Developments in Environmental Science, Volume 5
D. Sarkar, R. Datta and R. Hannigan (Editors)

ISSN: 1474-8177/DOI:10.1016/S1474-8177(07)05018-8

Chapter 18

Factors affecting spatial patterns of vadose-zone nitrate in south-central Kansas

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Abstract

Vadose-zone nitrate concentrations vary spatially and temporally as a function of multiple factors including soil properties, land use, and climate. Field studies in south-central Kansas used soil core and lysimeter techniques to study factors affecting temporal and spatial variations in vadose-zone nitrate. Statistical analysis of data from 34 irrigated and 31 dryland sites indicated that vadose-zone nitrate concentrations at the end of the growing season were most strongly influenced by: (1) the nitrogen fertilizer-application rate, (2) the amount of nitrate present below the root zone before planting, and (3) the amount of nitrate in the root zone prior to planting. Soil-water lysimeter data indicated that nitrate was moving through most soils but not leaching out of all soils. Analysis of within-field variability of plant-available nitrogen (PAN = nitrate and ammonium) at two of the 65 fields mentioned above (1 dryland and 1 irrigated) indicated that a higher percentage of the PAN was nitrate in the dryland farmed soils. Irrigated soils had more total PAN but a greater percent of the PAN in these soils was ammonium. Nitrate was apparently preferentially used and/or leached from these soils by irrigation water. Spatial patterns of PAN were strongly influenced by topography and internal stratigraphy with more PAN occurring at lower landscape positions with less permeable stratigraphy at both sites.

18.1. Introduction

Much research has been conducted to determine soil characteristics that affect the movement or retention of nitrogen particularly in the upper root zone. Examples of these properties include the hydraulic conductivity, bulk density, pH, and cation exchange capacity as well as the underlying stratigraphy and the surface topography (Burrough, 1991; Hall and Olson, 1991; Lammers and Johnson, 1991; Townsend et al., 1997). In addition, studies in Canada, South Dakota, and California illustrate the impact that landforms have on soil moisture and other soil properties influencing the field-scale variability of soil nitrogen and ultimately on crop yield and yield predictions (Pennock, 1998; Franzen and Kitchen, 1999; Moulin et al., 2002; Onsoy et al., 2005). It is also known that farming practices such as nitrogen fertilizer application rates and irrigation versus dryland cropping practices can affect retention and leaching rates for nitrate (Townsend et al., 1995).

18.1.1. Spatial and temporal variability of vadose-zone nitrate

Spatial representation of soil variability is important in order to evaluate the soil properties that affect the vertical movement of water and solutes, including nitrogen, through the soil and underlying vadose zone. Several important properties include the underlying stratigraphy, surface topography, and land use, as well as measurements of nitrate, ammonium, and total nitrogen (Burrough, 1991; Hall and Olson, 1991; Lammers and Johnson, 1991; Townsend et al., 1997).

Spatial variability in vadose-zone nitrate can result from variations in land use (e.g., types of crops, tillage practices, fertilization-application rates, types of fertilizer applied, and irrigated versus dryland farming techniques), which can cause between-field variations in nitrogen loading and nitrate movement/retention. Soil variability with respect to organic-matter content, permeability, bulk density, pH, stratigraphy, and other properties causes within-field variations in initial nitrogen content (before fertilization), nitrate retention, nitrate transformations, plant uptake, and ultimately nitrate leaching through the unsaturated zone to underlying aquifers. This type of variability can be difficult to quantify at different spatial scales due to the inherently large variability in soil and underlying unconsolidated sediments that are alluvial in origin (Wilding and Drees, 1973; Weerts and Bierkens, 1993; Townsend et al., 1996). All the listed factors can impact the analysis of nitrate data when trying to determine soil-nitrogen loading rates, nitrate movement, and sources of nitrate contamination as measured in soils and groundwater samples from wells. Determination of the spatial variability of soil stratigraphy, topography, and land use at a field scale and how this spatial variability affects the movement and retention of potential contaminants such as nitrate is necessary for vadose-zone studies as well as aquifer impact studies.

Temporal variability can be evaluated on the basis of anthropogenic and environmental factors. Temporal variability of nitrate is related to crops grown and activities related to farming type (irrigated or dryland), and water application (Bruckler et al., 1997). Land uses, including such factors as the timing and quantity of fertilization, or irrigation and crop growth stage strongly influence the amount of total nitrogen and nitrate in the soil that is available for plant uptake or leaching at any given point in time. Environmental factors such as precipitation events and soil temperature also impact temporal variability by providing water for nitrate leaching and by influencing the rates of microbial nitrification/denitrification processes. Most studies have evaluated these properties with respect to potential groundwater contamination (Whittemore et al., 1987; Townsend and Sleezer, 1995; Igbal et al., 1997; Townsend et al., 1997) and not to the impact on spatial variability of soil properties in the vadose zone.

18.1.2. Description of study area

This paper summarizes results from two studies that were designed to evaluate factors influencing the temporal and spatial variability of vadose-zone nitrate. The study areas are in Harvey County in south-central Kansas, USA (Fig. 18.1). Land uses in the area that have the potential to impact groundwater nitrate concentrations include irrigated and dryland farming, dairies, and cattle feedlots. Harvey County is an area underlain by a significant aquifer, locally referred to as the Equus Beds (Macfarlane, 2000), that is part of the larger High Plains aquifer system as defined by the U.S. Geological Survey (2005). The Equus Beds aquifer is a thick and productive system that provides water for domestic, agricultural, and industrial use for approximately 21 percent of the population of Kansas (Sleezer, 2001), and it has been a major water supply system for the area for more than 70 years (Williams and Lohman, 1949; Stramel, 1967). It is, therefore, an important water resource that is potentially at risk for contamination by nitrate because it is overlain in places by permeable soils, relatively thin unsaturated zones ($<10\,\mathrm{m}$), and numerous sources for nitrate pollution.

18.1.3. Description of study objectives

The first study was designed to evaluate the relationship between farming type (irrigated versus dryland) and fertilization differences between

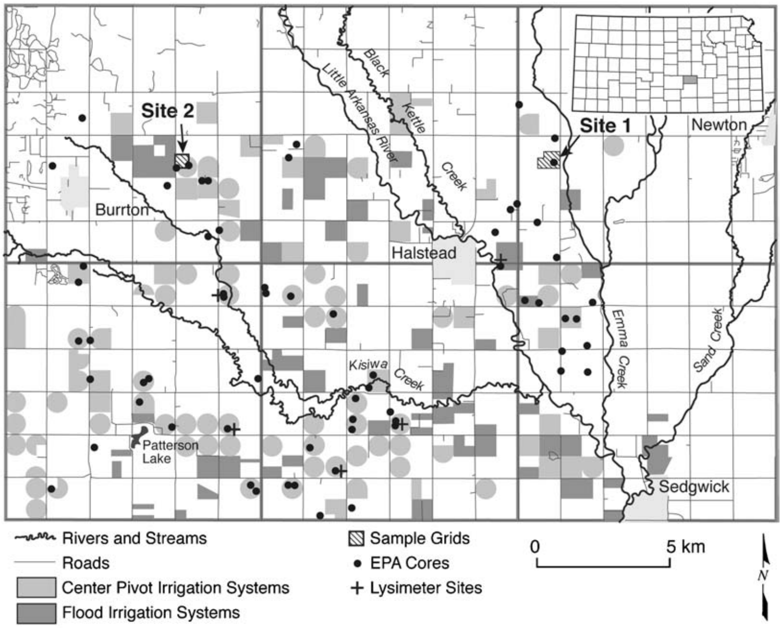

Figure 18.1. Location of soil-coring sites, soil-water lysimeter sites, land use by irrigation or dryland-farming practice, and two field sites (site 1 and site 2) for investigation of effects of topography and soil stratigraphy on nitrate movement in the vadose zone in south-central Kansas.

farming types on the occurrence of vadose-zone nitrate and observed groundwater nitrate values. A variety of temporal and land-use factors were statistically evaluated in this study to determine their influence on soil-nitrate retention and movement (Townsend and Sleezer, 1995). These factors included crop type, cropping history, irrigated versus dryland farming practices, and fertilizer-application rates. The study was funded by the U.S. EPA (1992–1994; Townsend and Sleezer, 1995) and will be referred to as the EPA study. It was a two-year soil-nitrogen monitoring study. Sampling by cores was performed at fixed locations in 65 fields (34 irrigated and 31 dryland) prior to planting in the spring and after harvest in the fall for two years. Methods used for soil sampling and analyses are presented in Appendix 1.

The second study evaluated field-scale spatial variability of nitrate using soil cores, soil-characterization pits, electromagnetic-induction measurements, and measurements of root-zone plant-available nitrogen (PAN, $NO_3 + NH_4$) at two study sites used previously in the EPA study. Sampling methods used in this study are presented in Appendix 1. This study was funded by the Kansas Water Resources Research Institute (KWRRI; USGS funds, 1994–1995; Townsend et al., 1997) and will be called the KWRRI study.

During the course of the EPA study two general observations were made about soils in the study area: (1) descriptions of soils sampled often did not match with soils described in the Harvey County soil survey (Hoffman and Dowd, 1974); and (2) most soil descriptions indicated similar surface textures (e.g., loamy sand or sandy loam), but subsurface horizons in many cases had strongly contrasting and highly variable textures (e.g., loam, clay loam, silty clay loam, or silty clay). Both of the chosen sites for the KWRRI study had soils with sandy surface textures and rolling sand-dune topography, but cores from the previous EPA study indicated that subsurface textures could be expected to vary. Soils at the two sites were not mapped as the same units in the Harvey County soil survey (Hoffman and Dowd, 1974) but, due to the observations from the EPA study, the soils were considered to be relatively similar. Site 1 was farmed using dryland methods and site 2 was irrigated with a center-pivot system. While the EPA study focused on temporal variations in vadose-zone nitrate at single core or lysimeter locations within fields, the KWRRI study focused on characterizing within-field spatial variability in vadose-zone nitrate and comparing soil-nitrate variability between fields farmed with different techniques (dryland versus irrigated).

18.2. Results

18.2.1. Temporal and land-use affects on nitrate movement—EPA study

Figure 18.1 shows the spatial patterns of irrigated cropland (center-pivot versus flood), the location of soil-coring sites at irrigated and dryland farms, and soil-water lysimeter sites that were evaluated in the EPA study. The two sites used for the evaluation of the field-scale spatial variability of soil nitrate in the KWRRI study are also indicated. The majority of the irrigated sites sampled in this study were center-pivot irrigated sites.

At the sites sampled in the EPA study, dryland crops included milo (grain sorghum, 80%) and wheat (15%) while irrigated crops included corn (45%), soybeans (32%), and milo (20%). Median fertilizer-application rates by farming method (dryland versus irrigated) and crop grown are shown in Fig. 18.2 (Appendix 2, Table A1). This figure illustrates the much higher nitrogen fertilizer-application rates that are used with irrigated farming practices. Differences in fertilizer-application rates were evaluated

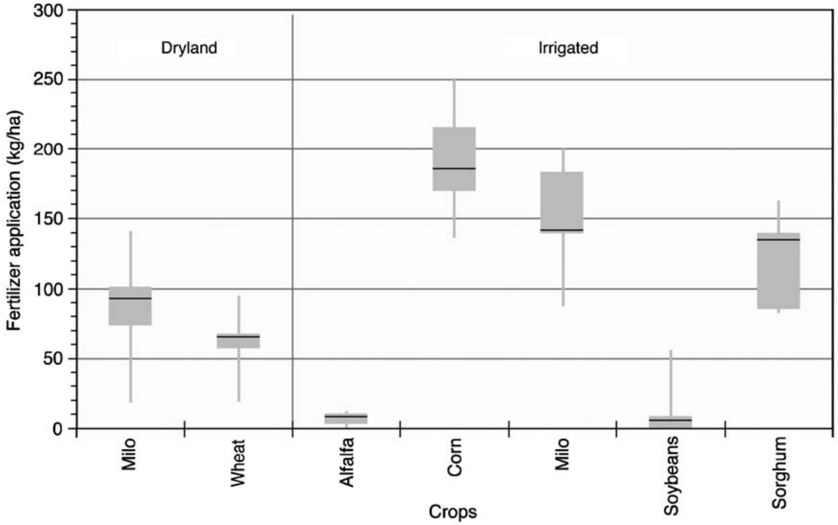

Figure 18.2. Median fertilizer-application rates (shown by black lines in box plot) by farm type and crop grown in study area. Note that irrigation fertilizer rates are higher than dryland.

using the non-parametric Kruskal–Wallis test (Appendix 1; Appendix 2; Table A1). The Kruskal–Wallis value of $\rho = 0.0013$ indicates that differences in fertilizer-application rates between dryland and irrigated farming practices were statistically significant ($\alpha = 0.1$; Townsend and Sleezer, 1995).

The higher nitrogen fertilizer-application rates result in increased nitrogen loading on these soils. Soil-nitrate concentrations were therefore expected to be higher in soils in irrigated fields. The combination of higher soil-nitrate concentrations and the addition of irrigation water to these fields were expected to represent a greater risk for nitrate leaching through the vadose zone into the underlying aquifer.

Because most soil nutrient testing methods focus on evaluating the root zone (upper 1.2 m or shallower) (Fjell et al., 1994), soil-nitrate values were evaluated in two sections: upper root zone (0–1.2 m) and below the root zone (1.2–3 m). Figures 18.3A and B show the separated soil-nitrate values for both years and land uses. In all cases median soil-nitrate concentrations were higher in irrigated soils regardless of sampled interval (Appendix 2, Table A2, significance level $\alpha = 0.1$, range of ρ values from 0.0002 to 0.089). This can largely be explained by higher nitrogen fertilizer-application rates applied to irrigated fields with higher crop-yield goals. The values for 1993 were lower than those for 1992 due to the intense rainfall and flooding that occurred during the growing season (Townsend and Sleezer, 1995). In most cases the range in soil-nitrate concentrations was greater in irrigated fields as compared to dryland fields reflecting the variability in nitrate concentrations associated with plant uptake, soil properties, leaching, and fertilizer application differences.

18.2.1.1. Soil-water lysimeter study

Six lysimeter sites were chosen as a subset of the original EPA irrigated core study sites for a more time-intensive study of soil nitrate (Fig. 18.1). Each site was an irrigated field in which corn or sorghum was planted and nitrogen fertilizer-application rates were between 196 and 246 kg ha^{-1}. Soils varied from very sandy throughout the upper 3 m to soils that were silt loam at the surface with silty clay subsoil and coarse sand at 3-m depth. The soil-water lysimeters were installed at 0.6-, 1.2-, 1.8-, and 3-m depth at each site without regard for differences in stratigraphy (Appendix 1). Soil cores and lysimeter samples were obtained and analyzed at four different times during the growing season (May, June, July, and August).

The fertilizer-application information provided by the farmers indicated either a spring, pre-plant application and an application later in the

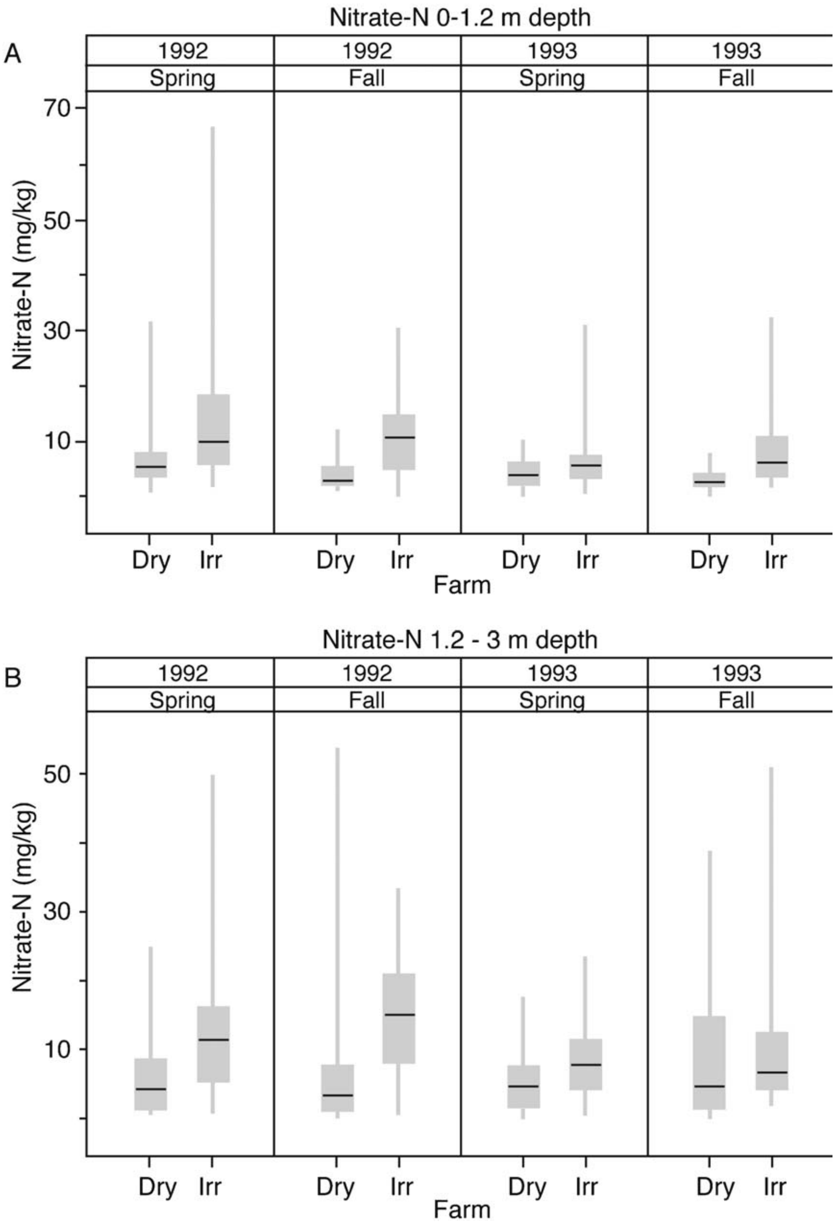

Figure 18.3. A and B Comparison of range and median nitrate-N concentration for dryland and irrigated site soil cores. Median values shown by lines in boxes. Irrigated sites show higher soil-nitrate concentrations than dryland sites for all time periods except fall 1993.

season or just a spring pre-plant application. In either case there was not a continuous input of nitrogen into these systems. The soils at these six sites had a variety of surface textures and subsurface horizons. Surface-soil textures ranged from coarse (loamy-fine sand) to fine (silty-clay loam). At four of the sites the lysimeters installed at 3 m were located within a horizon described as sand or coarse sand with finer-textured horizons directly above them. Soil water perched in or directly above the finer-textured horizons, and no sample was recovered from the lysimeters installed at a 3-m depth in coarse sand. The permeability contrast between the overlying fine-textured layers and the underlying coarse sand (Fetter, 1980) may have prevented water and nitrate movement downward to the 3-m depth. Also, the large pores in the unsaturated coarse sand probably allowed the lysimeters to lose vacuum relatively rapidly. This may have caused the lysimeters to miss any flow through these coarse sandy layers if flow occurred too long after vacuum was applied to the lysimeters (Townsend and Sleezer, 1995).

Table 18.1 contains the soil-water nitrate-concentration data obtained from the six lysimeter sites. The highest concentrations ($>200\,\mathrm{mg\,l^{-1}}$) were obtained at site I-14. Soils at this site were classified as a Punkin series (Fine, mixed, superactive, mesic Leptic Vertic Natrustolls). These soils were salty with electrical-conductivity measurements of soil water

Table 18.1. Soil-water nitrate concentrations from lysimeters installed at six sites in Harvey county, Kansas summer of 1992

Month	Depth (m)	I-14 ($\mathrm{mg\,l^{-1}}$)	I-15 ($\mathrm{mg\,l^{-1}}$)	I-18 ($\mathrm{mg\,l^{-1}}$)	I-29 ($\mathrm{mg\,l^{-1}}$)	I-30 ($\mathrm{mg\,l^{-1}}$)	I-32 ($\mathrm{mg\,l^{-1}}$)
May	0.6	221.2	99.1	39.5	32.7	26.9	N.D.
	1.2	76.1	89.2	40.2	33.6	15.3	19.9
	1.8	46.7	66.8	62.3	98.9	38.8	N.D.
	3.0	N.D.	N.D.	N.D.	31.6	52.8	N.D.
June	0.6	230.2	101.8	47.9	58.7	50.1	64.1
	1.2	79.2	97.5	36.3	42.0	21.9	19.4
	1.8	53.3	76.7	55.8	86.9	22.4	22.2
	3.0	N.D.	N.D.	N.D.	37.7	60.1	N.D.
July	0.6	224.2	129.1	37.0	61.6	75.4	9.9
	1.2	84.4	104.3	41.8	78.3	31.2	30.0
	1.8	58.2	85.8	47.0	51.7	8.8	20.3
	3.0	N.D.	N.D.	N.D.	36.3	67.0	N.D.
August	0.6	N.D.	164.8	8.1	84.4	67.3	0.8
	1.2	94.1	111.1	47.9	131.2	37.2	36.1
	1.8	61.4	90.1	40.4	62.5	10.4	41.8
	3.0	N.D.	N.D.	N.D.	32.1	76.7	N.D.

N.D., not determined.

extracted in lysimeters as high as 20,000 μmhos cm^{-1}. Nitrate concentrations in soil water remained relatively constant throughout the growing season at this site probably related to evapoconcentration of solutes in the soil profile, lower plant uptake due to salty conditions, and low denitrification rates due to high pH (Townsend and Sleezer, 1995).

The lowest nitrate concentrations in soil water were measured at I-32, which was the only flood-irrigated site and had silty-clay loam textures throughout its profile (Elandco—fine-silty, mixed, superactive, thermic Cumulic Haplustoll). The highest soil-water nitrate concentrations measured at sites I-15 (unnamed series—fine, mixed, superactive, thermic Udertic Haplustalf) and I-29 (Pratt—sandy, mixed, thermic Psammentic Haplustalf) were sampled toward the end of the growing season and at shallow depths (0.6 and 1.2 m, respectively). Clearly defined pulses of nitrate movement were not readily observable in the lysimeter data, and nitrate concentrations remained relatively constant in some soils (e.g., I-14, I-15, I-29 in Table 18.1).

The lysimeter data show that high nitrate concentrations occur in irrigated soils with higher fertilizer-application rates (Fig. 18.2). The data also indicate that if the soil is not uniformly sandy with depth, other factors such as organic-matter content, silt and clay content, and perching layers in the vadose-zone impacted the movement of nitrate through the profile.

18.2.3. Factors affecting spatial variability of plant-available nitrogen—KWRRI study

The second study in Harvey County (KWRRI) evaluated the field-scale spatial variability of plant-available nitrogen ($PAN = NO_3 + NH_4$) and determined the effects of topography, soil stratigraphy, and farming method (irrigated versus dryland) on the spatial variability of PAN. Its focus was on the upper part of the root zone (upper 75 cm of soil).

18.2.3.1. Stratigraphic effects

Both sites had soils with an eolian sand component in the near surface. The soil map units delineated in the Harvey County soil survey at the two sites were representative of soils found in approximately 30 percent of the study area. The sites were also previously sampled during the EPA study (Townsend and Sleezer, 1995). The locations of the two sites are shown in Fig. 18.1 (site 1 and site 2). Soils at each site were sampled by 19 soil cores and one soil characterization pit for a total of 20 sample points at each site (Appendix 1). The sample points were selected based on topographic and electromagnetic surveys conducted at regularly spaced grid-sampling points across each study site (Figs. 18.4 and 18.6) to represent the field-scale variability in topographic position and electromagnetic ground conductivity (Townsend et al., 1997).

Site 1 is dryland farmed. Figure 18.4 shows the soil map units as delineated by the Harvey County soil survey (Hoffman and Dowd, 1974), the grid points where elevation and electromagnetic-conductivity

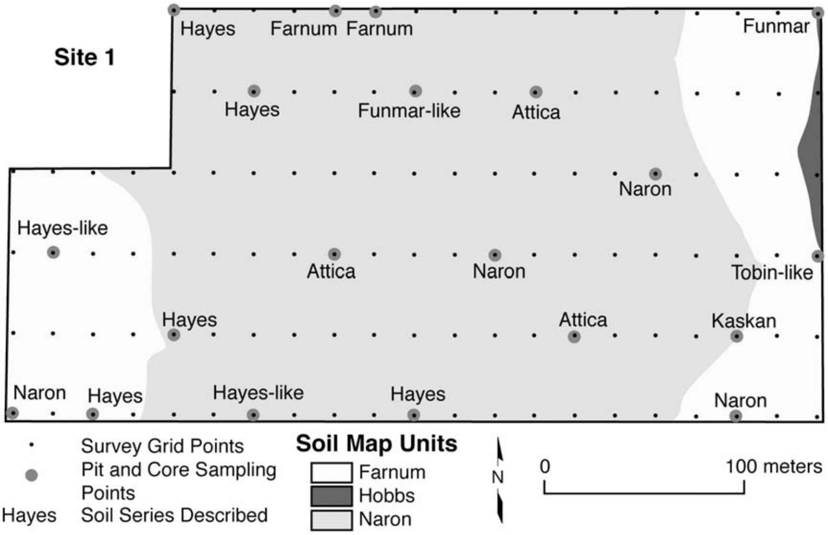

Figure 18.4. Soils map of site 1 based on USDA soil map (Hoffman and Dowd, 1974) and soil cores collected at the field site. Note variability of soil textures across the site.

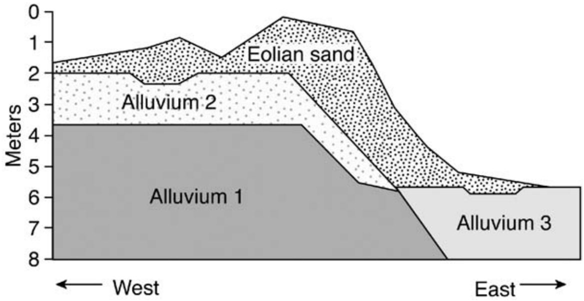

Figure 18.5. Simplified conceptual model of stratigraphy at site 1. Note the two different terrace levels (top of alluvium 2 and 3). Textural characteristics for the three alluvial strata are not uniform.

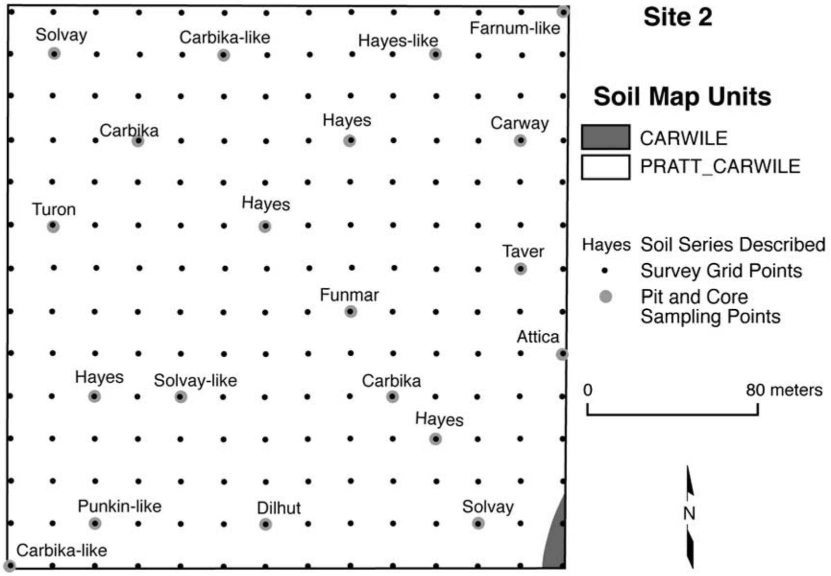

Figure 18.6. Soils map of site 2 based on USDA soil map (Hoffman and Dowd, 1974) and soil cores collected at the field site. Note variability of soil textures across the site. Soil textures are more similar to each other at this site than at site 1.

measurements were performed, and the locations where the soils were sampled by pit or core.

Deep cores (>4 m) described at site 1 indicated that four different stratigraphic units were observable in the vadose zone at site 1. Surface-soil horizons are formed in eolian sand at all sampled locations across the site, but in the subsurface three different alluvial units, two of which occur at apparent terrace breaks at the site were observed. Figure 18.5 shows a conceptual cross section of the soil stratigraphy at site 1. At least two distinct terrace surfaces exist under the eolian sand (Fig. 18.5). The boundary between the eolian and alluvial sediments is therefore not level.

The textural characteristics of the alluvium are not uniform at site 1. Alluvium 1 consists of horizons with silty clay loam, silty clay, or clay textures, and generally contains more than 35 percent clay. Alluvium 2 is much coarser textured than alluvium 1. It consists of horizons with sandy clay loam or heavy sandy loam textures, and clay contents range from about 15 to 32 percent. Alluvium 3 consists of stratified sediments with a wide range of textures (silt loam, loam, sandy loam, loamy sand, sandy clay loam, and clay loam). Clay contents range from 5 to >30 percent. Water at this site tended to perch above the less-permeable alluvium and move laterally toward the lower landscape positions carrying with it nitrate-rich vadose-zone waters.

Site 2 is irrigated. Figure 18.6 shows the soil map units as delineated by the Harvey County soil survey (Hoffman and Dowd, 1974), the grid points where elevation and electromagnetic-conductivity measurements were performed, and the locations where the soils were sampled by pit or core (Appendix 1).

The soil stratigraphy at site 2 is much simpler. Most of the soils at site 2 have formed in only two parent material strata (Fig. 18.7). The upper layer consists of eolian sand, which ranges in thickness from approximately 15 to 225 cm. Most of this material has a texture of sandy loam, fine sandy loam, or loamy fine sand. The clay content is less than 20 percent in all horizons, and the depth-weighted average clay content ranges from 7.4 to 14.5 percent. The lower layer consists of fine-textured alluvium whose upper surface appears to be nearly level. Topography at site 2 is therefore, principally a function of the thickness of the eolian sand. Textures within the alluvium are most commonly silty clay loam, silty clay, clay, or clay loam. Clay content within this layer ranges from 28 to 60 percent. Maximum clay contents are most commonly between 35 and 50 percent.

The boundary between these horizons is most commonly described as abrupt or clear. In quantitative terms, this means that the transition zone from eolian sand to clayey alluvium occurs in less than 5 cm. Wetness and redoximorphic features at the base of the eolian sand indicate that infiltrating water tends to perch for extended periods of time above the alluvium. In most cases the alluvium represents an aquitard or aquiclude for infiltrating water. This has potential to impact the movement of nitrate through the vadose zone at this site.

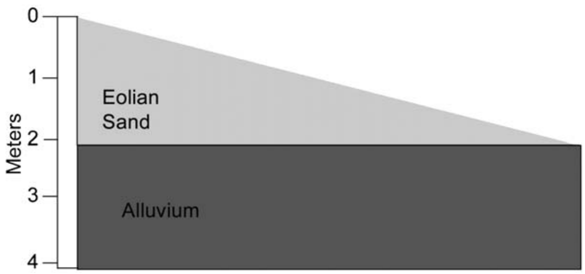

Figure 18.7. Simplified conceptual model of stratigraphy at site 2. The surface of the clay layer is relatively flat. Topographic relief is a function of the thickness of the eolian sand.

18.2.3.2. Spatial variation of plant-available nitrogen

Soil tests are routinely used to evaluate residual plant-available nitrogen in the soil between growing seasons to determine the quantity of fertilizer needed for the next crop to be planted (Fjell et al., 1994). In most soils, nitrate is the most common form of plant-available nitrogen in the soil profile, although in the Harvey County area measurable quantities of ammonium were also present. Plant-available nitrogen includes both nitrate and ammonium forms of nitrogen.

Table 18.2 contains summary statistics for nitrate-N, ammonium-N, and Total Plant Available Nitrogen (TPAN) for two depth intervals (0–30 and 30–75 cm). Median nitrate-N concentrations in the upper 30 cm are significantly different at the two sites. Nitrogen values were calculated in kg ha^{-1} in order to compare the results with fertilizer-application rates.

What is surprising is that they are generally lower at the irrigated site (site 2) where fertilizer-application rates are considerably higher. However, median ammonium-N values in the upper 30 cm are higher at the irrigated site. The net effect of these disparities is that there is no statistically significant difference ($\rho = 0.7359$) in the amount of Total Plant Available Nitrogen in the upper 30 cm of soil between the two sites even though the nitrogen fertilizer-application rate is considerably higher at the irrigated site. A similar pattern of observations occurs in the deeper depth interval sampled (30–75 cm). There are statistically significant differences in nitrate-N and ammonium-N measured at the two sites with

Table 18.2. Plant-available nitrogen and farm type

Number of samples, depth interval (cm) and nitrogen sample type	Mean (kg ha^{-1})		Median (kg ha^{-1})		Kruskal–Wallis ρ value
	Dryland (Site 1)	Irrigated (Site 2)	Dryland (Site 1)	Irrigated (Site 2)	
Number of samples	19	20	19	20	
0–30					
Nitrate-N	14.6	11.0	14.0	9.9	0.0022
Ammonium-N	12.7	17.9	10.4	18.4	0.0492
TPAN	27.3	28.9	26.6	28.5	0.7359
30–75					
Nitrate-N	35.2	26.4	30.5	24.6	0.0018
Ammonium-N	21.0	45.3	16.9	37.6	0.0003
TPAN	56.2	71.7	54.4	63.9	0.1032

TPAN, total plant available nitrogen.

Note: One sample from dryland site not used in statistical analyses due to unusually high value. See Fig. 18.9 for outlier values.

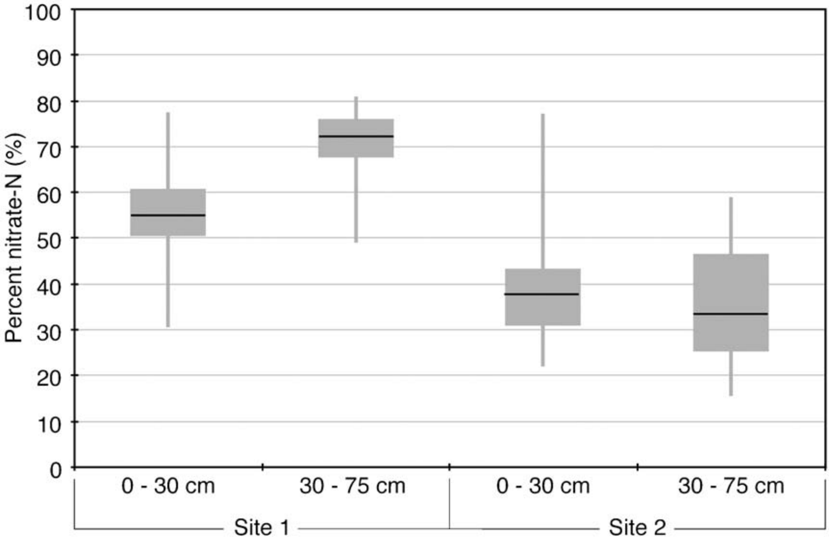

Figure 18.8. Percent of plant-available nitrogen that is nitrate-N in the upper and lower root zone. Lines in boxes indicate median values for each site.

higher concentrations of nitrate-N at the dryland farm (site 1) and higher concentrations of ammonium-N observed at the irrigated site (site 2).

Figure 18.8 shows the percentage of plant-available nitrogen that is nitrate available for movement in the upper and lower root zone at each site. The dryland site (site 1) shows a higher percentage of nitrate available for movement. However, the lack of additional water means that this nitrogen may be stored for a longer period of time within the root zone instead of moving. At the irrigated site (site 2), the median percentage of plant-available nitrogen that is nitrate is similar for both the upper and lower root zone suggesting that the additional water causes a homogenizing effect resulting in more uniform nitrate concentration throughout the vadose zone in irrigated soil.

Figure 18.9 shows the quantity of soil nitrogen in kilograms of plant-available nitrogen per hectare that are stored in the upper 75 cm of the soil profiles at sites 1 (dryland) and 2 (irrigated). The median quantities in the upper root zone are similar at both sites with a slightly higher median value measured at site 2. At both sites lower root-zone plant-available nitrogen values are higher than those calculated for the upper root zone, but this is partly attributable to the greater soil thickness (45 versus 30 cm) used in this calculation. More plant-available nitrogen is available at greater depth at the irrigated site (site 2) as compared with the dryland

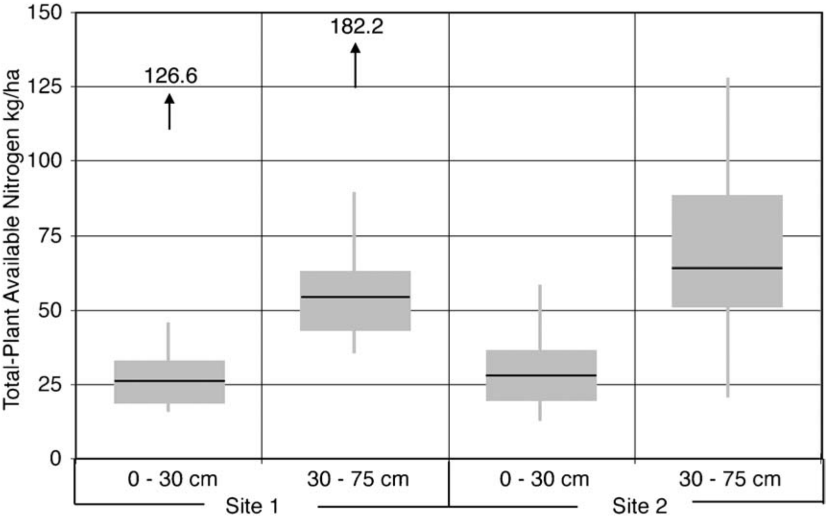

Figure 18.9. Quantity of plant-available nitrogen potentially stored in soil based on concentrations measured at 19 points (dryland, site 1) and 20 points (irrigated, site 2). Note similarity of stored nitrogen in upper 30 cm at both sites. Differences occur at depth most likely due to increased water and fertilizer application at the irrigated sites.

site (site 1) probably due to increased leaching of the higher fertilizer application at the site.

18.2.3.3. Impact of topographic position and stratigraphy on nitrogen variability

In addition to the vertical variability of plant-available nitrogen in the vadose zone, the KWRRI study looked at the impact of topography on the occurrence of plant-available nitrogen in a given field. Soil scientists have recognized for some time that topography has a strong influence on soil properties including soil nitrogen (Aandahl, 1949) and that analysis of terrain variables has the potential to increase the accuracy of soil-attribute prediction (Moore et al., 1993). Both sites had observable topographic features that are either simple or complex internally.

Site 1 has eolian sand overlying three different alluvial strata (Fig. 18.5). The topography at this site is a result of dune-sand deposits overlying fluvial terraces. Some of the topographic relief at site 1 is therefore a function of the thickness of the dune sand, and some is a function of the terrace treads and risers that are beneath it. At site 2 the internal stratigraphy is much simpler. The eolian sand is deposited on what appears to be a relatively flat alluvial surface. Topography is therefore a function of the thickness of the dune sand sitting on the alluvium (Fig. 18.7). At the time of sampling the landscape position (summit, shoulder, backslope, footslope, toeslope) was described and recorded for each core and pit location. The desire was to determine if there were observable relationships between plant-available nitrogen within the root zone and landscape position.

Figure 18.10 shows the relationship between plant-available nitrogen and topographic position for the combined data from both sites. In general, more plant-available nitrogen is in soils at lower topographic

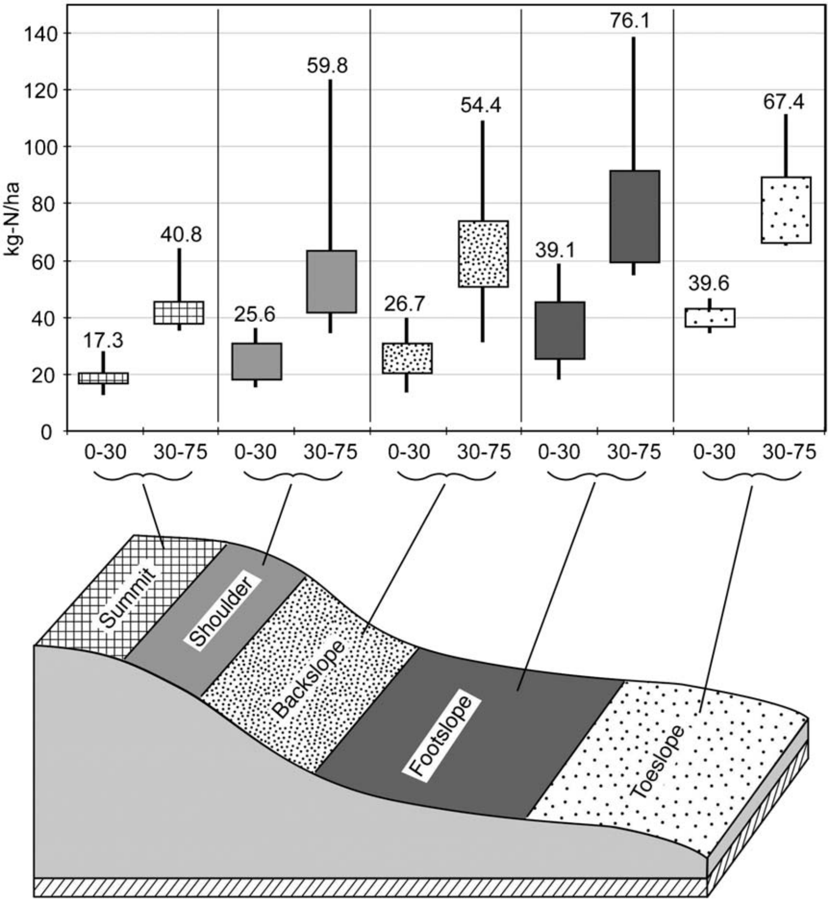

Figure 18.10. Relationship of increasing plant-available nitrogen in the vadose zone with decreasing topographic position in a field. Note that the highest concentrations occur in the foot-slope and toe-slope positions (modified from Hall and Olson, 1991).

positions (backslope, footslope, toeslope) and less plant-available nitrogen in soils at higher slope positions (summit and shoulder). Concentrations of plant-available nitrogen are also different between the upper and lower root zones at higher and lower topographic positions (Kruskal–Wallis $\rho = 0.0099$ upper root zone (TPAN 0–30 cm); $\rho = 0.0325$ lower root zone (TPAN 30–75); Appendix 2, Table A3). It would appear that there is a tendency for higher plant-available nitrogen concentration at lower topographic positions. These findings suggest that topographic position needs to be considered when sampling for soil nitrogen, when monitoring soil-nitrate concentrations, and when attempting to model nitrate retention versus movement in the vadose zone.

18.3. Discussion

The EPA study was originally designed to monitor changes in soil-nitrate concentrations and to determine what factors most strongly influence changes in vadose-zone soil nitrate content that occur during the growing season. Sampling by cores was performed at fixed locations in 65 fields (34 irrigated and 31 dryland) prior to planting in the spring and after harvest in the fall for two years. Not all sites were sampled each time due to weather, field conditions, and changes in crop grown. At six of the irrigated sites, soil-water samplers (lysimeters) were also installed to monitor the concentrations of nitrate in soil water throughout one growing season. Of particular concern in this project was determining how much nitrate was below the root zone after harvest. Soil-nitrate data indicated that the three factors most strongly influencing the amount of nitrate below the root zone after harvest were (1) the nitrogen fertilizer-application rate, (2) the amount of nitrate already below the root zone before planting, and (3) the amount of nitrate in the root zone prior to planting. A vadose zone with high nitrate concentration prior to planting to which additional nitrogen fertilizer is added at a high application rate is likely to result in a high concentration of nitrate below the root zone at the end of the growing season. If sufficient precipitation or irrigation water is available, this nitrate has the potential to leach downward to underlying aquifers and to contaminate groundwater.

A number of unexpected complications and findings occurred in the EPA project. It is easy to make the assumption that all nitrate moves, but this is not always the case. At site I-14 for example, soil-water nitrate concentrations were very high and did not change significantly throughout the growing season. In these salty soils, nitrate concentrates with evaporation just like any other salt. Its concentration is apparently not significantly reduced by denitrification or plant uptake, but it also is not removed by leaching due primarily to the low permeability of the soil. The net effect is that nitrate can build up in some soils without immediate adverse effects on groundwater quality.

The core sampling for the EPA project also served to inspire a number of questions about the soils and vadose-zone stratigraphy in the study area. Early in the project many discrepancies between the soils mapped in the Harvey County soil survey (Hoffman and Dowd, 1974) and the soils observed in the cores became apparent. The extreme variability in vadose-zone properties both vertically within a single core description (e.g., dune sand, over alluvial clay, over coarse sandy alluvium) and spatially within each field (sandy to clayey subsoil transitions over short distances) was considerable. In many cases cores described in close proximity (<10 m) to each other were drastically different (Townsend et al., 1997).

In the KWRRI project intensive core sampling was performed at two fields after harvest. Farming at site 1 was dryland and site 2 was irrigated. Both sites had what appeared to be sand-dune topography and though they were mapped as different soil series in the Harvey County soil survey (Hoffman and Dowd, 1974), they were deemed similar enough based on cores described during the EPA project to allow for useful comparisons. Looks were deceiving and the internal vadose-zone stratigraphies at the sites were very different. The range in soil-nitrate concentrations at these two sites was similar to the range in soil-nitrate values found in the EPA cores taken at 65 fields across the study area. This finding indicates that within-field variability in soil nitrate is quite large, and that single cores probably do not represent whole-field soil-nitrate conditions very well.

Soil-nitrate concentrations were more uniform with depth in the vadose zone at site 2, which was irrigated as compared with site 1, which was farmed with dryland techniques. It is likely that this is a result of irrigation providing more water for deeper movement of nitrate combined with the higher nitrogen fertilizer-applications providing more nitrate for movement and increased soil moisture producing greater crop uptake of nitrogen. The fact that the soil stratigraphy within the root zone was less complex at site 2 also may have contributed to the uniformity of nitrate concentrations with depth at individual core locations.

Another important question within the KWRRI study was to determine how much of the plant-available nitrogen in the root zone is nitrate and how much is ammonium. Differences between the two fields may be important to point out. At site 1, greater than 50 percent of the plant-available nitrogen was nitrate, and nitrate concentrations generally increased with depth. At site 2 greater than 50 percent of the plant-available nitrogen was ammonium and the relative percentages of nitrate and ammonium did not appear to change with depth. Nitrate appeared to be retained more readily in the dryland-farmed soils even though the total amount of plant-available nitrogen at depth was greater at the irrigated site. This is most likely related to lack of sufficient water to move solutes through the vadose zone. Retention of nitrogen in the vadose zone of dryland farms is similar to that noted in rangeland areas that do not have nitrogen inputs (McMahon et al., 2003).

Finally, topography seems to be an important factor influencing spatial patterns of plant-available nitrogen in these soils. Soils in the upper landscape positions (summit and shoulder) tend to have less plant-available nitrogen than do the soils at lower landscape positions (backslope, footslope, and toeslope). This may be due to a variety of factors, but two seem to be most likely: (1) the underlying alluvial materials are less permeable and therefore soils at lower landscape positions are not leached as rapidly as the sandy soils near crests of landforms; and (2) water perches above the less-permeable alluvium and moves laterally toward the lower landscape positions carrying with it nitrate-rich vadose-zone waters. The net result is that lower landscape positions have higher plant-available nitrogen concentrations.

18.4. Conclusions

The results from the two studies in Harvey County have broad implications for vadose-zone studies. The exclusive use of soil surveys for soil-characterization information may result in erroneous decisions concerning vadose-zone stratigraphy at a given site. Site characterization of soil stratigraphy using many cores, characterization pits, and/or geophysical instruments is strongly suggested if the data are needed for nitrate flux calculations and/or modeling.

Overland- and subsurface-flow processes are strongly impacted by topography and stratigraphy. Careful analysis of landforms may provide a means to better understand spatial patterns of plant-available nitrogen and the processes that cause the spatial patterns to exist. Field analysis of landforms should also help to design field-sampling methods that better account for spatial variability of soil properties potentially affecting vadose-zone nitrate. If these features are not characterized on the surface by site evaluation, topographic-map analysis, and aerial-photo studies, then site evaluation of nitrate movement in the vadose zone may not be correct.

Analyses of soil cores for nitrate, ammonium, total organic nitrogen, organic matter, bulk density, moisture content, and permeability are necessary for estimation of nitrate flux in the vadose zone. Work from these two studies strongly indicates how the lack of information results in the inability to accurately characterize spatial and temporal patterns of soil nitrogen that are essential for modeling nitrate fluxes. In addition, information from farmers concerning fertilizer applications, crop histories, irrigation rates, and precipitation in study areas are also vital pieces of information necessary to evaluate field- and regional-scale patterns of vadose-zone nitrate occurrence and flux.

The data obtained from the two studies discussed in this paper show that movement of nitrate is impacted by many factors, anthropogenic as well as natural. The studies illustrate the impacts of farming practices on nitrate retention and movement in the vadose zone as well as the impacts of topographic features and stratigraphic information. These studies illustrate the need for more detailed information in order to do more complex evaluation of nitrate movement and retention in the vadose zone.

ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance of the NRCS personnel with the electromagnetic-conductivity measurements and soil coring and descriptions for the KWRRI study, and Groundwater Management District #2 personnel and the Harvey County Soil Conservation committee for assistance in obtaining landowners permission for access to their fields in the EPA-funded study. Also, we wish to thank the personnel at the Kansas State University soils laboratory for their help with the soil-chemistry analyses and the USGS for assistance in collecting cores. We also wish to acknowledge the Kansas Geological Survey for field support and use of equipment.

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Appendix 1. Methods

Sampling methods for the EPA study consisted of soil sampling with a 5-cm-diameter Shelby tube sampler and an auger rig. In the EPA study soils were sampled in 0.6-m intervals to depths of 3-m twice a year for two years to monitor soil nitrate in the upper 3-m of the unsaturated zone at 32 irrigated and 28 dryland fields. In addition soil-water samplers (lysimeters) were installed at six of the irrigated fields to monitor the movement of nitrate through the unsaturated zone. Methods of lysimeter installation and collection and analysis of soil-water and groundwater samples were described by Townsend and Sleezer (1995).

Sampling for the KWRRI study involved use of a trailer-mounted Giddings Soil probe and 5–7.5-cm-diameter soil cores. Samples were collected by soil horizon to depths of 3 m. Each soil profile was described using standard National Resource Conservation Service (NRCS) techniques and correlated to the soil series that was deemed the closest match to its properties. Of the 40 soil profiles described, only two of the sampled points matched the soil described in the existing soil survey.

In both studies sub-samples from soil cores were placed in plastic bags, labeled, and stored on ice until delivered to the Soil Testing Laboratory at Kansas State University where they were refrigerated until analyzed. Both inorganic nitrogen forms, NH_4^+ and NO_3^-, were extracted with 20 ml of 1 M KCl, using 2 g of prepared soil (Keeney and Nelson, 1982; Gelderman and Beegle, 1998). Cadmium reduction and colormetric procedures were used for nitrate and an indophenol colorimetric reaction was used for ammonium. Both analyses were run in separate channels in a flow analyzer to measure these ions simultaneously (Alpkem Corporation, 1986a, b).

Statistical analysis

Statistical analyses were done using non-parametric methods available in S-Plus 6 for Windows Users Guide (2001). The Kolmogorov test for normality was performed and all data were found to have a non-normal distribution. The non-parametric Kruskal–Wallis test for comparison of independent samples was used. The non-parametric Wilcoxon rank sum test was used for hypothesis testing of whether values of one type of sample were greater or less than another. A level of significance of $\alpha = 0.10$ was used for all tests because of the high level of uncertainty involved when dealing with spatially and temporally variable data (Davis, 1986). For both the Kruskal–Wallis and Wilcoxon test if the reported ρ value is less than $\alpha = 0.10$ the results are considered significant. The S-Plus for Windows v.6 was also used for graphing.

Appendix 2. Statistical test results

Table A1. Fertilizer application by farming type (dryland vs. irrigated)

Crop	Number of samples	Maximum	3rd Quartile	Mean	Median	1st Quartile	Minimum
Dryland							
Milo	46	141.1	100.8	89.3	91.8	72.8	20.2
Wheat	46	94.1	67.2	62.2	67.2	57.4	20.2
Irrigated							
Alfalfa	56	11.2	10.1	6.9	10.1	2.5	137.8
Corn	56	249.8	215.0	193.6	185.4	169.1	88.5
Milo	56	199.4	183.7	150.3	142.2	140.0	0.0
Soybeans	56	56.0	9.0	7.5	7.8	0.0	84.0

Note: Hypothesis: H_0: Fertilizer application rate independent of farming method; H_1: Amount of fertilizer used in irrigated farming is different from dryland farming; Kruskal–Wallis $\rho = 0.0013$ ($\alpha = 0.10$).

Table A2. Median nitrate-N values by year, season, and farm type

Season and sample interval (m)	Median nitrate-N ($\mathrm{mg\,kg^{-1}}$)		Wilcoxon rank sum test ρ value	Number of samples	
	Dryland	Irrigated		Dryland	Irrigated
1992					
Spring 0.0–1.2	5.9	9.9	0.0040	27	30
Spring 1.2–3.0	4.5	11.5	0.0011	27	30
Spring 0.0–3.0	10.1	20.2	0.0002	27	30
Fall 0.0–1.2	2.9	11.3	0.0002	17	24
Fall 1.2–3.0	3.5	15.4	0.0011	17	24
Fall 0.0–3.0	8.7	27.1	0.0002	17	24
1993					
Spring 0.0–1.2	4.2	6.1	0.0340	26	40
Spring 1.2–3.0	4.6	8.1	0.0113	26	40
Spring 0.0–3.0	8.6	13.5	0.0081	26	40
Fall 0.0–1.2	2.9	6.3	0.0002	22	17
Fall 1.2–3.0	4.7	6.7	0.0892	22	17
Fall 0.0–3.0	7.9	13.2	0.0097	22	17

Note: Hypothesis tested: H_0: Irrigated values = dryland values for each sample interval. H_1: Dryland values < irrigated values for each sample interval. Wilcoxon rank sum test used (S-plus 7.0, 2005).

Table A3. Nitrogen values for topographic position and depth

Topographic hillslope position	Nitrate-N 0–30 cm		Ammonium-N 0–30 cm		TPAN 0–30 cm		Nitrate-N 0–75 cm		Ammonium-N 0–75 cm		TPAN 30–75 cm	
	Mean kg ha^{-1}	Median kg ha^{-1}	Mean kg ha^{-1}	Median kg ha^{-1}	Mean kg ha^{-1}	Median kg ha^{-1}	Mean kg ha^{-1}	Median kg ha^{-1}	Mean kg ha^{-1}	Median kg ha^{-1}	Mean kg ha^{-1}	Median kg ha^{-1}
Summit	10.7	11.7	8.6	7.9	18.7	17.3	25.1	26.0	18.9	15.8	44.0	40.8
Shoulder	10.9	10.5	14.0	12.4	24.9	25.6	27.6	27.1	33.5	20.8	61.1	59.8
Backslope	11.9	11.0	14.8	12.8	26.7	26.7	29.2	26.9	31.7	25.5	61.0	54.4
Footslope	15.5	17.8	21.4	23.5	36.9	39.1	36.8	34.4	44.7	34.6	76.1	76.1
Toeslope	19.2	16.5	20.8	21.8	40.0	39.6	41.4	37.3	39.6	38.7	80.9	67.4
Kruskal–Wallis ρ value	0.0735		0.0474		0.0099		0.0653		0.1744		0.0325	

Note: Hypothesis: H_0 = No difference in nitrogen content between topographic positions sampled; H_1 = Differences between sampled sites related to topographic position sampled.