha^{-1} , respectively, applied through the irrigation system. In 2002, the Pretty Prairie East site received 16 kg N ha^{-1} applied as starter and 42 kg N ha^{-1} applied through the irrigation system. Total N applied at the Pretty Prairie sites was in excess of the intended N rates (see Table 2). There were two irrigation treatments (IS) at the Ellinwood site (optimal water rate [1.0 \times] and 125% of optimal [1.25 \times] water rate), each of which included a RCBD with the described N treatments. Geographic plot locations were identical between years at all sites except Manhattan, and in 2002 the West plots at Pretty Prairie were not included in the study.

Soil samples were collected within 2 wk of planting (pre-plant) and post-harvest to a depth of 240 cm in 30-cm increments, with the exception that the 2001 post-harvest samples

Table 1. General description of soil at each field site (Soil Survey Division, 2005).

Site	Soil series	Parent material	Characteristics
St. John	Carwile fine sandy loam†	loamy alluvium or aeolian sediments	very deep, poorly drained, slowly permeable soils on terraces of the uplands
Scandia	Carr fine sandy loam‡	calcareous stratified alluvium	very deep, well-drained or moderately well-drained, moderately rapidly permeable soils on flood plains
Pretty Prairie West	Albion sandy loam,§ 1–4% slopes	loamy sediments over sandy alluvium	deep, somewhat excessively drained or well-drained, moderately rapidly permeable soils on paleo-terraces in river valleys
	Shellabarger sandy loam, 1–4% slopes	alluvium	deep, well-drained, moderately permeable soils on paleo-terraces in river valleys
Pretty Prairie East	Farnum loam,# 0–3% slopes	alluvium	very deep, well-drained soils on paleo-terraces in river valleys
	Eudora silt loam†† Eudora silt loam	silty or loamy alluvium	very deep, well-drained, moderately permeable soils on flood plain steps
Ellinwood	Pratt loamy fine sand,‡‡ hummocky	sandy eolian deposits	very deep, well-drained, rapidly permeable soils on dunes on paleo-terraces in river valleys

† Fine, mixed, superactive, thermic Typic Argiaquolls.

‡ Coarse-loamy, mixed, superactive, calcareous, mesic Typic Udifluvents.

§ Coarse-loamy, mixed, superactive, mesic Udic Argiustolls.

|| Fine-loamy, mixed, superactive, mesic Udic Argiustolls.

Fine-loamy, mixed, superactive, mesic Pachic Argiustolls.

†† Coarse-silty, mixed, superactive, mesic Fluventic Hapludolls.

‡‡ Sandy, mixed, mesic Lamellic Haplustalfs.

at Pretty Prairie East were collected only to 180 cm due to difficult sampling conditions. Preplant samples were collected before fertilizer application. At Ellinwood, one core from within the row and one core from between the rows were collected from each plot using a hydraulic soil probe with a 5-cm i.d. core, and then combined. At the other sites in 2001, preplant soil samples were collected using the same protocol as described for Ellinwood except only from those plots designated to receive the 300 kg N ha⁻¹ and control treatments. In 2002, preplant samples were taken from all plots at all sites except Manhattan, where preplant samples were taken only from the plots designated to receive the 300 kg N ha⁻¹ and control treatments. Post-harvest soil samples consisted of one 5-cm i.d. core taken from each plot at all sites except Ellinwood, where two cores were collected from each plot as already described. The soil cores from each sampling event were composited by plot and depth, dried at 50°C, ground to pass a 2-mm sieve, and analyzed for NO₃-N and NH₄-N using flow injection analysis of 1 M KCl extracts (Quik-Chem Methods, Lachat Instruments, Milwaukee, WI). After harvest in 2002, 15, 2.5-cm i.d. cores were randomly collected and combined from each site. The composite samples were dried at 50°C, ground to pass a 2-mm sieve, and analyzed for pH, Bray-1 P, K, and soil organic matter content (SOM) using methods recommended for soils in the North Central Region (Brown, 1998).

Soil samples to determine dry bulk density were collected after the 2003 harvest from each site except Ellinwood. Six cores were collected at each site to a depth of 240 cm in 30-cm

increments using a hydraulic soil probe with a 5-cm i.d. core. Samples at Ellinwood were collected in May 2003 by taking five cores using a hydraulic soil probe with a 6.71-cm i.d. core. Samples from all sites were dried at 105°C for 2 d and the dry soil mass recorded. Bulk density was determined by dividing the oven-dry mass by the sample core volume (Blake and Hartge, 1986). Mean dry bulk density (g cm⁻³) was determined by averaging across all cores for each depth at each site. Soil texture analysis was also completed for 30-cm increments to a depth of 240 cm using the hydrometer method (Gee and Bauder, 1986), with sodium hexametaphosphate as the dispersing agent. Clay fraction was determined by reading an ASTM no. 152H standard hydrometer with a Bouyoucos scale (g L⁻¹) after 8 h of settling. Sand fraction was determined by separation with a 20-cm-i.d. 53-µm sieve.

At maturity, grain yield at all sites except Rossville was determined by hand harvesting ears from a 6-m length of each of the middle two rows from each plot. Ears were shelled and grain weight recorded, and final yield adjusted to 155 g kg⁻¹ moisture content. The middle two rows of each plot at Rossville were harvested with a combine modified for plot work, and final yield adjusted to 155 g kg⁻¹ moisture content.

Statistical analyses were performed using General Linear Procedures (SAS Institute Inc., 1998). *F*-tests for analysis of variance (ANOVA) were considered significant at the 0.10 probability level. PROC GLM (SAS Institute Inc., 1998) was used to analyze treatment differences in grain yield and profile

Table 2. Nitrogen treatments and additional N applied by producers.

N fertilizer	St. John	Scandia	Pretty Prairie				Ellinwood†	
			East	West	Rossville	Manhattan	1.0×	1.25×
kg N ha ⁻¹ yr ⁻¹								
Applied at planting	35		16	16				
Planned N treatments	0	0	0	0	0	0	0	0
20% at planting, 40% at six-leaf, 40% at 10-leaf	90	125	110	110	125	125	125	125
33% at planting, 67% at sidedress	150	185	170	170	185	185	185	185
50% at planting, 50% at sidedress	215	250	170	170	250	250	250	250
100% at planting	215	250	225	225	250	250	250	250
100% at planting	270	300	280	280	300	300	300	300
Applied with irrigation (2001)			52	121				
Applied with irrigation (2002)			42					
Total N applied to "control"	35	0	68 or 58	138	0	0	0	0

† Irrigation treatments of 1.0× (recommended rate) and 1.25× (125% of recommended rate).

soil NO₃-N content at each site. Repeated measures analysis (SAS Institute Inc., 1998) was used to evaluate depth effects on profile NO₃-N, and pairwise comparisons were completed using the LSMEANS (SAS Institute Inc., 1998) statement to determine differences among N treatments at a given depth. PROC MIXED (SAS Institute Inc., 1998) was used to analyze differences in NO₃ content among sites.

RESULTS AND DISCUSSION

Site Characteristics and Grain Yield

Detailed discussion of the site characteristics and grain yield response to N treatments is provided by Gehl et al. (2005a). Soil nutrient characteristics (pH, P, K, SOM) for the surface 30 cm at each study site were adequate for corn production. Soil physical characteristics at these sites were representative of the sandy soils along main Kansas rivers, where there is concentrated irrigated corn production. Dry bulk densities ranged from 1.31 to 1.81 g cm⁻³ across all sites and depths, and are consistent with values previously determined for the study soils (Soil Survey Staff, 2005).

Sandy textured soils were predominant at these sites, with sand content exceeding 0.80 g g⁻¹ within the 0- to 240-cm soil profile at every site except Manhattan (Table 3). At Ellinwood, sand content exceeded 0.88 g g⁻¹ throughout the 0- to 240-cm profile, and Pretty Prairie West was quite similar with sand content exceeding 0.81 g g⁻¹ in every horizon. Pretty Prairie East differed slightly from these two sites, with less sand content (minimum of 0.51 g g⁻¹) in the top 90 cm. The textural profiles at Rossville and Scandia were similar to Pretty Prairie East, but with slightly more sand in the top 90 cm at Rossville (minimum of 0.62 g g⁻¹) and slightly less sand (0.33 g g⁻¹) at the 60- to 90-cm depth at Scandia. St. John had a textural profile that was inverted compared to Pretty Prairie East, with 0.84 g g⁻¹ sand content in the top 90 cm and between 0.43 and 0.65 g g⁻¹ sand content below 90 cm. The soil at Manhattan had the lowest sand content for all sites, not exceeding 0.60 g g⁻¹ throughout the 0- to 240-cm profile. Despite these differences, these soils are generally categorized as the “sandy” soils along Kansas rivers, and thus, are often considered similar with regards to N management for irrigated corn.

Precipitation for the 2001 growing season exceeded the 30-yr average for each site (on average by 11.4 cm), with the exception of Pretty Prairie (Gehl et al., 2005a). Pretty Prairie had an April to September 2001 pre-

cipitation 8.3 cm less than the 30-yr average. Droughty conditions in Kansas during the 2002 growing season resulted in rainfall exceeding the 30-yr average only at Pretty Prairie and Ellinwood, with 0.8 and 9.0 cm precipitation above the average, respectively. Precipitation at St. John, Scandia, Manhattan, and Rossville was less than the 30-yr average by 15.9, 25.8, 11.3, and 18.3 cm, respectively (Kansas State University Research and Extension, 2004). Supplemental irrigation provided sufficient water to maintain corn yields at all sites except Scandia (2002), where water availability was insufficient to allow for irrigation during the growing season.

Maximum grain yield was achieved with a split application of 185 kg N ha⁻¹ at all sites, and in most instances 125 kg N ha⁻¹ was sufficient to achieve maximum yield (Gehl et al., 2005a). Site and year combinations where maximum yield was observed with 185 kg N ha⁻¹ included Ellinwood (1.0× IS, 2001), Manhattan (2001, 2002), Pretty Prairie East (2002), and St. John (2001). A response to N fertilizer was not observed at Scandia (2002), Pretty Prairie East (2001), Pretty Prairie West (2001), and St. John (2002). At sites where yield responded to N fertilizer, the control treatment resulted in less yield than any other N fertilizer treatments. At those sites and N rates where N was applied in excess of that required for maximum yield, elevated post-harvest soil NO₃ would provide conclusive evidence of an environmental risk. Currently, a generalized approach to N management (Leikam et al., 2003) that is typical for most states suggests an expectation that all of these sites should behave similarly with regard to corn response to N fertilizer, implying that the environmental risk associated with NO₃ leaching is also similar.

Profile Soil Nitrogen

Profile soil NO₃ was evaluated each year before planting (preplant) and after harvest (post-harvest). Preplant sampling in 2002 was used to evaluate the impact of the previous year’s N treatments on soil NO₃, to assess leaching losses during the winter fallow period, and to consider the potential impact on the current year’s response to N treatments.

Total soil NO₃-N in the post-harvest 0- to 240-cm profile varied considerably among sites in both years (Table 4). Mean total soil NO₃ at St. John exceeded 300 kg N ha⁻¹ on each sampling date after preplant 2001, and was the greatest among all sites. By contrast,

Table 3. Sand and clay content by depth for each location.

Depth cm	Pretty Prairie													
	Ellinwood		Manhattan		East		West		Rossville		Scandia		St. John	
	Sand	Clay	Sand	Clay	Sand	Clay	Sand	Clay	Sand	Clay	Sand	Clay	Sand	Clay
	g g ⁻¹													
0–30	0.93	0.03	0.11	0.35	0.60	0.14	0.89	0.02	0.65	0.12	0.73	0.09	0.85	0.03
30–60	0.92	0.05	0.42	0.24	0.51	0.26	0.83	0.04	0.62	0.11	0.38	0.15	0.84	0.06
60–90	0.90	0.07	0.54	0.16	0.75	0.14	0.81	0.08	0.68	0.09	0.33	0.16	0.84	0.05
90–120	0.89	0.08	0.60	0.13	0.83	0.09	0.84	0.08	0.74	0.08	0.52	0.11	0.65	0.13
120–150	0.90	0.09	0.57	0.19	0.89	0.08	0.84	0.10	0.74	0.08	0.83	0.07	0.43	0.23
150–180	0.90	0.08	0.41	0.25	0.86	0.11	0.86	0.10	0.83	0.07	0.91	0.05	0.47	0.21
180–210	0.87	0.10	0.42	0.27	0.80	0.13	0.88	0.08	0.81	0.08	0.94	0.05	0.51	0.20
210–240	0.88	0.09	0.38	0.30	0.80	0.12	0.87	0.09	0.76	0.08	0.94	0.04	0.51	0.18

Table 4. Mean (across all N treatments) preplant and post-harvest (2001 and 2002) soil NO₃-N content in the 0- to 240-cm profile.

Site	2001		2002	
	Preplant†	Post-harvest	Preplant‡	Post-harvest
	kg NO ₃ -N ha ⁻¹			
St. John	287	313	311	353
Pretty Prairie West	295	249	—	—
Pretty Prairie East	190	230§	272	226
Scandia	338	189	193	238
Ellinwood 1.25×	178	158	156	115
Ellinwood 1.0×	173	138	130	122
Manhattan	—	108	147	173
Rossville	173	85	117	144
Mean	233	184	189	196
LSD (0.10)	NA¶	33	55	62

† Preplant samples collected only from the control and 300 kg N ha⁻¹ treatments at all sites except Ellinwood, where samples were collected from all treatments.

‡ Preplant samples collected only from the control and 300 kg N ha⁻¹ treatments at Manhattan.

§ Mean value for 0- to 180-cm depth, not included in statistical analysis.

¶ NA, not applicable. Statistical analysis not completed due to differences in sampling scheme.

soil NO₃ content at Rossville was consistently the lowest among sites on any sampling date, as low as 85 kg N ha⁻¹ at post-harvest 2001 to as great as 144 kg N ha⁻¹ at post-harvest 2002. Mean soil NO₃ content (0–240 cm) before initiation of this study (preplant 2001), while not statistically evaluated, reflected the same general trends as observed during the study (Table 4). Although consideration of mean total soil NO₃ ignores differences among N treatments, these results suggest differences about

how these sites were managed or inherent site characteristic differences.

Nitrogen rate influenced the quantity and distribution of NO₃ within the soil profile at Ellinwood on all three sampling dates (Fig. 1). Although mean soil NO₃ content (0–240 cm) was similar between the two irrigation treatments (1.0× and 1.25×; Table 4), the horizon in which differences among N treatments were observed was not the same between the two irrigation treatments.

Single preplant N applications at Ellinwood resulted in the greatest post-harvest (2001) NO₃-N between 120 and 180 cm for the 1.0× IS (as determined by pairwise comparisons, Fig. 1). The depth at which differences among N treatments were detected was lower for the 1.25× IS (150 to 210 cm), suggesting that the increase in irrigation shifted NO₃ down the profile more quickly during the growing season for the 1.25× IS. As reported by Gehl et al. (2005b), the 1.25× IS resulted in much greater leaching losses during the 2001 growing season than the 1.0× IS (16 vs. 133 kg N ha⁻¹, averaged across N treatments, based on in situ lysimeter measurements). Based on these latter results, the post-harvest profile NO₃ content could be expected to be as much as 100 kg N ha⁻¹ greater for the 1.0× IS, but soil NO₃ appeared only to be redistributed within the profile.

The distribution of NO₃ within the soil profile at Ellinwood shifted during the fallow period between post-harvest sampling in 2001 and preplant sampling in 2002. Soil NO₃ decreased with increasing depth at Ellinwood

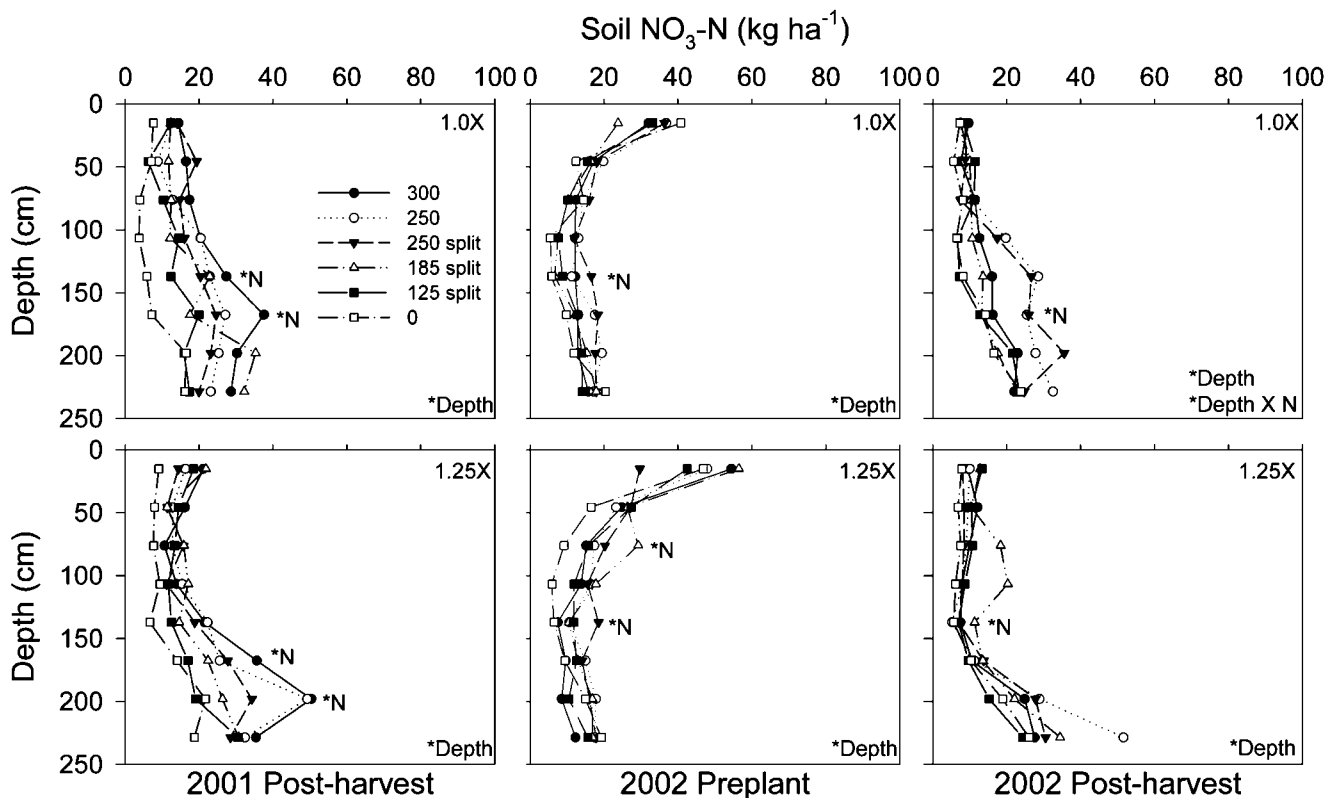


Fig. 1. Preplant and post-harvest soil NO₃-N concentration (0- to 240-cm depth) at Ellinwood for six N treatments (kg N ha⁻¹) and two irrigation treatments (1.0× and 1.25×). Significant differences in NO₃-N among N treatments for a given depth are indicated with a *N, in NO₃-N among sampling depth with a *Depth, and N treatment by depth interactions with a *Depth × N, as determined by repeated measures analysis at $\alpha = 0.10$.

(both irrigation treatments) at preplant sampling in 2002 (Fig. 1), whereas the depth effect indicated increasing NO₃ content with depth for the 2001 post-harvest sampling date. The increase in NO₃ near the soil surface can only be explained by net mineralization during the fall–spring period, because there was no other source of N during this period. Similar NO₃–N content (0 to 60 cm) for all N treatments, including the control, also support this presumption. The comparison between post-harvest (2001) and preplant (2002) soil NO₃ also suggests that NO₃ may have leached out of the lower part of the profile between fall and spring (Fig. 1). Roth and Fox (1990) and Hergert (1986) also attributed decreased spring soil profile NO₃ concentrations to over-winter NO₃ leaching.

By the end of the 2002 growing season, total NO₃–N in the 240-cm profile at Ellinwood was 122 kg ha⁻¹ for the 1.0× IS and 115 kg ha⁻¹ for the 1.25× IS (Table 4), and a significant depth effect indicated that NO₃–N content increased with increasing depth in the soil profile (Fig. 1). These are similar results as were observed post-harvest 2001.

Ellinwood has high sand content throughout the soil profile (Table 3). Post-harvest soil NO₃ redistribution suggests that leaching occurred during the growing season; but perhaps more leaching had occurred than indicated with the results presented here. Gehl et al. (2005b) indicated that 117 kg N ha⁻¹ more NO₃–N leached from the 1.25× IS treatment compared to the 1.0× treatment; yet this large difference was not observed in the post-harvest soil profile (Table 4). Increasing soil NO₃–N con-

tent with depth indicated that NO₃ may have leached below 240 cm before collecting post-harvest samples; in which case, post-harvest sampling underestimates the environmental risk of NO₃ leaching on these soils.

Mean total NO₃ content (0–240 cm) at Rossville was similar to Ellinwood, except at post-harvest 2001 when NO₃ content was slightly less at Rossville (85 kg N ha⁻¹; Table 4). Also similar to Ellinwood, soil NO₃–N at post-harvest 2001 increased with increasing soil depth at Rossville (Fig. 2); however, soil NO₃–N content was not different among N treatments in the lower part of the profile (below 30 cm).

Preplant 2002 soil samples at Rossville depicted a drastically different profile distribution of soil NO₃ (Fig. 2) than observed on any sampling dates at Ellinwood (Fig. 1). Soil NO₃–N for the 300 kg N ha⁻¹ treatment increased to greater than 60 kg N ha⁻¹ in spring 2002. Nitrogen was not applied during this fallow period, so this increase in soil NO₃–N must be a consequence of immobilization during the growing season (2001) and subsequent mineralization and redistribution within the soil profile between fall and spring 2002. The same mechanism was implicated in the slight redistribution of soil NO₃–N in the Ellinwood profile (Fig. 1); but because the sand content in the upper 90 cm at Rossville is less (<0.68 g g⁻¹; Table 3), water percolation could have been slower at Rossville compared to Ellinwood resulting in slower movement of NO₃ down the soil profile.

The distribution of post-harvest soil NO₃–N in 2002 clearly indicated that N applied in excess of 185 kg

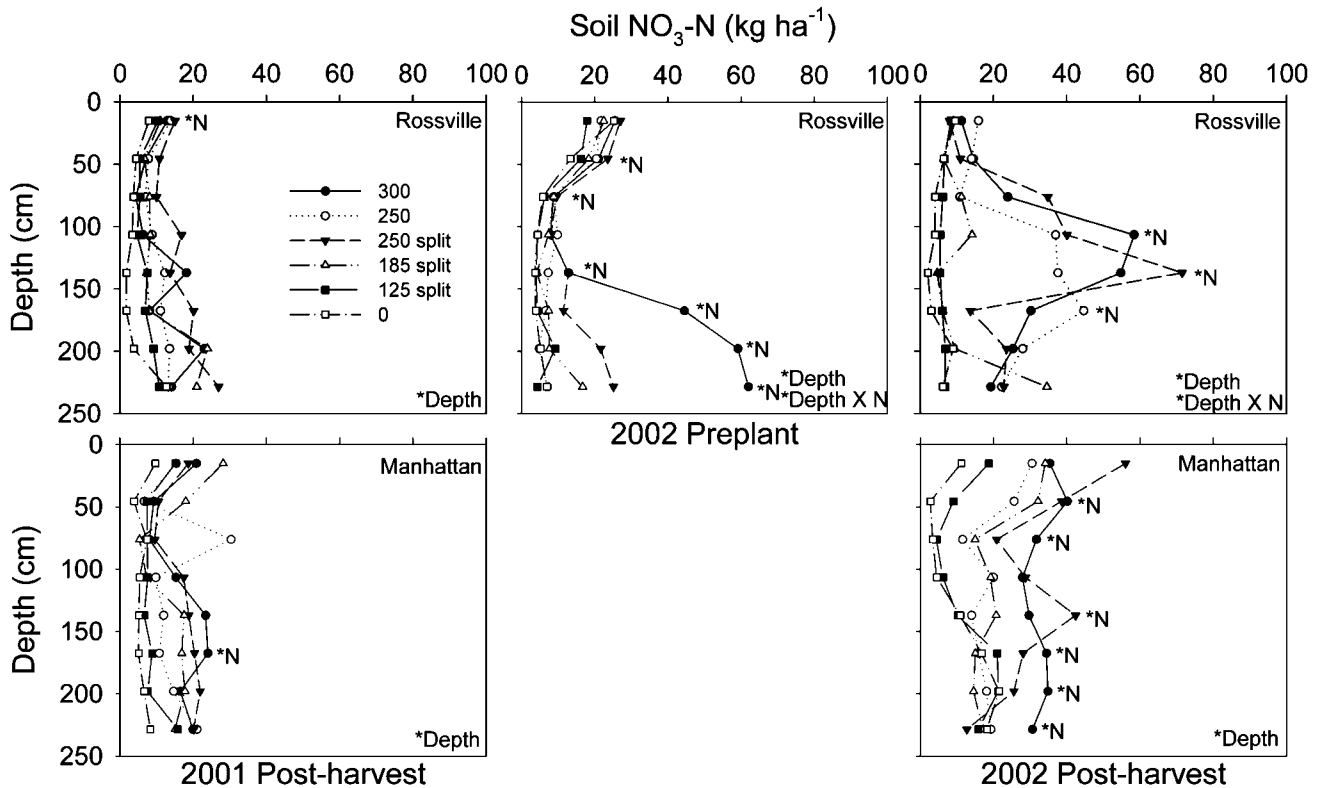


Fig. 2. Preplant and post-harvest soil NO₃–N concentration (0- to 240-cm depth) at Rossville and Manhattan for six N treatments (kg N ha⁻¹). Significant differences in NO₃–N among N treatments for a given depth are indicated with a *N, in NO₃–N among sampling depth with a *Depth, and N treatment by depth interactions with a *Depth × N, as determined by repeated measures analysis at α = 0.10.

N ha⁻¹ exceeded crop requirements, resulting in elevated NO₃-N between 90 and 180 cm for the 250 kg N ha⁻¹ and 300 kg N ha⁻¹ treatments (Fig. 2). The primary difference between the 2001 and 2002 growing seasons at Rossville was an additional 13.5 cm of total precipitation (rainfall plus irrigation) received in 2001 compared to 73.1 cm received in 2002 (Gehl et al., 2005a). Variability in rainfall can substantially effect NO₃ movement through the soil. Endelman et al. (1974) reported that as little as 2.5 cm of irrigation or rainfall can move soil NO₃ 15 to 20 cm in a loamy sand soil. Based on this estimate, the difference in rainfall between 2001 and 2002 at Rossville could account for as much as 190 cm (depending on crop evapotranspiration, precipitation frequency, and soil water status) of additional downward movement at this site in 2001, compared to 2002; and provides a probable explanation for the differences observed in NO₃ distribution between the post-harvest profiles at Rossville.

The Ellinwood 1.0× IS treatment received 73.9 cm of total precipitation (rainfall plus irrigation) during the 2002 growing season (similar to Rossville in 2002); yet post-harvest soil samples did not indicate nearly as much NO₃ in the soil profile (Fig. 1) as observed at Rossville (Fig. 2). The same N treatments were applied at Rossville and Ellinwood, mean grain yield were within 0.3 Mg ha⁻¹ for these two sites (Gehl et al., 2005a), and similar amounts of water were received at both sites. One distinction that was evident was the difference in sand content in the top 90 cm (Table 3). Lesser sand content at Rossville (<0.68 g g⁻¹) represents a textural transition at 90 cm that would impede water movement until the soil was sufficiently saturated to allow water movement into the sandier textured lower horizons. Despite the many similarities between these two sites, post-harvest soil samples provided two slightly different conclusions about the environmental risk associated with NO₃ leaching.

The impact of below average growing season rainfall in 2002 was also evident at Manhattan. Growing season rainfall plus irrigation was 61.5 cm in 2002, 12 cm less than recorded in 2001 (Gehl et al., 2005a). Nitrogen treatment effects were observed throughout the post-harvest profile in 2002 compared with only one sample depth in 2001 (Fig. 2). The 300 kg N ha⁻¹ single application in 2002 resulted in the greatest NO₃ content between 60 and 90 cm and between 210 and 240 cm (based on pairwise comparisons). At a depth between 120 and 210 cm, the 300 kg N ha⁻¹ rate and the 250 kg N ha⁻¹ split application resulted in the greatest NO₃ content, which is consistent with the observation that these rates were above the minimum rate required to obtain maximum yield (185 kg N ha⁻¹ split). The more pronounced effects of N fertilizer treatments observed in the profile in 2002, compared with 2001, was likely a function of below average rainfall in 2002. While sufficient precipitation to induce downward movement and redistribution occurred in 2002, precipitation may have been less than required to move most of the soil NO₃ to below 240 cm (as perhaps occurred in 2001). Although sand content was generally less in the soil at Manhattan, an abrupt textural transition

zone that might impede downward water movement was not present at Manhattan.

The 2001 results from post-harvest soil sampling at Pretty Prairie provided a marked contrast to the results found at Ellinwood, Rossville, and Manhattan. Total post-harvest NO₃-N content (averaged across all N treatments) in 2001 for the 240-cm profile at Pretty Prairie East was 230 kg N ha⁻¹ compared with 249 kg N ha⁻¹ at Pretty Prairie West (Table 4). Distribution of NO₃ within the profiles varied greatly between the two Pretty Prairie sites in 2001 (Fig. 3). Although these two sites were located in the same field, differences in soil textural properties within each plot site (Table 3) likely influenced the distribution of NO₃ found in the post-harvest soil profiles. Lesser sand content (0.51 to 0.75 g g⁻¹) between 0 and 90 cm was observed at Pretty Prairie East. Mean total NO₃-N content above 60 cm for the four N treatments > 110 kg N ha⁻¹ was 213 kg ha⁻¹, while mean total NO₃-N content below 60 cm for these same N treatments averaged 93 kg ha⁻¹ (Fig. 3). Sand content at Pretty Prairie West exceeded 0.81 g g⁻¹ throughout the 240-cm profile, and there was not a significant depth effect observed in 2001 at this site for post-harvest soil NO₃ (Fig. 3), suggesting that considerable NO₃ had already leached at the West site during the 2001 growing season.

Large quantities of soil NO₃ remaining in the Pretty Prairie East profile after the 2001 harvest presented a substantial leaching risk during the winter. However, results from the 2002 preplant sampling showed that the total quantity of NO₃ in the profile was similar to the post-harvest 2001 amount (272 kg ha⁻¹, Table 4), and distribution of NO₃ did not change dramatically between fall 2001 and spring 2002 (Fig. 3). Despite N rates in excess of that required for maximum yield (at Pretty Prairie the farmer had inadvertently applied additional N fertilizer), NO₃ did not move substantially down the soil profile at the East site between spring 2001 and spring 2002.

The relatively large amount of NO₃-N observed near the surface at Pretty Prairie East in 2001 were not evident after the 2002 harvest, and an increase in NO₃ content occurred with depth (Fig. 3). The shift in soil profile NO₃ distribution in 2002, compared with 2001, may be a function of the increased precipitation observed for this site in 2002 (+14 cm relative to 2001, Gehl et al., 2005a). When sufficient precipitation was received to move water, and thus NO₃, below the textural transition observed in the top 90 cm at Pretty Prairie East (Table 3), continued downward movement would proceed unimpeded in the sandy textured subsoil (sand content > 0.80 g g⁻¹). Lund et al. (1974) showed a close relationship between NO₃ concentration below the root zone and soil texture in the root zone. A linear relationship ($r^2 = 0.68$) indicated that as clay content of the control section increased there was a decrease in the amount of NO₃-N below the 1.8-m depth. Similarly, Hahne et al. (1977) reported less total NO₃ after the growing season and greater NO₃ leaching losses in a fine sandy loam soil compared with clay loam and silt loam soils; while Linville and Smith (1971) reported an ef-

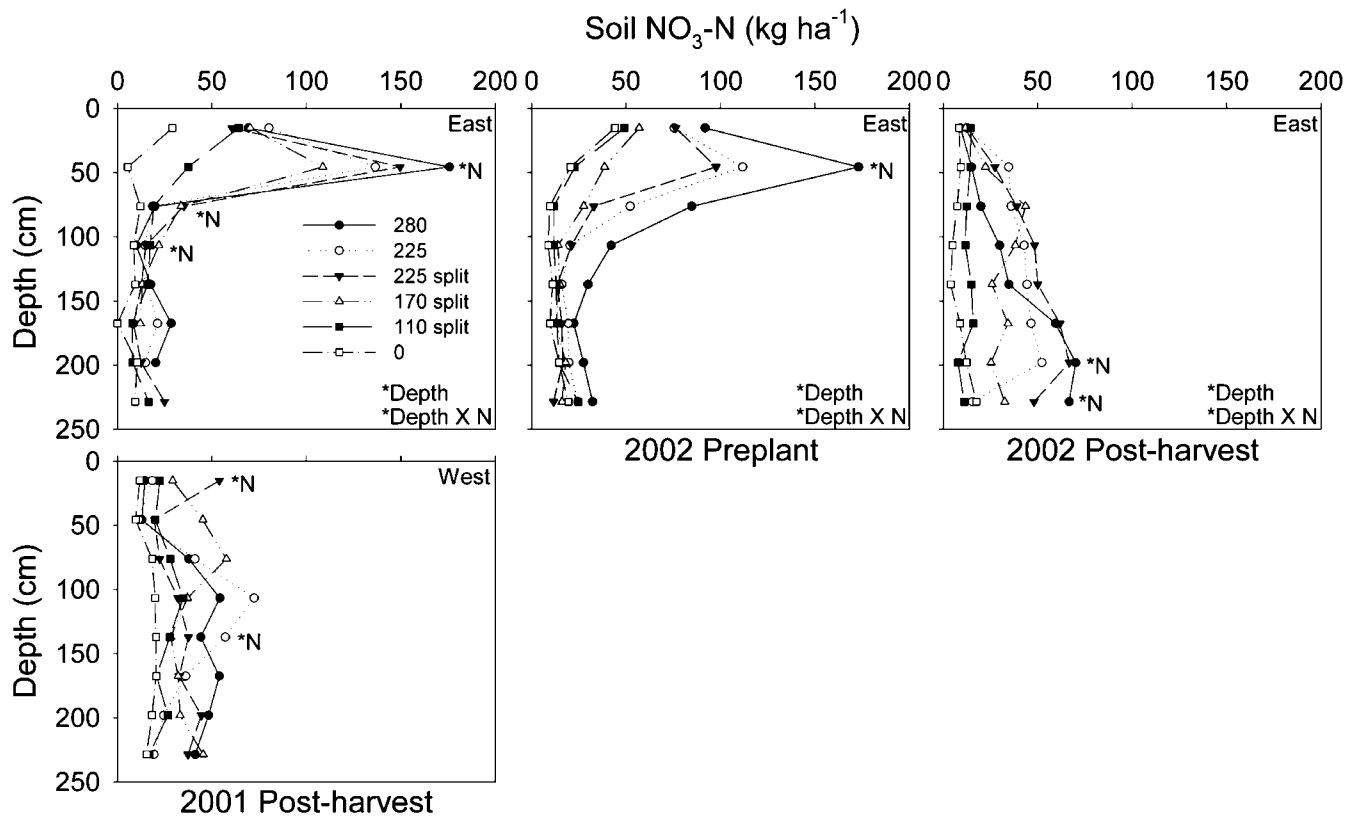


Fig. 3. Preplant and post-harvest soil $\text{NO}_3\text{-N}$ concentration (0- to 240-cm depth) at Pretty Prairie for six N treatments (kg N ha^{-1}). Significant differences in $\text{NO}_3\text{-N}$ among N treatments for a given depth are indicated with a *N, in $\text{NO}_3\text{-N}$ among sampling depth with a *Depth, and N treatment by depth interactions with a *Depth \times N, as determined by repeated measures analysis at $\alpha = 0.10$.

fect of seasonal precipitation on NO_3 distribution in soil profiles. In the drier years of the latter study, NO_3 was concentrated in the upper profile horizons (<60 cm), indicating relatively less leaching through the profile. While the difference in NO_3 distribution in the Pretty Prairie East profile observed between 2001 and 2002 seems conspicuous, the magnitude of difference between years is not improbable, given the greater sand content lower in the soil profile and the greater precipitation at this site in 2002. In any case, post-harvest soil $\text{NO}_3\text{-N}$ was not a certain indicator of NO_3 leaching risk at Pretty Prairie, depending on rainfall and location within the field.

The importance of N management and growing season precipitation on profile NO_3 content and distribution can be illustrated when observed grain yield is considerably less than anticipated yield. The post-harvest 240-cm profile at Scandia in 2001 had a total $\text{NO}_3\text{-N}$ content of 189 kg ha^{-1} (Table 4). In 2001, grain yield did not respond to N fertilizer rates greater than 125 kg ha^{-1} , regardless of application timing; yet, N treatment differences in post-harvest NO_3 were significant only between 30 and 60 cm (Fig. 4). By contrast, the 2002 results from post-harvest sampling at Scandia indicated that movement of soil NO_3 down the profile during the growing season was limited to about 120 cm (Fig. 4). Single preplant applications resulted in significantly greater NO_3 content than the NO_3 content observed for all other N treatments for each sampled depth between 30 and 210 cm, with the exception of the 250 kg N ha^{-1} split

application between 30 and 60 cm (based on pairwise comparisons). Nitrate movement to the lower 120 cm of the post-harvest profile was likely limited by two factors: precipitation and profile soil texture. Rainfall during the 2002 growing season (April to September) at Scandia was 26 cm less than the 30-yr average (Gehl et al., 2005a). Because of water use restrictions, supplemental irrigation at this site was not applied in 2002, so the corn crop only received about 31 cm of total precipitation. Consequently, grain yield averaged only 3.3 Mg ha^{-1} across all N treatments, and no response to N fertilizer was observed. This yield level is well below what would normally be expected at this site (mean yield was 10.8 Mg ha^{-1} in 2001). A difference in yield of 7.5 Mg ha^{-1} between years translates to about 110 kg N ha^{-1} less N used by the growing crop at this site in 2002 (based on 1.5% N content in corn grain, Pierre et al., 1977). The amount of excess N (applied as fertilizer) accounts for the relatively greater NO_3 content in the top 120 cm of soil in 2002. Hahne et al. (1977) reported that proper irrigation of soils with rapid internal drainage can markedly reduce NO_3 leaching, with reductions in loss from 48% when irrigation was not applied to 5% when the crop was properly irrigated. Additionally, precipitation likely was insufficient to move the NO_3 to lower depths of the sampled profile. An increase in sand content from 0.52 to 0.83 g g^{-1} at about the 120-cm depth (Table 3) would impede water and NO_3 movement below this depth during a relatively drier growing season, similar to

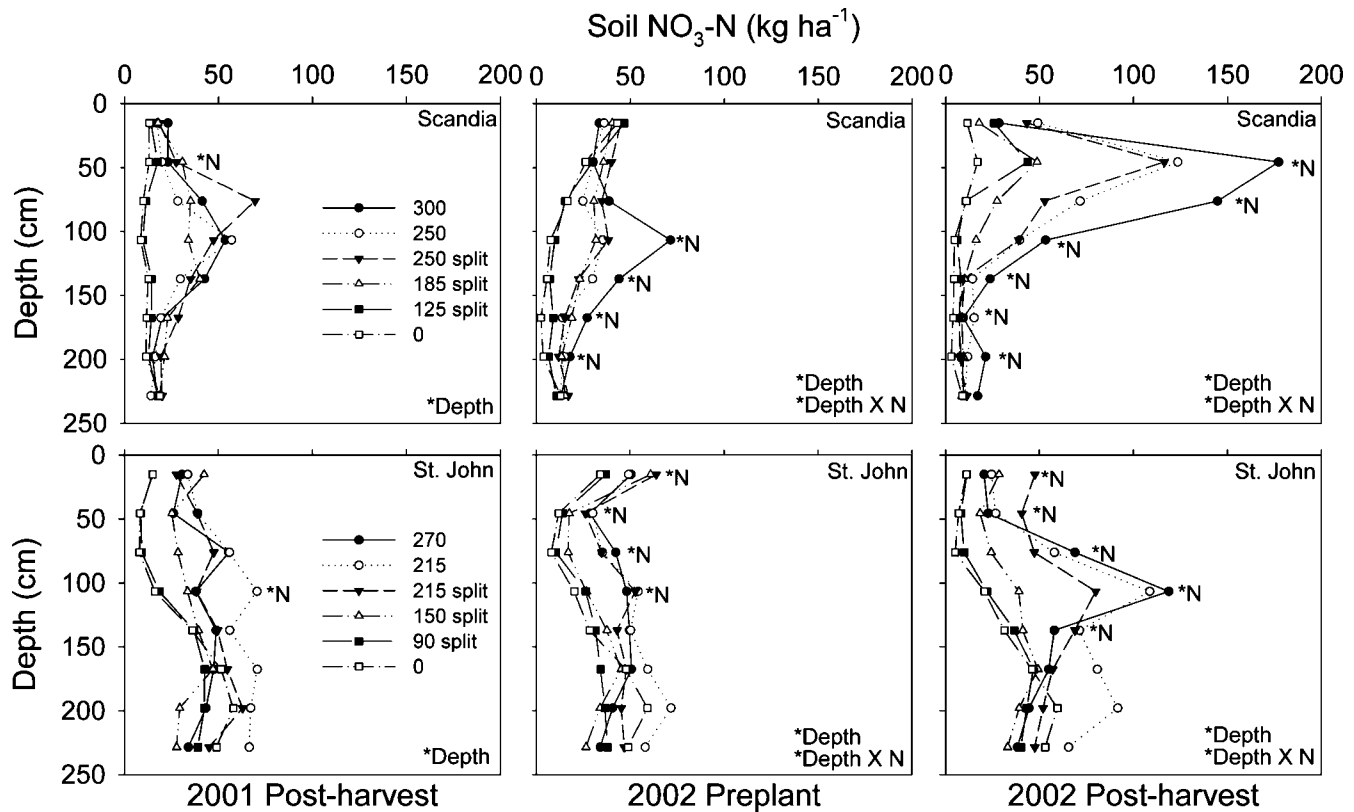


Fig. 4. Preplant and post-harvest soil NO₃-N concentration (0- to 240-cm depth) at Scandia and St. John for six N treatments (kg N ha⁻¹). Significant differences in NO₃-N among N treatments for a given depth are indicated with a *N, in NO₃-N among sampling depth with a *Depth, and N treatment by depth interactions with a *Depth X N, as determined by repeated measures analysis at $\alpha = 0.10$.

the conditions and results observed at Rossville in 2002 (Table 3; Fig. 2). In a stratified soil, an advancing wetting front moving through fine soil material is restricted by underlying coarse material. The wetting front will not advance further until the soil above this transition becomes nearly saturated (Gardner, 1979).

The impact of profile textural changes (Table 3) on NO₃ distribution in the soil was notable at Rossville (Fig. 2), Pretty Prairie East (Fig. 3), Scandia (Fig. 4), and St. John (Fig. 4). These effects were consistent with those reported by Lund et al. (1974) and Hahne et al. (1977), who indicated that greater NO₃ leaching occurs in sandy textured soils compared with soils with greater clay contents. The confounding role of growing season precipitation was also evident at several of the sites evaluated here. Generally, sites receiving below average rainfall had greater profile NO₃ content than sites receiving average or above-average rainfall. Changes in total NO₃ content and distribution appeared to be impacted by growing season precipitation at individual sites. Similarly, MacGregor et al. (1974) attributed increases in NO₃ concentration 7 to 10 m deep in the profile to above average rainfall in consecutive years of a 15-year study.

CONCLUSIONS

The sandy textured soils along Kansas rivers were selected for this study, which are loosely grouped together when considered in the context of N management in

Kansas. Despite similarities among these sites, post-harvest soil NO₃ content was not conclusive evidence for determining NO₃ leaching risk associated with N rates in excess of plant uptake (>185 kg N ha⁻¹). Post-harvest NO₃ distributions in the soil profile (0–240 cm) were variable among sites, variable within a field, and sometimes variable between years for the same site. At Ellinwood and Pretty Prairie West, where sand content was uniformly high (>0.81 g g⁻¹) throughout the soil profile (Table 3), post-harvest soil NO₃ increased slightly with depth. Additional irrigation (125% optimal) at Ellinwood resulted in N treatment effects on soil NO₃ content lower in the soil profile compared to optimal irrigation; and results suggested that NO₃ was moving below the 240-cm depth. When silt and clay content were greater in the upper part of the soil profile, as at Rossville and Scandia, and rainfall plus irrigation was less than usual, post-harvest soil NO₃ was elevated under excess N applications. At these same sites but with the additional water inputs observed in 2001, post-harvest soil NO₃ did not provide conclusive evidence of NO₃ leaching with the higher N rates. Two sites within the same field at Pretty Prairie illustrated the contrasting results that can be observed in post-harvest soil NO₃ content under similar growing conditions, but slightly different soil characteristics. The soil at the East site had greater silt and clay content in the top 90 cm, whereas the sand content at the West site was uniformly high throughout the 240-cm profile. Post-harvest soil NO₃ in 2001 were

elevated in the top 90 cm at the East site, reflecting the risk of NO₃ leaching. Post-harvest soil samples from the West site did not provide the same evidence, and NO₃ had probably leached below the 240-cm during the growing season.

Findings of this research illustrate that relatively low post-harvest NO₃ content does not necessarily indicate that N and water management practices at a site were not contributing to N leaching. In several instances, evidence of increased NO₃ for above-optimum N rates was not apparent in the post-harvest profiles. While the lack of NO₃ accumulation lower in the soil profile may signify a relatively low winter leaching potential, results from this study indicated that significant amounts of NO₃ may have already leached to below the 240-cm depth by the end of the growing season.

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