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NITRATE CONCENTRATION OF GROUND WATER IN NORTHERN STAFFORD COUNTY, KANSAS

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by

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B.S., University of Kansas, 1986

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ABSTRACT

Ground water in northern Stafford County is known to have some nitrate (NO_3^-) contamination and was judged to be vulnerable because of the sandy soils, shallow water table, and fairly widespread practice of irrigation in the area. The objectives of this study were to 1) discover the extent of ground-water nitrate contamination in the study area, 2) determine variables affecting nitrate concentrations, and 3) make recommendations based on the results. Water samples were taken from 61 wells and analyzed for nitrate-nitrogen. To identify those variables which affect nitrate concentrations in the study area, a number of hydrologic, land use, and stratigraphic variables were examined. To determine the source(s) of nitrate with more certainty, 12 wells were resampled and analyzed for ^{15}N, an isotope of nitrogen.

Nitrate-N concentrations ranged from 0.1 to 23.0 mg/L. The maximum contaminant level (MCL) of 10 mg/L was exceeded in five wells, two of which supply water for human consumption. Of the variables examined, land use variables were the most strongly correlated with nitrate. Nitrate-N concentrations were significantly different under the three major land uses, highest under irrigated cropland areas, intermediate under non-irrigated cropland, and lowest under uncultivated pastureland. Concentrations were highest where irrigation well densities were greatest, indicating that the large amounts of fertilizer and water applied have resulted in significant quantities of nitrate leaching to ground water.

In cropland areas, nitrate-N concentrations were lowest under the soil association with the least permeable horizon in the soil profile. It is likely that clay layers (or lenses) are retarding the downward movement of nitrate and/or resulting in denitrification. No significant correlation was found between nitrate concentrations and hydrologic (depth) variables.

Many potential point sources of contamination exist in the study area, including areas of livestock confinement, abandoned wells, and sinkholes. Locally, animal wastes can be more of a problem than fertilizer, particularly when livestock are concentrated near a well, constituting a potential point source.

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INTRODUCTION

In the United States about half of the population relies on ground water for drinking water. The percentage is much higher in rural areas. In recent years, widespread reports of contamination have increased public concern about ground-water quality. For owners of private wells, the problem of ground-water contamination is particularly serious. Private wells are not covered by the Safe Drinking Water Act and usually supply water that is neither tested nor treated.

Nitrate (NO_3^-) contamination is receiving increasing attention because nitrate is one of the most prevalent ground-water contaminants, particularly in agricultural regions. Nitrate is the most common inorganic contaminant of ground water in Kansas. A statewide survey of farmstead wells found nitrate concentrations to exceed the maximum contaminant level (MCL) in 28 percent of the wells (Steichen *et al.*, 1988). Human health hazards such as methemoglobinemia, which can be fatal in infants, may occur when the MCL of 45 mg/L NO_3^- (10 mg/L NO_3-N) is exceeded.

Many studies have suggested that agricultural activities are responsible for increasing nitrate concentrations, but questions remain about specific causes, extent of contamination, and remedies. Quoting from Hallberg (1986): "In most technical circles the debate is no longer about whether or not agricultural activities contaminate groundwater. Current discussions focus on where, when, why, the seriousness of the problem, and what can be done about it..." Because of concern about ground-water quality in northern Stafford County, Kansas, this research project was initiated in an attempt to answer these questions. Ground water in this area presently is experiencing some nitrate contamination and was judged to be vulnerable because of the area's sandy soils, shallow water table, and fairly widespread practice of irrigation. The research consisted of two parts, literature review and field study, which are described as follows.

Literature Review

For background information, an extensive literature review was conducted concerning nitrate in ground water. The review discusses health concerns, the nitrogen cycle (sources and sinks), factors affecting the transport of nitrate through the vadose zone, land uses, and agricultural practices aimed at minimizing the leaching of nitrate to ground water. The literature review explores agriculture in general, but focuses on the Midwest and Kansas, and particularly on areas where irrigation is practiced on sandy soils.

Field Study

The objectives of the field study were to 1) discover the extent of ground-water nitrate contamination in northern Stafford County, 2) determine variables affecting nitrate concentrations, and 3) make recommendations based on the results.

The potential for ground-water contamination with nitrate may be related to a number of hydrologic, land use, and stratigraphic variables. To identify those variables which affect nitrate concentrations in the study area, seven variables (depth to water, depth of well, depth of well below water table, land use, irrigation well density, soil type, and stratigraphy) were selected for evaluation.

Water samples were taken from 61 wells (domestic, irrigation, and stock) during the summer of 1990 and analyzed for nitrate-nitrogen. Map overlays, including land uses, irrigation wells, sampled wells, and soil types, were generated using a geographical information system (GIS); and statistical analyses were performed in order to discover the extent of and factors affecting nitrate ground-water contamination in the study area.

In addition, 12 wells were resampled in the summer of 1991 and analyzed for nitrate-nitrogen and ^{15}N, an isotope of nitrogen, in order to determine the source(s) of nitrate with more certainty.

LITERATURE REVIEW

A. Health Concerns

The MCL for public drinking water of 45 mg/L nitrate equivalent to 10 mg/L nitrate as nitrogen (NO_3-N) was promulgated by the EPA because of the health effects of ingesting nitrate. The primary concern with drinking water high in nitrate is methemoglobinemia, or blue-baby disease, which can be fatal to infants. Through bacterial action in the digestive tract, nitrate is reduced to nitrite (NO_2^-) which causes hemoglobin in the blood to change into methemoglobin, interfering with the blood's oxygen-carrying capacity. The level of oxygen carried by the blood decreases in proportion to the amount of hemoglobin converted to methemoglobin (Hergert, 1986b).

Victims of the disease may show signs of suffocation including a bluish skin color. Methemoglobinemia can be treated successfully with an injection of methylene blue, which changes methemoglobin back to hemoglobin (Lamond *et al.*, 1989).

Infant deaths from methemoglobinemia are rare but have been documented. As recently as 1986, officials in South Dakota announced that a two-month-old infant had died from the disease, attributed to high-nitrate ground water used in mixing its formula (Hallberg, 1986). Young infants are more susceptible than adults to methemoglobinemia because nitrate is more readily reduced in infants. The pH of the digestive tract is relatively high during the early months of life, permitting growth of nitrate-reducing bacteria in the stomach (Hergert, 1986b).

Long-term effects on adults from drinking water high in nitrate are less clear but are under study. Through reduction to nitrite and reaction with amines in the oral cavity or stomach, nitrosamines, known carcinogens, can be formed (Bouwer, 1990). Although the health effects of nitrosamines on humans are not well understood, exposure to the compounds may pose a risk of human cancer. Epidemiological studies suggest that various cancers, birth defects or other chronic illnesses are associated with nitrate in drinking water, but such studies do not prove cause and effect (Hallberg, 1988). In laboratory studies with rats, a positive correlation has been made between nitrate and cancer (Wolff and Wasserman, 1972 cited in Kreitler, 1975).

Consumption of high-nitrate water also may threaten the health of livestock. Known effects on livestock include: oxygen deficiency (methemoglobinemia), decrease in milk production, abortions, thyroid disturbances, and death (Keller and Smith, 1967). Two herds of cattle died in Texas in 1969 from drinking water with excessive nitrate concentrations (Kreitler, 1975).

B. Nitrogen Cycle

The dynamic range of nitrogen (N) reactions in an agricultural soil-plant-water system is illustrated in Figure 1. Sources of nitrogen to the system may include fertilizers, animal manures, human wastes, crop residues, nitrogen fixed by symbiotic and non-symbiotic microorganisms, and to a lesser extent, additions of ammonium (NH_4^+) and nitrate in precipitation. Nitrogen may be lost from the soil system only via the following mechanisms, shown in Figure 1:

1) removal by crop harvest;

2) denitrification-- in the absence of oxygen (O_2), nitrate is biologically reduced to nitrous oxide (N_2O) and/or nitrogen gas (N_2), and lost to the atmosphere;

3) soil erosion-- organic nitrogen or ammonium may be attached to soil particles and carried away during erosional events;

4) ammonia volatilization-- NH_4^+ in the soil solution (not adsorbed to soil particles) may be converted to ammonia gas (NH_3) and lost to the atmosphere; the amount of ammonia formed increases as the pH of the soil solution increases;

5) leaching-- nitrate, an anion, may move with soil water below the root zone; once below the root zone, nitrate may be transported to ground water.

Ammonium and nitrate are the forms of nitrogen usable by plants. Generally, nitrate is used in larger quantities than ammonium because it is more available in arable soils than ammonium and it is mobile (Fairchild, 1987). Processes by which this plant-available nitrogen is formed-- nitrogen fixation, mineralization, and nitrification-- are described as follows.

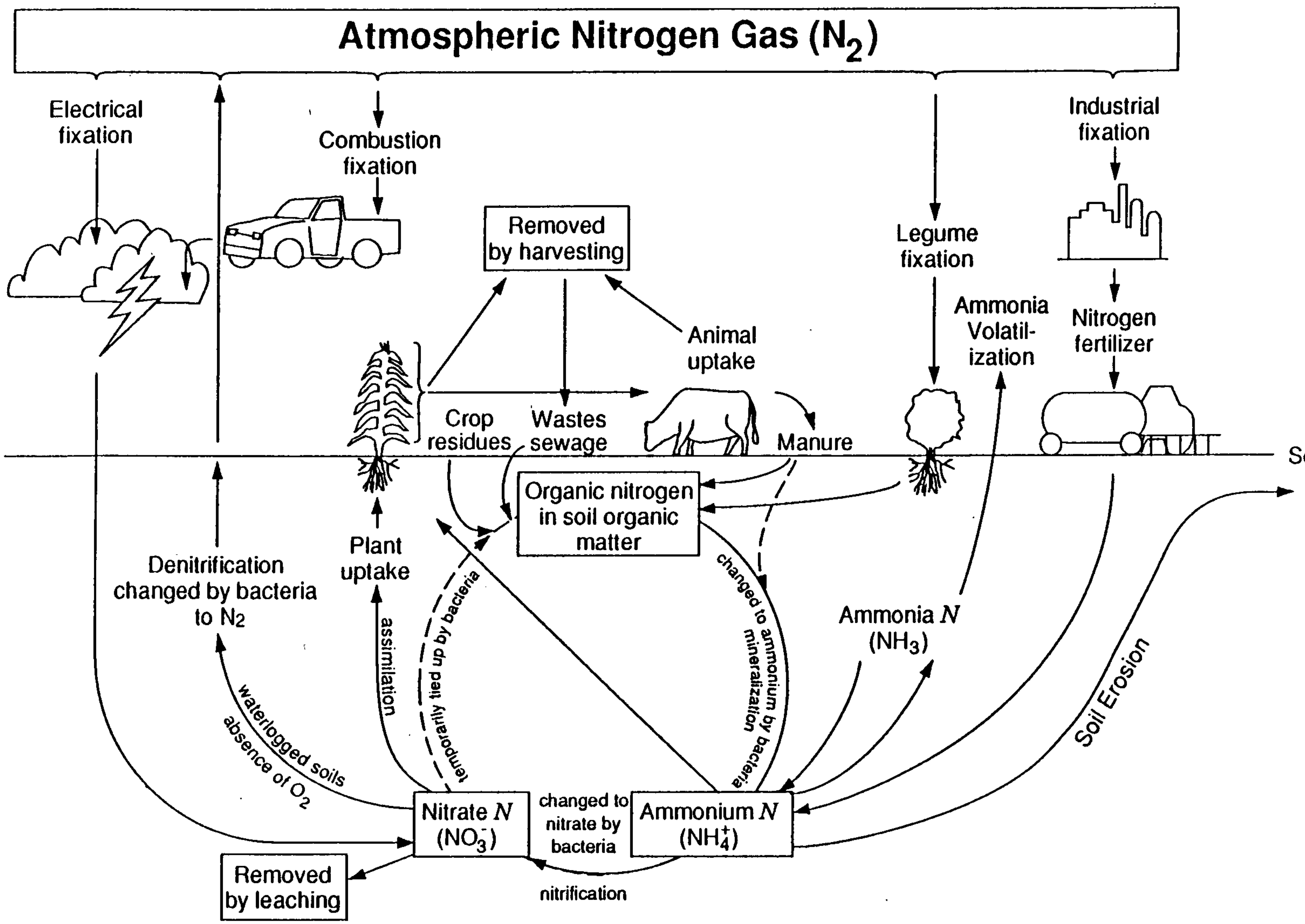


Figure 1. The Nitrogen Cycle (adapted from Follett et al., 1981).

Nitrogen Fixation

Traditionally, nitrogen has been supplied to cropland largely through crop rotations including legumes. *Rhizobia* bacteria in a symbiotic relationship with a leguminous plant can change atmospheric nitrogen gas into a form usable by the host plant and subsequent crops. In this process, called symbiotic nitrogen fixation, the host plant provides energy for bacteria inhabiting the nodules of the host plant's roots. Some free-living bacteria also may fix nitrogen, but symbiotic nitrogen fixation is more rapid and far more important in agricultural systems (Postgate, 1987). Because the atmosphere is 78 percent N_2, this supply of nitrogen is inexhaustible.

Mineralization

Mineralization or ammonification refers to the transformation of organic nitrogen to inorganic nitrogen, principally ammonia. Most soils are neutral or acidic and the ammonia goes rapidly to ammonium (Kreitler, 1975). Some authors include ammonification and nitrification under the term mineralization. Nitrogen in crop residues, manure, and urea-containing fertilizers becomes available to plants via this process. Mineralization, and the reverse process, immobilization, are performed by a variety of soil organisms. Mineralization is favored during decay of organic materials having low carbon to nitrogen ratios (D'Itri and Wolfson, 1987).

Nitrification

The biological oxidation of ammonium to nitrate is called nitrification. It is a two-step process performed by nitrifying bacteria:

$$NH_4^+ + O_2 \text{-->} NO_2^- + 4H^+;$$

$$NO_2^- + 1/2\ O_2 \text{-->} NO_3^-.$$

In the first step, *Nitrosomonas* oxidize ammonium to nitrite, which is unstable. *Nitrobacter* oxidize nitrite to nitrate in the second step. All forms of nitrogen applied to an aerobic soil system eventually are transformed to nitrate. The widespread use of synthetic fertilizers represents a threat to ground-water quality because many fertilizers are, at least partially, in the ammonia or ammonium-salt form, and nitrification occurs rapidly. Once nitrified, the nitrate is subject to leaching with percolating water. Nitrification inhibitors may reduce the risk of nitrate leaching caused by fertilizer addition, and will be discussed in section F, Efficient Management of Fertilizer and Irrigation Water.

C. Transport

Understanding the transport of nitrate to ground water requires knowledge of ground-water recharge as well as the nitrogen cycle. Although nitrate is present in some rare geologic formations, the main source of nitrogen normally is at the land surface. Therefore, shallow aquifers are generally more susceptible to nitrate contamination than deeper aquifers.

Because of its anionic form, nitrate is very mobile. Moving with the bulk liquid, it can be leached easily with percolating water toward the water table. Once in the ground water (assuming aerobic conditions), nitrate moves with the ground water with no transformation and little or no retardation (Freeze and Cherry, 1979). The rate at which water moves through the vadose zone can be estimated by dividing the Darcy velocity by the volumetric moisture content, resulting in the pore velocity or molecular velocity (Bouwer, 1990):

$$v = \frac{-K\frac{\Delta h}{\Delta x}}{\theta}$$

where, K = hydraulic conductivity (length/time);

$\frac{\Delta h}{\Delta x}$ = hydraulic gradient (length/length or dimensionless); and

θ = volumetric moisture content (volume/volume or dimensionless).

Determining the rate of flow in the unsaturated zone, however, can be complicated by a number of factors. First, the hydraulic conductivity, K, is dependent on volumetric moisture content. The hydraulic conductivity of an unsaturated soil can be as little as one hundred thousandth of the value of the same soil when saturated (National Research Council, 1978). Hypothetical relations between K and θ for sand, loam, and clay are shown in Figure 2. For coarse-textured (sandy) soils hydraulic conductivities are low under unsaturated conditions and

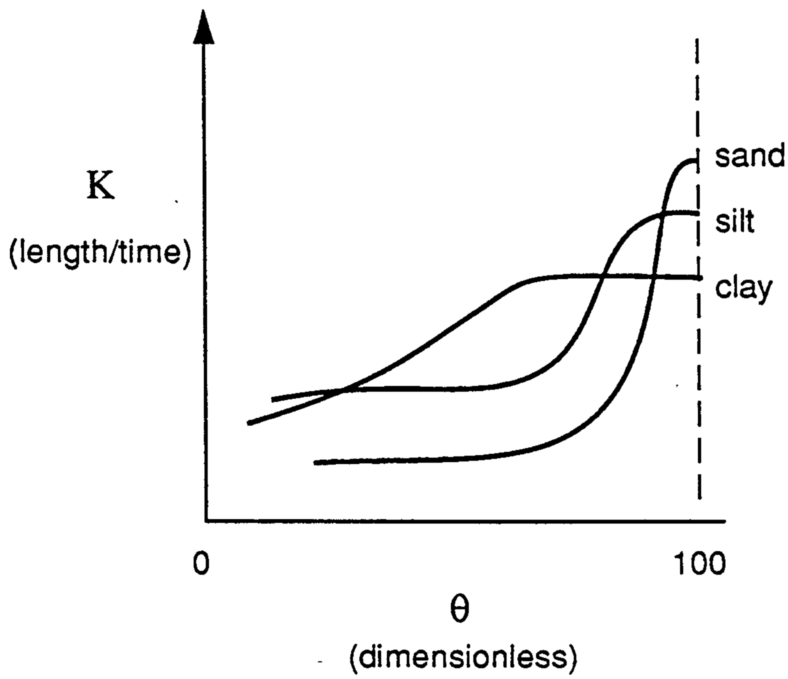


Figure 2. Hypothetical curves for hydraulic conductivity (K) vs. volumetric moisture content (θ) for sand, silt and clay.

increase dramatically as saturation is approached. Fine-grained (clayey) soils (compared with coarser-grained soils) have higher hydraulic conductivities at low moisture contents and lower K values at high moisture contents.

Further, preferential flow may occur and result in dissolved chemicals, including nitrate, moving faster (typically two to 20 times) than indicated by the pore velocity (defined above). Preferential flow occurs not only in cracks, root holes, and worm holes, but also in soils without obvious macropores (Bouwer, 1990). Bouwer (1987) proposed that not all water in the vadose zone is actually moving, and that the active or "effective" water content is much less than the total water content θ. Therefore, resulting velocities are much greater than the Darcy velocity divided by θ. Preferential flow, on a larger scale, could allow contaminants to enter an aquifer directly via sinkholes or through the gravel pack outside of the well casing of an improperly constructed well, especially if a chemical spill occurs near the well head.

While obtaining accurate estimates of unsaturated flow is difficult, the rate of movement of nitrate and the amount ultimately leached to ground water depend in part on the soil type and its hydraulic conductivity. Madison and Brunett (1984) compared different soil types and determined that: "Hydraulic conductivity values for saturated uniform-grain size sandy soils can be several hundred times greater than corresponding values for clay soils or soils with heterogeneous mixtures of grain sizes. Thus, clean sandy soils will transmit more water and more dissolved materials ... than the fine-grain or organic-rich soils."

In many studies, well-drained soils have been correlated with high ground-water nitrate levels, particularly when fertilized and irrigated. Reeves and Miller (1978) reported that nitrate concentrations in ground water from the Ogallala aquifer in Texas have increased in counties having sandy soils. However, virtually no change was found in counties with fine-textured soils. Studies in Nebraska and Iowa indicate a strong relationship between increased ground-water nitrate concentrations and fertilized and irrigated sandy soils (Hergert, 1982; Spalding, 1984; Spalding *et al.*, 1978; Thompson *et al.*, 1986).

It has been proposed that aquifers under poorly-drained soils may have lower nitrate concentrations either because the soils block the entrance of nitrate into the aquifer or because denitrification may occur. Bachman (1984) found significantly lower median ground-water concentrations below poorly-drained soils compared with well-drained soils. Muir *et al.* (1973) found the nitrate content of ground water in Nebraska to be negatively correlated with clay content. Gambrell *et al.* (1975) recognized conditions favorable for denitrification in a poorly-drained soil while analyzing oxidation-reduction measurements and noting a decrease in the nitrate to chloride ratios (NO_3^-/Cl^-) with depth. Because chloride is conservative and assuming that its source is at the land surface, decreasing nitrate to chloride ratios below rooting depth suggest that some nitrate has been lost, presumably by denitrification.

Similarly, textural discontinuities (particularly clay layers or lenses) may retard the downward movement of nitrate and/or result in denitrification (Townsend and Marks, 1990). Devitt *et al.* (1976) reported that redox potentials and nitrate to chloride ratios indicated that subsurface layers of high clay content promote denitrification. Hergert (1982) proposed that denitrification could occur in saturated areas (perched water tables) above sandy loam lenses. Pratt *et al.* (1972) also suspected denitrification to have occurred at or above a clayey horizon sufficient to create water-saturation during irrigation, resulting in relatively low nitrate concentrations below.

Most importantly, the amount of nitrate available for leaching depends on the amount of nitrogen applied to the land surface and the amount of water applied. When the amount of water applied (precipitation plus irrigation) exceeds evapotranspiration, percolation may occur. The practice of irrigation significantly increases the amount of water applied, and in turn the amount of nitrate that can be leached to ground water. Further, the timing of both fertilization and irrigation are important management decisions influencing nitrate leaching, and will be discussed in subsequent sections.

Because of the slow rate of recharge in some aquifers, contaminants from the land surface may not reach an aquifer or be detected in ground water for decades. By the time an aquifer is found to be contaminated, the overlying unsaturated zone may be enriched with the contaminant. Remedial action may take decades to improve water quality, and/or expensive treatment may be required to provide high-quality water.

D. Grassland

Grasslands generally represent less of a threat to ground-water quality than other agricultural land uses. In unfertilized grasslands, uptake of nitrogen by plants and microorganisms generally exceeds the mineralization potential of the systems. Therefore, virtually all of the mineral nitrogen produced (mostly ammonium) is immobilized in living organisms. In fact, in most grasslands mineral nitrogen accounts for less than 0.5 percent of the total nitrogen in the system (Clark and Rosswall, 1981). Because ammonium is taken up as rapidly as it produced, little nitrification and, consequently, little nitrate leaching occurs. In addition to competition for ammonium, some authors (cited in Kreitler, 1975) have attributed low soil-nitrate concentrations in grasslands to toxic effects of grass roots on bacteria. According to Bergstrom (1987), once a perennial grassland is established little nitrate leaching should be expected.

Once a grassland is plowed, however, substantial nitrate leaching is likely to occur. Cultivation generally increases aeration and rate of microbial decay of residues. Consequently, tillage enhances such processes as oxidation of organic matter, mineralization of organic nitrogen, and nitrification of ammonium ions (Clark and Rosswall, 1981). According to Clark and Rosswall, soil organic matter and organic nitrogen content may decrease for 25 to 50 years after natural grasslands are put into cultivation, and the rate of soil nitrogen loss is generally proportional to the amount of cultivation used.

Many authors have observed large amounts of nitrate available for leaching following the plowing of grasslands. Vrba and Romijn (1986) stated that especially high amounts of nitrate (180 to 270 pounds of N per acre per year (lb N/acre/yr)) become available in freshly plowed grassland. An investigation in England found that high nitrate concentrations in interstitial water were related to the plowing of temporary grassland (Cameron and Wild, 1984). The authors concluded that, potentially at least, the plowing of grassland forms a major source of nitrate pollution of aquifers. Bergstrom (1987) found lower nitrate leaching fluxes, mostly below 4.5 lb N/acre/yr, and concentrations below fertilized forage grass compared with fertilized and unfertilized barley (an annual crop) in Sweden.

While most studies comparing cultivated and uncultivated areas concerned nitrate in soil water, a Minnesota study found lower mean nitrate concentrations in ground water in uncultivated areas than in cultivated areas. According to Anderson (1989), the concentrations were not significantly different, which suggested that water quality in both settings had been affected similarly, apparently by past agricultural practices.

E. Conventional Crop Production

Nitrogen is required in relatively large amounts as a plant nutrient and is one of the main limiting factors in crop production. In the past nitrogen has been supplied to cropland in manures and through rotations including leguminous crops. Since World War II, production and use of synthetic fertilizers has increased tremendously, although it has levelled off since the mid 1970's. Figure 3 exhibits fertilizer use in Kansas, which parallels the national trend, over the past four decades. According to Hallberg (1986), in many respects agriculture has become another victim of "chemical dependency." It has evolved from rotation to fertilization. Because of the current widespread use of nitrogen fertilizers in crop production, this section will begin with a brief description of the fertilizers commonly applied--anhydrous ammonia (NH_3), urea-ammonium nitrate solution (UAN), urea, and ammonium nitrate.

The two most widely used fertilizers today are anhydrous ammonia and urea-ammonium nitrate solution (Figure 4). Anhydrous ammonia is dry ammonia gas compressed into liquid and stored under pressure. "Anhydrous" is 82 percent N and is relatively inexpensive. It is normally injected at a depth of six to eight inches and immediately covered with soil. In moist soil, ammonia reacts with hydrogen (H^+) ions to form ammonium:

$$NH_3 + H_2O \longleftrightarrow NH_4^+ + OH^-.$$

To lessen the amount of ammonia lost to the atmosphere, the soil should not be disturbed for a few days after application. Anhydrous ammonia is caustic to external and internal body tissue and may cause suffocation at certain concentrations.

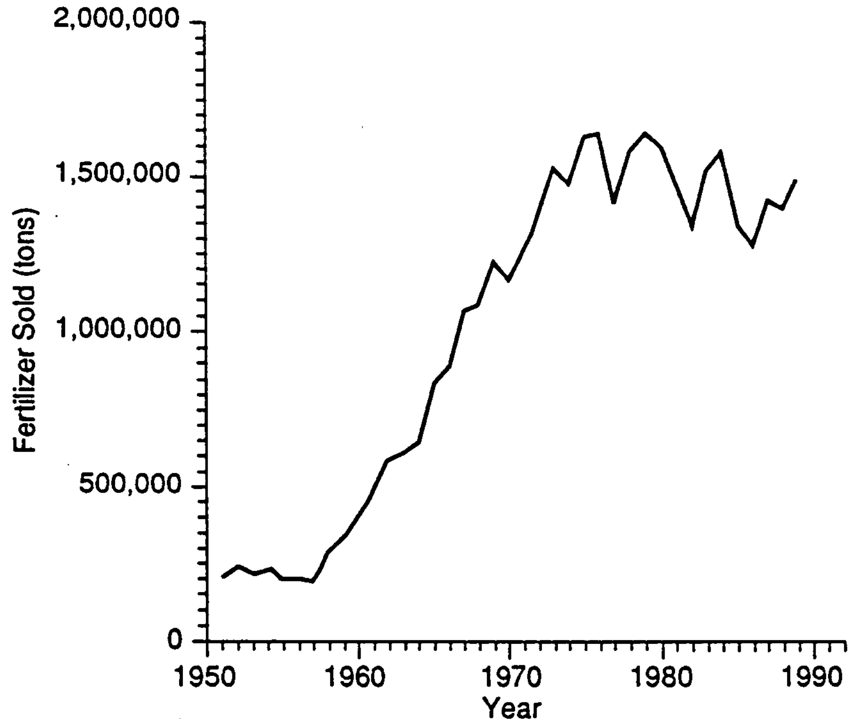


Figure 3. Fertilizer use in Kansas, 1951 - 1990 (Kansas State Board of Agriculture, 1991).

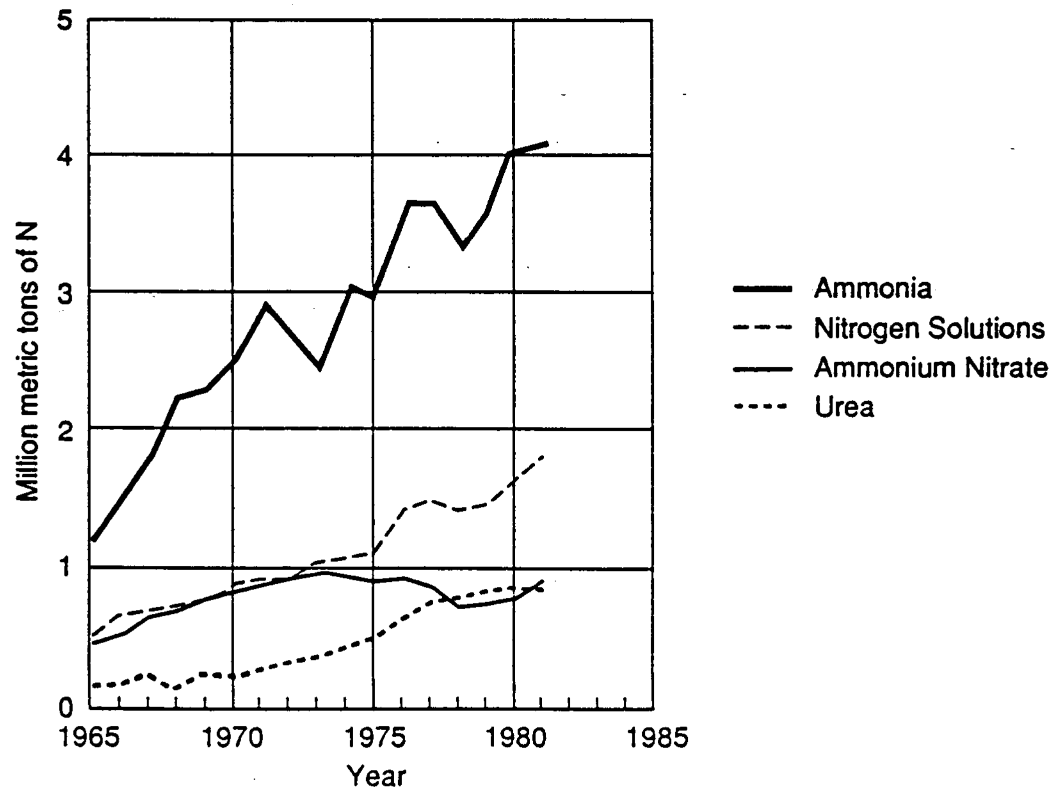


Figure 4. Consumption of N fertilizer materials in the United States (Russel, 1984).

UAN solutions (NH_4NO_3 + $(NH_2)_2CO$ + H_2O) are pressureless liquids ranging from 28 to 32 percent N. UAN may be applied by spraying, sidedressing, and injection through irrigation systems.

Urea, $(NH_2)_2CO$, may be applied in dry prill (or pellet) form. This water soluble form is made by combining liquid ammonia and liquid carbon dioxide at very high temperatures and pressures. Urea dry prills, which are 45 percent N, may be broadcast or sidedressed. Urea applied to soil reacts with water and the soil enzyme urease and is converted rapidly to ammonia. This conversion, called urea hydrolysis, is represented in the following reaction:

$$(NH_2)_2CO + H_2O \text{-->} 2NH_3 + CO_2 .$$

Surface applications should be incorporated to prevent volatilization loss of ammonia.

Use of ammonium nitrate for direct application peaked in 1973 and has declined since then. However, its use has been increasing in the production of UAN solution (Russel, 1984). Ammonium nitrate in dry prill form is 33 percent N. It may be broadcast or sidedressed. Care must be used in the handling of ammonium nitrate because of its explosive properties.

Although septic tanks, heavy manure use and natural soil nitrogen may contribute to ground-water contamination by nitrate in agricultural areas, much attention has been given to fertilizer N. This is due partly to the sheer magnitude of fertilizer use, but also because nitrate contamination has developed in many areas where no source other than fertilizer N exists (Hallberg, 1986).

Even when conventional best management practices are followed, some loss of nitrogen can be expected. As fertilizer application rates exceed crop requirements, the potential for loss likewise will increase. Many studies have reported low efficiencies of fertilizer N recovery. With good management the efficiency, or percent recovery, of applied N may be in the range of 50 to 70 percent (Keeney, 1982; Stanford, 1973). However, efficiencies well below 50 percent are not uncommon (Avnimelech and Raveh, 1976; Hallberg, 1986; Pryor, 1988; Power, 1981). In the United States in 1977 removal of nitrogen in harvested crops accounted for only 36 percent of the N intentionally returned to cropland by man (Power, 1981). Accordingly, the potential is great for improving efficiency of N use.

Although many producers set their goals at maximum yields, evidence suggests that, economically and environmentally, an optimum yield somewhat below maximum is a better goal. Researchers have observed that the point of greatest economic return to applied nitrogen (maximum profit) is usually somewhere below the point of maximum yield because the last increments of fertilizer to produce a little more yield cost more than the yield increase is worth (Miller and Donahue, 1990; Parr, 1973). Figure 5 illustrates the diminishing yield response of corn grain to successive fertilizer N increments and the rapid decrease in utilization efficiency with increased application rates. According to Parr (1973), striving for maximum yield by applying additional fertilizer N probably is not justified. Similarly, Stanford (1973) notes the sharp decline in N use efficiency in progressing from 90 percent of the maximum to the theoretical maximum corn yield. Reducing the amount of fertilizer may reduce nitrate leaching without affecting yield.

While the fate of nitrogen lost from the soil-plant system is site specific and not easily quantified (because of the difficulties in measuring denitrification and ammonia volatilization *in situ),* generally most of the applied nitrogen not used by plants is subject to leaching. Hallberg (1986) reviews a variety of agricultural engineering and agronomic studies showing that losses of nitrogen, particularly

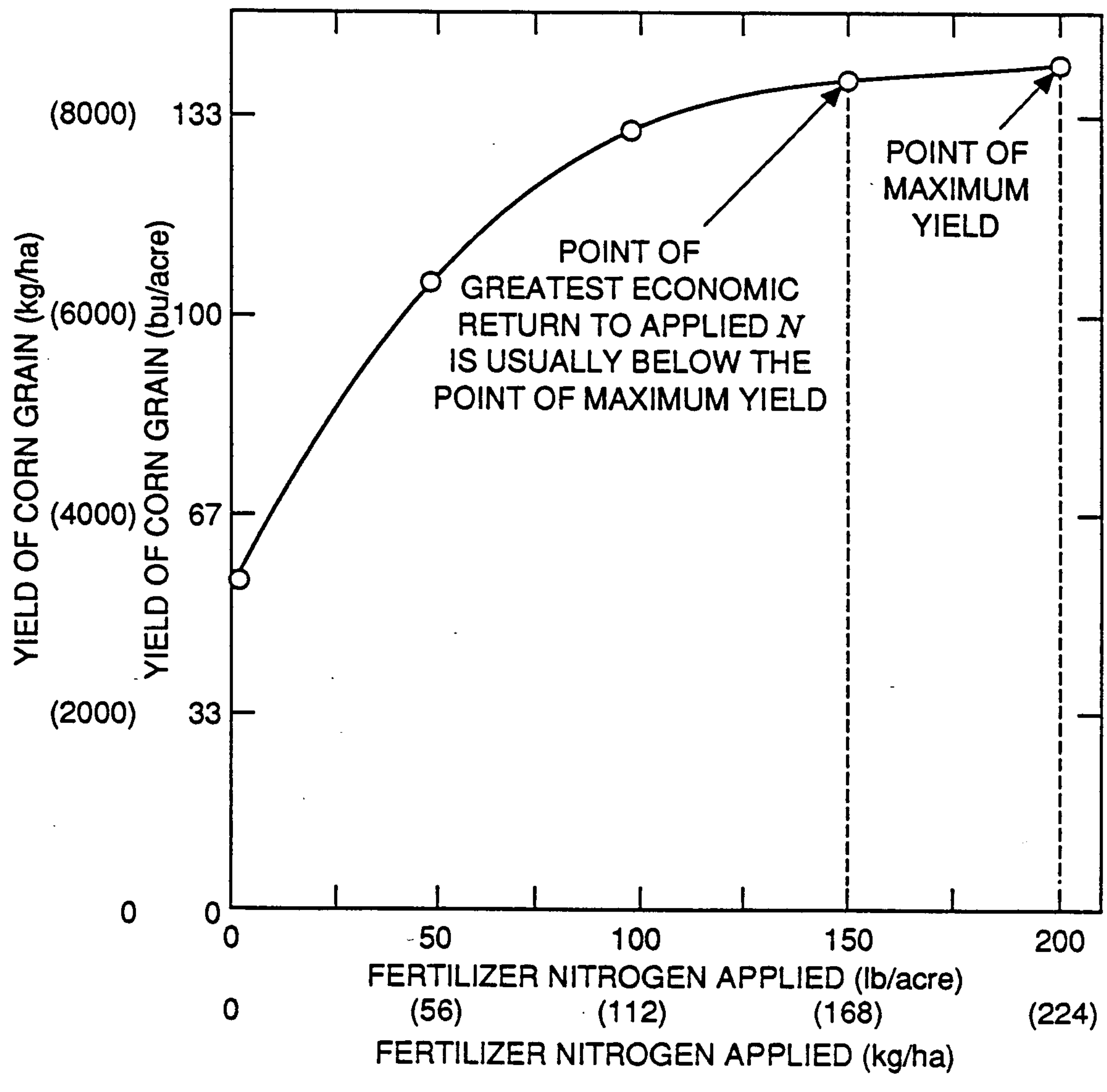


Figure 5. Hypothetical representation of crop response as a function of N rate (Parr, 1973).

nitrate, below the crop root zone occur directly as a function of N-fertilization, especially at high application rates.

Many authors have observed large increases of nitrate in leachate below cropland coincident with increasing fertilizer N rates, especially in irrigated areas (Bergstrom and Brink, 1986; Chichester, 1977; Timmons and Dylla, 1981). Data presented by Pratt (1984) showed a high correlation between nitrate leached and fertilizer N input for three drainage volumes. This relationship is illustrated in Figure 6. Interpretation of data from sites representing various soils, crops, climates and N managements revealed that the main factor controlling leachable nitrate was fertilizer N input. Clearly, the amount of nitrate leached also increased as drainage volume increased indicating that better water management can help keep fertilizer nitrogen in the root zone during the growing season.

Under irrigated corn in Nebraska, extractable nitrate concentrations were found to be similar for 0 and 100 lb N/acre/yr fertilizer applications, indicating that the corn had used most of the applied N. However, the average nitrate concentrations approximately doubled for each additional 100 lb N/acre/yr (Spalding and Kitchen, 1988). At fertilizer rates of 200 lb N/acre/yr, nitrate had accumulated below the root zone in sufficient quantities to potentially contaminate the underlying ground water. Watts (1990) stated that for irrigated corn on coarse-textured soils in Nebraska, maintaining N application rates below 200 lb N/acre/yr should hold down leaching losses, and that the optimum rate is closer to 150 lb/acre under good irrigation management.

Rising ground-water nitrate concentrations also have been linked to dryland farming. Kreitler and Jones (1975) found that the oxidation and leaching of natural soil nitrogen due to dryland farming has caused ground-water contamination by

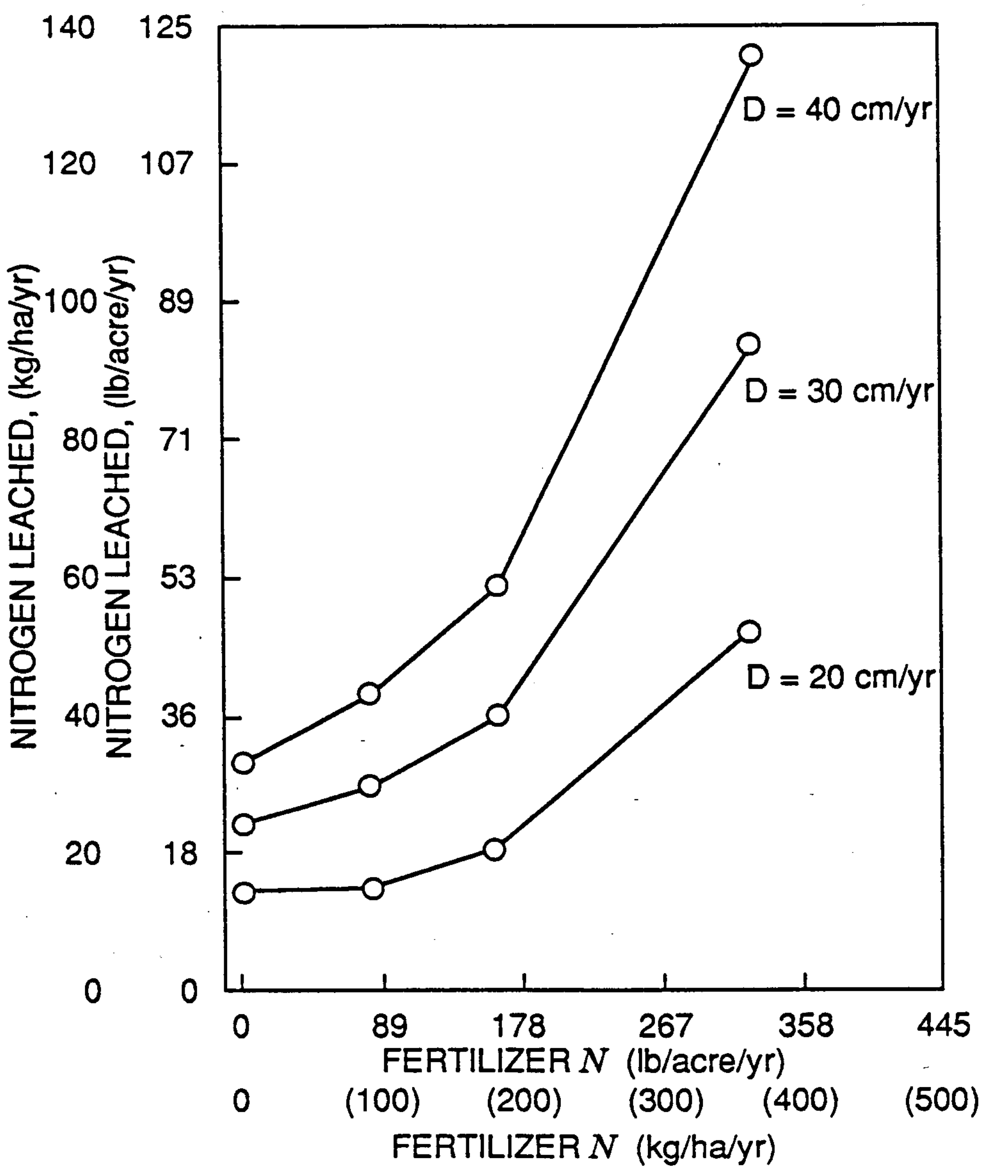


Figure 6. Relationships between N leached and fertilizer N input for three drainage volumes (Pratt, 1984).

nitrate in Runnels County, Texas. Minimal fertilizer had been used in Runnels County, but high and increasing ground-water nitrate concentrations have been related to fertilizer use in other studies. Thompson *et al.* (1986) reported that nitrate concentrations in alluvial aquifers in parts of western Iowa have increased ten-fold, concurrent with a ten-fold increase in N-fertilizer use. Hallberg (1986) cites many studies which show direct relationships between nitrate leaching to ground water and N-fertilizer rates and/or fertilizer history.

Fertilizer often appears to be the source of nitrogen, but irrigation can inflate the amount of nitrate leaching to ground water in more than one way. First, irrigation increases nitrate leaching potential because the larger amount of water applied to the land enhances transport of nitrate (and other solutes). Also, almost twice as much nitrogen fertilizer is used on irrigated crops compared with dryland crops. In addition, heavy pumpage eventually may cause recycling and subsequent concentration of leachates from the land surface (Stullken *et al.*, 1987). (Contamination from point sources also may occur, and will be discussed in Section H, Point Sources.)

Many studies have discovered high or inflated ground-water concentrations related to irrigated agriculture (Anderson, 1989; Endelman *et al.*, 1974; Exner and Spalding, 1990; Exner and Spalding, 1979; Hergert, 1986a; Muir *et al.*, 1976; Spalding, 1984; Spalding *et al.*, 1978; Timmons and Dylla, 1981; Watts, 1990). Spalding *et al.* (1978) reported exceptionally good correlation between irrigated coarse-textured soils and higher ground-water nitrate concentrations in Merrick County, Nebraska. Higher nitrate levels also were found to be related to irrigation well density in this study, and in other areas of Nebraska (Chen and Druliner, 1987). In Holt County, Nebraska, large areas of nonpoint source contamination have been attributed to fertilization and irrigation of sandy soils. A model proposed by Exner and Spalding (1979) suggested that 50 percent of the applied N-fertilizer infiltrates to the ground water in Holt County. In general, areas most vulnerable to contamination have irrigated and fertilized crop production on well-drained soils with a shallow water table.

F. Efficient Management of Fertilizer and Irrigation Water *

The timing and amount of fertilizer and water applications are important management decisions affecting the amount of nitrogen losses. While dryland farming probably has less impact on ground-water quality than irrigated agriculture in a given area, better irrigation and fertilizer management may attenuate N losses. This section will discuss management practices aimed at increasing nitrogen use efficiency and reducing nitrate leaching and potential ground-water contamination, with particular emphasis on areas with sandy soils.

Regardless of whether irrigation is practiced or not, fertilizer management (amount, timing, form and placement) merits special attention. To be considered are N requirements of crops, periods of rapid uptake, and other sources of nitrogen.

Sources of N

First, all the sources of nitrogen (including residual nitrate already in the soil, a previous legume crop, manure, and nitrate in irrigation water) should be taken into account when considering N-fertilizer addition. Many farmers hire commercial soil testing services to analyze for residual soil nitrogen. Samples should be taken from the subsoil (7 - 24") of each field as well as the surface soil. Testing services make fertilizer recommendations based on the results of the analysis. A free soil test offered to wheat farmers in Oklahoma in 1985 resulted in a reduction in fertilizer use of 29 million pounds of nitrogen that year (Fairchild, 1987). Unfortunately,

* It should be noted that the author is not implying that most farmers are negligent or haphazard in their management practices-- they are not. Also, the author realizes that not all of the practices mentioned in this and following sections are practical at this point in time, because of economic constraints, for example.

studies of fertilizer recommendations have revealed that some commercial soil testing services consistently recommended the use of far more fertilizer than was needed (National Research Council, 1989).

Another source of N, potentially a significant source and oftentimes overlooked, is nitrate in irrigation water. The magnitude of this source (lb N/acre) can be evaluated using the following equation (Schepers, 1990):

lb N/ acre = depth of water applied (inches) x NO_3-N concentration of water applied (mg/L) x 0.227.

Therefore 10 inches of water containing 10 mg/L NO_3-N would comprise 22.7 lb N/acre.

Mineralization of organic nitrogen may represent a substantial source of N but is difficult to quantify and represents a small contribution to the soil-nitrate pool at any one time. Mineralization occurs predominantly in the surface foot of soil. The rate of mineralization may increase under irrigation due to more favorable moisture conditions and the likelihood of an abundant supply of recently incorporated residues (Schepers, 1990). Nitrogen available from manure and from previous legume crops will be discussed in section G, Alternatives to Continuous Cropping.

Amount of N

After existing sources of N are accounted for, the amount of nitrogen addition is probably the most important variable affecting nitrate leaching. Nitrogen addition in excess of crop needs will be lost from the soil-plant system, largely by nitrate leaching, representing an environmental hazard and an economic loss to the farmer. Already stated was the frequent inefficient use of N-fertilizer. Often fertilizer is applied in excess of crop needs. On irrigated corn, for example, nitrogen additions well in excess of 200 lb/acre/yr are not uncommon. But research has shown that under good management, even on sandy soils, the optimum rate is probably closer to 150 lb/acre (Batchelor, 1986; Watts, 1990).

One reason overfertilization occurs is that unrealistic yield goals can result in excessive fertilizer N recommendations. Figure 7 shows the relationship between actual yield and yield goal for participants in a two year project in Hall County, Nebraska. Note that most of the points fall below the 1:1 line in both years, indicating an overestimation of yield goal by a large amount (Peterson, 1985). Studies on irrigated corn in Nebraska revealed that overoptimistic yield goals resulted in excessive fertilizer N recommendations in a number of years. On top of that, a 1988 study found that producers applied an average of 43 lb/acre above recommendations (Schepers, 1990).

Timing of N Additions

Besides regulating the rate of fertilizer addition, it is important that fertilizer N be applied at times of rapid plant uptake. Frequently a single preplant application is used. This may result in a loss of nitrogen along with a waste of energy and resources, especially if heavy rains occur shortly after addition. Research has shown that split applications can increase N use efficiency and decrease the potential for nitrogen loss, especially on coarse-textured soils (Batchelor, 1986; Gerwing *et al.*, 1979; Hanks *et al.*, 1983; Lamond *et al.*, 1989). Promising techniques are being developed which give quick measures of soil N and crop N status in the field (Schepers, 1990; Watts, 1990).

An experiment on irrigated corn in Minnesota found much higher concentrations of nitrate below the rooting zone under one-time fertilizer applications compared with split applications (Gerwing *et al.*, 1979). In this study, split applications had only minimal effect on the concentration of NO_3-N in the aquifer,

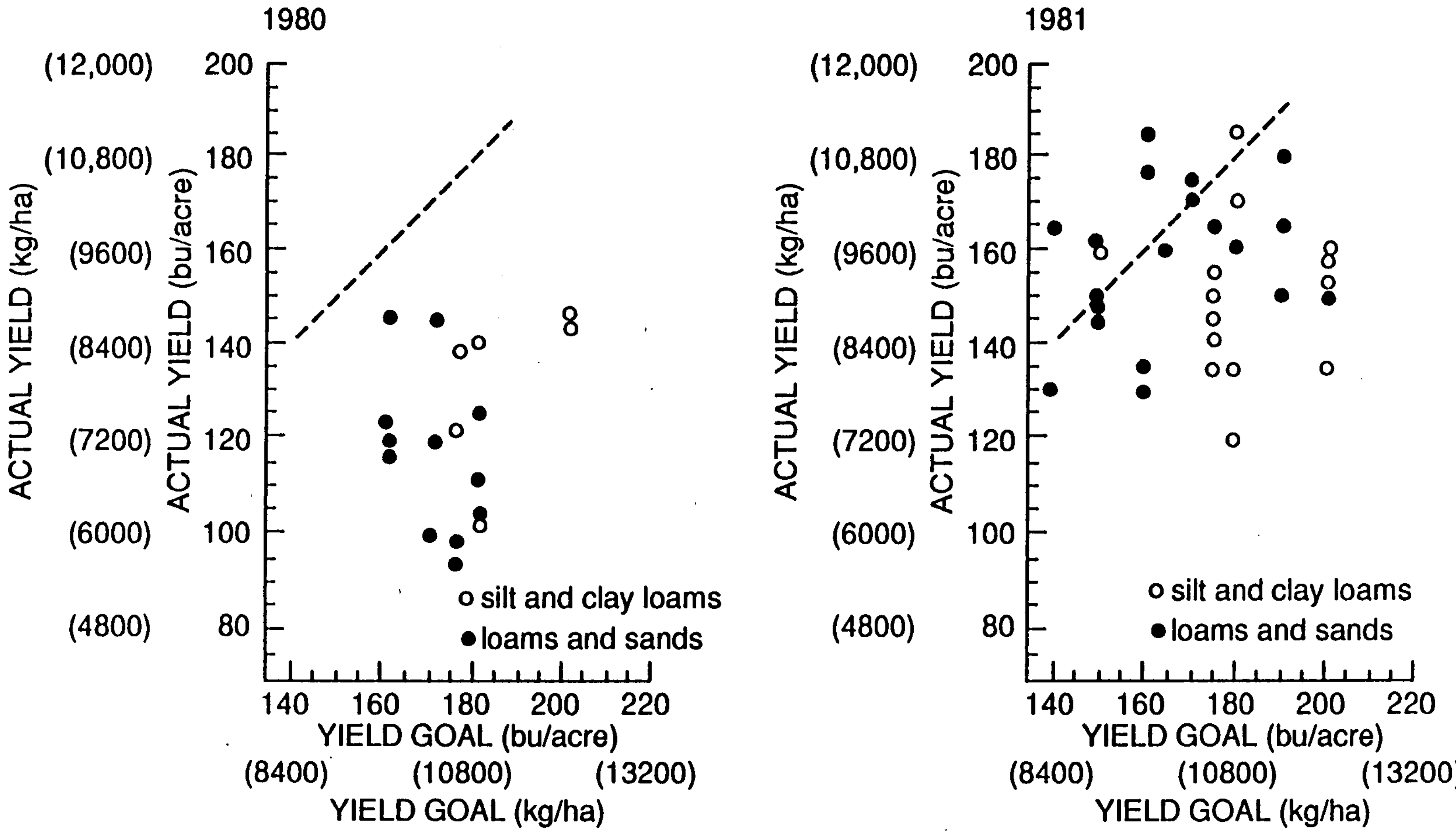


Figure 7. Relationship between yield goal and actual yield for farmer cooperators in the Hall County Water Quality Special Project (Peterson,1985).

while one-time applications increased the concentrations by 7 and 10 mg/l for 160 and 240 lb N/acre rates, respectively. At the application rate of 160 lb N/acre, split applications increased recovery of fertilizer N by the plant from 30.4 to 52.1 percent.

Split applications have not been accepted by some farmers because of the greater time and management required. However, in some situations, this practice may be used with minimal extra work. For example, if a farmer is cultivating between rows of crops, he or she may sidedress at the same time. Also, an irrigating farmer may add fertilizer to irrigation water. The latter practice, fertigation, has become fairly common in center-pivot systems (circles), where UAN can be injected easily. When chemigation is practiced, care must be taken to ensure that the point of injection or stinger is located downflow from the check valve to avoid backsiphoning of nitrogen or pesticides directly into an aquifer.

Fertilizer Additives

Another strategy, similar to split applications, is to reduce N losses by the use of fertilizer additives which inhibit nitrification or urease activity, enabling nitrogen to become available over a longer period of time. Nitrification inhibitors offer promise when used with ammoniacal fertilizers, and urease inhibitors may reduce N losses with urea fertilizers. Fertilizer additives are viable alternatives where sidedressing is infeasible or fertigation can not be practiced.

Nitrification inhibitors work by maintaining nitrogen in the ammonium form, whereby it is available to plants and not susceptible to leaching. Nitrificaton inhibitors are often effective in reducing nitrate leaching, increasing yields, and increasing nitrogen use efficiency. Consequently, a producer using a nitrification inhibitor may potentially use less fertilizer and produce higher yields. Advantages of nitrification inhibitors compared with fertilizer alone are greatest where conditions are favorable for leaching. Therefore, the greatest benefits are realized on sandy soils subject to irrigation or heavy rainfall (Follett *et al.*, 1981; Lamond *et al.*, 1989; Maddux, 1991; Pryor, 1988; Timmons, 1984; Walters and Malzer, 1990).

Nitrification inhibitors are applied most commonly in soluble forms with anhydrous ammonia or UAN, but are also available as coatings for solid N-fertilizers. One common compound, 2-chloro-6 (trichloromethyl)-pyridine, marketed as N-Serve (nitrapyrin), is toxic to *Nitrosomonas*, the bacteria which mediate the conversion of NH_4^+ to NO_2^-. Another nitrification inhibitor is dicyandiamide, which has a dual advantage. Dicyandiamide is a nitrogen source containing 66 percent slowly-available N. The chemical also has been demonstrated to temporarily retard the conversion of ammonium to nitrite in soil (Pryor, 1988).

Other slow-release nitrogen sources are under development. Frequently, the approach is to coat water soluble compounds with less soluble materials. One such example is sulfur-coated urea (SCU), in which nitrogen release rates can be altered by varying the thickness of the sulfur coating.

Urease inhibitors used with surface-applied urea or urea-containing fertilizers also may reduce N losses. Urease inhibitors temporarily slow down the activity of urease, an enzyme which helps convert urea to ammonia. Therefore, appied N remains as urea for several days, where it is less susceptible to N losses by ammonia volatilization. While this process in itself does not lower the amount of nitrate leaching, the tremendously lower amount of fertilizer that may be required does. A long-term study on corn in the U.S. showed that maximum grain yields could be obtained using an average of 74 lb/acre less N when a urease inhibitor, N-(n-butyl) thiophosphoric triamide (NBPT), was included with surface-applied urea

(Hendrickson, 1990). Use of urease inhibitors appears to be an environmentally safe alternative to excessive N-fertilization.

Placement

Results of studies on fertilizer placement are inconsistent, but generally indicate that surface broadcasting is the least efficient practice. Injection, incorporation of broadcast fertilizer, and banding provide better N availability to row crops and small grains. Banding (sidedressing or topdressing) may be used after a crop is growing as part of a split application scheme. Fertilizer may be applied in bands on the soil surface, inserted into the the soil at shallow depths, or dissolved in water and dribbled on the soil. Studies in Kansas indicated much greater efficiency and higher yields when N was knifed into the soil compared with surface applications (Maddux, 1991; Randall, 1984). Of course, availability of equipment will influence which placement technique(s) may be used.

When irrigation (particularly center-pivot irrigation) and good management are practiced, employing split applications of fertilizer in irrigation water is the most efficient technique. This affords the application of nutrients when plants can benefit most. Fertigation is most effective where nutrient retention is low, such as on sands and sandy soils with low organic content. Nebraska has reported that fertigation is 30 to 50 percent more efficient than any preplant application. Some Texas farmers are putting on 50 percent less nitrogen in irrigation systems and getting equal or better yields compared with conventional fertilizer application methods (Miller and Donahue, 1990). Any management practice which results in more of the applied nitrogen being taken up by the crop lessens the potential for ground-water contamination.

Irrigation

It is important to remember that ground water under irrigated agriculture on sandy soils is particularly vulnerable to nitrate contamination. Irrigation increases percolation and leaching of solutes. As with fertilizer, proper amount and timing of water applications are crucial in alleviating ground-water pollution potential. When water is applied in excess of crop requirements, it is likely that nitrate will be leached from the root zone (Duke *et al.*, 1978; Endelman *et al.*, 1974; Peterson, 1985; Watts, 1990). However, when irrigation is practiced, proper scheduling can minimize leaching losses during the growing season. Letting soil dry down at the end of the (summer) growing season reduces winter and springtime leaching losses as well as irrigation costs (Watts, 1990). Of course, precipitation can result in large amounts of percolation year-round.

Research indicates that reduced irrigation rates can decrease percolation and nitrate leaching without significantly affecting yields (Hergert, 1986a; Timmons and Dylla, 1981). Hergert (1986a) conducted a study on sandy soils in Nebraska comparing two different irrigation rates, one at 85 and one at 130 percent of evapotranspiration (ET). Lower mean leaching losses for the 0.85ET treatment showed the effectiveness of irrigation management on reducing nitrate leaching losses. The author realized that even if nitrogen is applied incrementally in irrigation water, nitrate leaching can be substantial if sandy soils are overirrigated. Total dry matter, grain yield and crop N uptake were not significantly affected by irrigation level. Off-season nitrate losses were high, indicating that the fertilizer rate of 187 lb/acre was much higher than required for the (corn) yields produced.

Generalizations

In general, matching N applications and irrigation amounts to crop need should increase nitrogen use efficiency and reduce the potential for nitrate leaching to ground water. Based on literature reviewed, the following management guidelines for conventional agriculture on sandy soils are suggested:

1) Set a realistic yield goal on which to base fertilizer N rate.

2) Evaluate all sources of nitrogen, including residual soil nitrogen and nitrate in irrigation water, when considering N addition.

3) Limit preplant applications of N to avoid early season leaching.

4) Apply nitrogen during periods of rapid plant uptake, if possible, or consider using nitrification inhibitors or delayed release N products.

5) If irrigation is practiced, base water applications on crop uptake or ET, and fertigate using a number of small N applications.

Research has proven that, with proper management, efficiency of nitrogen use may be improved dramatically with no loss in yield. A cost-share study was conducted in Hall County, Nebraska during 1979-83. Nitrate content of soil rooting zone, nitrate in irrigation water, and producer's yield goal were used in determining fertilizer rate. Nitrogen additions were significantly reduced from usual rates by an average of 79 lbs/acre with no loss in yield. At the same time, NO_3-N concentrations, which had grown to an average of 18 mg/L in the shallow ground water, showed no further increase (Olson, 1985). Nitrate pollution of ground water by N-fertilizer can be reduced substantially if appropriate management decisions are made.

G. Alternatives to Continuous Cropping

Historically, agriculture in the Midwest has relied upon rotations with leguminous forage crops and livestock manure for fertility. In response to pressures for increased production over the past few decades, agriculture has come to rely heavily upon agricultural chemicals. With the proliferation of irrigation of large areas of land has come the practice of continuous cropping or monoculture (growing the same crop, frequently corn, year after year). Along with the heavy use of pesticides because of pest management problems, there has been heavy use, many times overuse, of fertilizers and irrigation water. This type of agriculture represents the most prominent source of ground-water pollution in many aquifers. Alternative management schemes, many of which are not new at all, exist which use little or no off-farm inputs (such as chemical additives), thereby reducing the potential for ground-water contamination.

Alternative agriculture, which also may be termed sustainable, regenerative or low-input agriculture, utilizes management options aimed at reducing costs, protecting health and environmental quality, and enhancing beneficial biological interactions and natural processes. Reduced use of chemical fertilizers and pesticides lowers production costs and lessens the likelihood of adverse environmental and health effects without necessarily decreasing, and in some cases increasing, per acre crop yields (National Research Council, 1989). Many farmers are finding that when they adopt low-input methods, along with careful management, gross returns decrease slightly, but net returns increase (Madden and O'Connell, 1990).

Although alternative farming is based on scientific principles and empirical evidence, many of the mechanisms and interactions need further study. Some of the components of alternative systems are well understood, but not enough is known about how the systems function as a whole. Some common characteristics typical of alternative agriculture systems include greater diversity of crops grown, use of rotations including legumes, integration of livestock and crop operations, and reduced synthetic chemical use.

Rotating crops results in advantages which parallel the goals of sustainable agriculture. Advantages of crop rotations over continuous cropping include increased yields, better control of weeds, insects and pathogens, and reduction in the use of commercial fertilizers and pesticides. Rotating legumes with non-legumes has the double advantage of growing the legume with little or no added fertilizer, plus a nitrogen credit (Table 1) for the subsequent non-legume crop. After a good alfalfa stand, with few grasses or weeds, a very good corn or grain sorghum crop can be grown without additional N-fertilizer (Lamond et al., 1988).

Table 1. Nitrogen credits from legumes in rotations.

Legume Crop	Nitrogen Credit (lb/acre)
Alfalfa	
> 80% stand	100-140
60-80% stand	60-100
< 60% stand	0-60
(Second year after alfalfa- half of first year credit)	
Sweet Clover	100-120
Red Clover	40-80
Soybeans *	30-60

*Allow 1 pound nitrogen credit per bushel of yield, no credit for wheat double-cropped after soybean harvest.

from: Lamond *et al.* (1988).

A simple and fairly common rotation is corn-soybean. Advantages of corn-soybean rotations over continuous cropping are well documented. Yields of both crops often are greater when rotated than when continuously cropped (Greenland and TenEyck, 1990; Helmers *et al.*, 1986; Maddux and Barnes, 1990). Increases in corn yields mostly are attributed to N fixation by the soybeans. Because of the soybean N credit, nitrogen inputs to corn may be cut, reducing input costs and ground-water pollution potential.

Additional reasons for increased corn yields have been proposed and include differences in soil moisture and soil physical properties, changes in weed, insect and/or disease populations, and effects from crop residues (Benbrook, 1991; Greenland and TenEyck, 1990). Rotating corn with soybeans helps control rootworm and such problem weeds as shattercane and johnsongrass, reducing or eliminating the need for pesticides. According to Lamond *et al.* (1988), no chemical control is needed for rootworms under a corn-soybean rotation, representing an average savings of eight dollars per acre over continuous corn. Jost (1991) found that rotating corn with soybeans, instead of continuous corn, can reduce weed pressure in rows by 75 percent or more; and that ridge tilled corn in rotation yielded as well without herbicides as with herbicides in a two-year study in Minnesota.

Several studies have revealed advantages of corn in different rotations compared with continuous corn (National Research Council, 1989; Helmers *et al.*, 1986). In general, yields of continuous corn are lowest. Also, corn requires less fertilizer when grown after a legume and less pesticide when rotations are used. Helmers *et al.* (1986) analyzed thirteen cropping systems and found that rotations had higher and less variable net returns than continuously cropped systems. Using longer, more complex rotations such as corn-soybean-corn-oat/clover provides more diversity and potential for stability (Francis, 1990). Olsen *et al.* (1970) proposed that reducing the acreage and frequency of corn and other crops receiving N in the rotation could help limit the amount of nitrate leaching to ground water. Reseeding marginal cropland to grassland would have several benefits: no fertilizers or pesticides used, less erosion, and more acreage for grazing.

Rotating other crops such as grain sorghum (milo) with legumes has benefits similar to those of corn. In addition, legumes can scavenge mineralized soil N and residual fertilizer nitrogen from the previous crop.

One legume, alfalfa (lucerne), seems to be particularly effective in scavenging residual soil nitrate. Alfalfa, with its root structure up to 20 feet deep, is very successful in recovering nitrogen that has leached out of the shallow root zone of other crops (Mathers *et al.*, 1975; Muir *et al.*, 1976; Parr, 1973). Including alfalfa in a rotation may require a longer-term rotation, but should increase nitrogen use efficiency and minimize the movement of nitrate to ground water. After residual nitrate is used up, fixed nitrogen results in a nitrogen credit for the subsequent crop (Table 1).

Maintaining a cover crop after harvest of a summer crop is perhaps the best way of minimizing overwinter nitrogen losses. Commonly used cover crops include clovers, rye, oats, barley, vetch and alfalfa. Cover crops often are used to control erosion, but are also effective in taking up inorganic nitrogen and reducing nitrate leaching losses (Bergstrom, 1987; Staver and Brinsfield, 1990; Keeney, 1982; Shirmohammad *et al.*, 1991; Steenvoorden, 1989). In some studies, N leaching was reduced by 45 to 95 percent when cover crops were grown (Steenvoorden, 1989). Cover crops are most effective in retaining N in the root zone when sown soon after harvest of a summer crop (Brinsfield *et al.*, 1988; Gold *et al.*, 1990; Steenvoorden, 1989).

When used as cover crops, legumes such as clover, alfalfa and hairy vetch have the added advantage of fixing N that can be used by a subsequent non-legume crop. When legumes are plowed under as green manure, they add organic matter to the soil and release nitrogen throughout the growing season of a spring crop. Because nitrogen is released slowly (unlike fertilizer nitrogen), nitrate leaching should be minimized. Benefits of organic matter include: increased granulation, water infiltration, nutrient content, soil biota activity, and soil fertility and productivity (National Research Council, 1989).

Animal manure has similar positive effects, adding nutrients and organic matter, when applied to soil. Cattle excrement contains about 138 lb N/yr per 1000 pounds of live animal weight (Taiganides and Hazen, 1966). Again, nitrogen from organic sources is released more continuously throughout the growing season, compared to inorganic fertilizer nitrogen, which is converted rapidly to leachable nitrate. Rate of release is a function of climate, composition of the manure, and storage (Follett *et al.*, 1981). The optimum time for applying animal wastes is shortly before or as close to planting time as possible (North Carolina Agricultural Extension Service, 1982). Table 2 shows typical nitrogen and moisture contents of certain animal manures.

Table 2. Nitrogen contained in manure.

	Dairy Cattle	Beef Cattle	Swine
Moisture, %	85	85	82
N, lb/Ton (wet)	10	14	10

from: Fixen (1985).

Integrating livestock and crop production (including crop rotations) on a farm may be the best way of using nitrogen efficiently. In this type of system, forages are included in rotations to feed livestock. Nutrients may be recycled to the soil from animal and green manures, and chemical fertilizer and pesticide use can be reduced or eliminated. This type of (organic) farming may be practiced with yields and net profits similar to those from conventional farms (Keeney, 1982). Madden and O'Connell (1990) discuss various case studies in which yields and net returns were higher on organic and low-input farms compared with conventional farms.

This discussion has only touched on the broad range of alternatives to continuous cropping. More thorough assessments of alternative (sustainable, regenerative, low-input, organic) agriculture are available (Francis, 1990; Madden and O'Connell, 1990; National Research Council, 1989). Certain drawbacks are inherent in the implementation of alternative agricultural practices. Alternative agriculture requires more intensive management and more varied expertise than conventional farming, and it may take time before economic benefits are realized. However, wider adoption of these practices should reduce environmental degradation, maintain productivity, and maintain or improve quality of rural life.

H. Point Sources

Even if regional nitrate leaching is minimized as a result of appropriate agricultural practices, local ground-water contamination can occur via point sources. The most obvious conduit would be a direct pathway to an aquifer, such as an abandoned or improperly constructed well or a sinkhole. Unplugged, abandoned wells open to the atmosphere are not uncommon in some rural areas. Farmstead surveys have indicated that large numbers of unsealed abandoned wells exist, posing risks of ground-water contamination (Jones and Jackson, 1990). A Colorado farmer fell to the bottom of an abandoned 100-foot well in May 1991 (Hutchinson News, 1991). Abandoned wells should be plugged in accordance with state laws and regulations.

Improper well construction also is not rare, especially in older wells. Prior to the mid 1970's, bore holes frequently were gravel-packed to the land surface, allowing contaminants in surface water to be transported easily to the water table. A Nebraska study found that only 10 percent of the wells tested met all of the criteria for private well construction (Exner and Spalding, 1985). To prevent surface water from flowing directly down the outside of the casing and entering a well, wells should be located on the highest ground available, and the casing should extend at least one foot above ground level and be properly sealed and grouted. Regulations for drilling and plugging wells in Kansas are contained in Kansas Statutes Annotated (K.S.A.) 82a-1201 to 82a-1215, but these regulations are not well enforced.

Location of wells with respect to potential sources of contamination deserves special consideration. Many cases of well contamination by nitrate and pesticides are caused by activities near the well. A recent study in Kansas found that, on the average, nitrate concentrations were lower the closer the well was to a field and the farther it was from the farmstead (Fawcett, 1990). Another Kansas study (Steichen *et al.*, 1988) found nitrate concentrations to be correlated with land use around the well, distance to a possible source of contamination, and age of well. Age of well may be indicative of how long potentially polluting activities have occurred at a location.

Potential for point-source contamination exists if wells are located near or down-gradient from septic systems or areas of livestock confinement, manure storage, or chemical storage or mixing. Mixing of fertilizers or pesticides near a well represents a serious threat to ground-water quality because of the possibility of spills or backsiphoning. Likewise, wells used for fertigation should have adequate devices to eliminate backsiphoning.

Abandoned or intermittently used areas of livestock confinement pose more of a threat of nitrate leaching than continuously stocked lots. Some studies comparing diffferent land uses have found the highest soil and ground-water nitrate concentrations below abandoned feedlots and barnyards (Exner and Spalding, 1985; Mielke and Ellis, 1976). Lots that are stocked continuously have an undisturbed and continually accumulating manure pack. Cattle hoof compaction and urine excretion keep the surface sealed and damp, limiting nitrification. When a lot is abandoned, drying and cracking of the surface promotes mineralization, nitrification, and increased infiltration; and the subsequent leaching of nitrate into the vadose zone and eventually into the ground water (Jones and Jackson, 1990; Meilke *et al.*, 1974). Alfalfa has been used successfully to remove nitrate from the soil profile below abandoned feedlots (Mielke and Ellis, 1976).

Significant nitrate leaching also can occur under feedlots on coarse-textured soil, when stocking rates are low, and when manure is removed frequently (Keeney, 1982). Waste management systems exist which reduce runoff and leaching. The U.S. Soil Conservation Service provides technical assistance to farmers for design of waste management systems.

Human wastes appear to be a much less frequent source of nitrate contamination than animal wastes in agricultural areas. The decline of the farm population in the last two generations and the substitution of the septic system for the privy lessen the potential of contamination from human wastes, however septic systems still contribute to local contamination. Human waste contains about 8.8 lb N per capita per year (Gold *et al.*, 1990).

I. Summary

Conventional agricultural practices are resulting in ground-water pollution by nitrate in some areas. Uncultivated pastureland seems to pose little threat to ground-water quality, but dry and irrigated cropland, which normally is fertilized, may result in non-point source pollution. Simply plowing a grassland may release enough nitrogen to potentially pollute an aquifer.

Most vulnerable to contamination are shallow aquifers under irrigated sandy soils. The proliferation of irrigation and the availability of synthetic fertilizers and pesticides has made continuous cropping a popular practice. This type of irrigated agriculture, along with the heavy use of fertilizers and pesticides, represents the most prominent source of pollution in many aquifers. Increasing nitrogen use efficiency, by such means as adjusting amounts and timing of fertilizer and water applications, and using fertilizer additives to slow the release of nitrate, reduces the risk of nitrate contamination in vulnerable areas.

Alternative management practices, many of which are not new at all, also may increase efficiency of nitrogen use and reduce risks of ground-water contamination. Examples include: using crop rotations including legumes, maintaining cover crops, and integrating livestock and crop production to recycle nutrients.

Point sources often result in local ground-water contamination. Contaminants at the land surface may enter an aquifer via improperly constructed wells, abandoned wells, and sinkholes. Point source contamination may occur if wells are located near or down-gradient from potential sources of contamination, such as septic systems, areas of chemical or manure storage, or areas of livestock confinement, particularly abandoned or intermittently used feedlots. Mixing of fertilizers or pesticides near a

well represents a serious threat to ground-water quality because of the possibility of spills or backsiphoning.

FIELD STUDY

A. Study Area

The study area is located in the Great Bend Prairie in south-central Kansas (Figure 8). The region is covered with wind-blown sand and is characterized by typical sand dune topography having moderate slopes and hills (Latta, 1950). The land is used primarily for dryland and irrigated crop production, but some pastureland remains. Also, oil production is extensive and oil wells are numerous. Ground water from the Great Bend Prairie aquifer is the sole source of usable water in the study area, supplying domestic, irrigation, oil field, and stock wells.

The alluvial aquifer consists of unconsolidated deposits of sand, gravel, silt and clay of Quaternary age. Subsurface clay lenses are scattered throughout the area. Saturated thickness varies from zero to about 200 feet. Depth to water is generally less than 30 feet, and flow is in an easterly direction (Figure 9). Recharge to the aquifer is principally by direct infiltration of precipitation at the land surface plus underflow laterally from the west and leakage upward from the bedrock (Fader and Stullken, 1978). On the average, a little over two inches of the 25 inches of rainfall is available for recharge anually (Sophocleous and McAllister, 1990). Discharge is by seepage to surface water in the east, evapotranspiration, and withdrawal by wells.

Withdrawal by wells has increased dramatically since the late 1960's, when center-pivot irrigation systems facilitated the conversion of sandy prairie grassland to cropland. Irrigation wells commonly yield 500 to 1000 gallons per minute (gpm). The water table in parts of the study area has declined more than 10 feet since 1974.

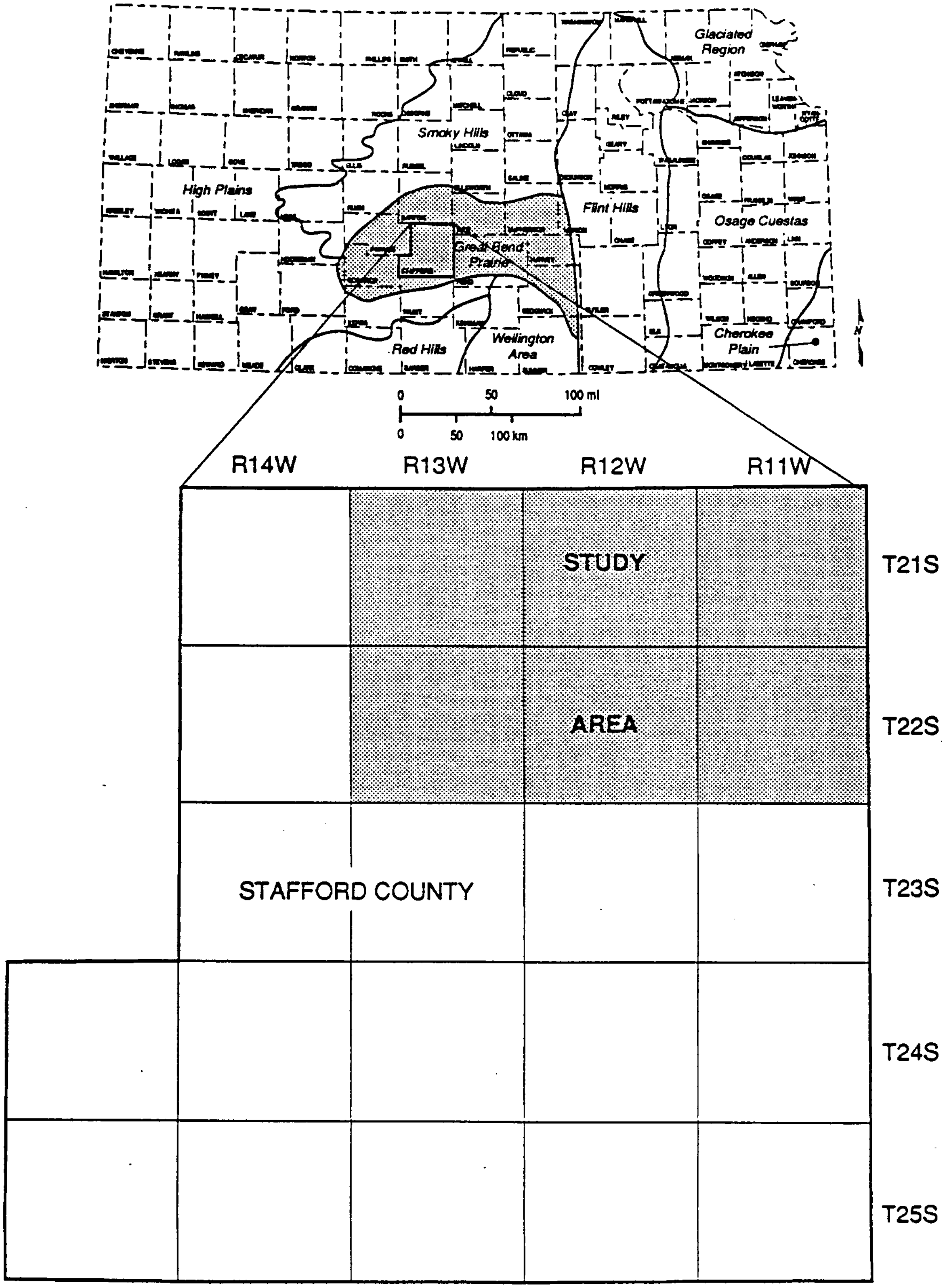


Figure 8. Location of study area.

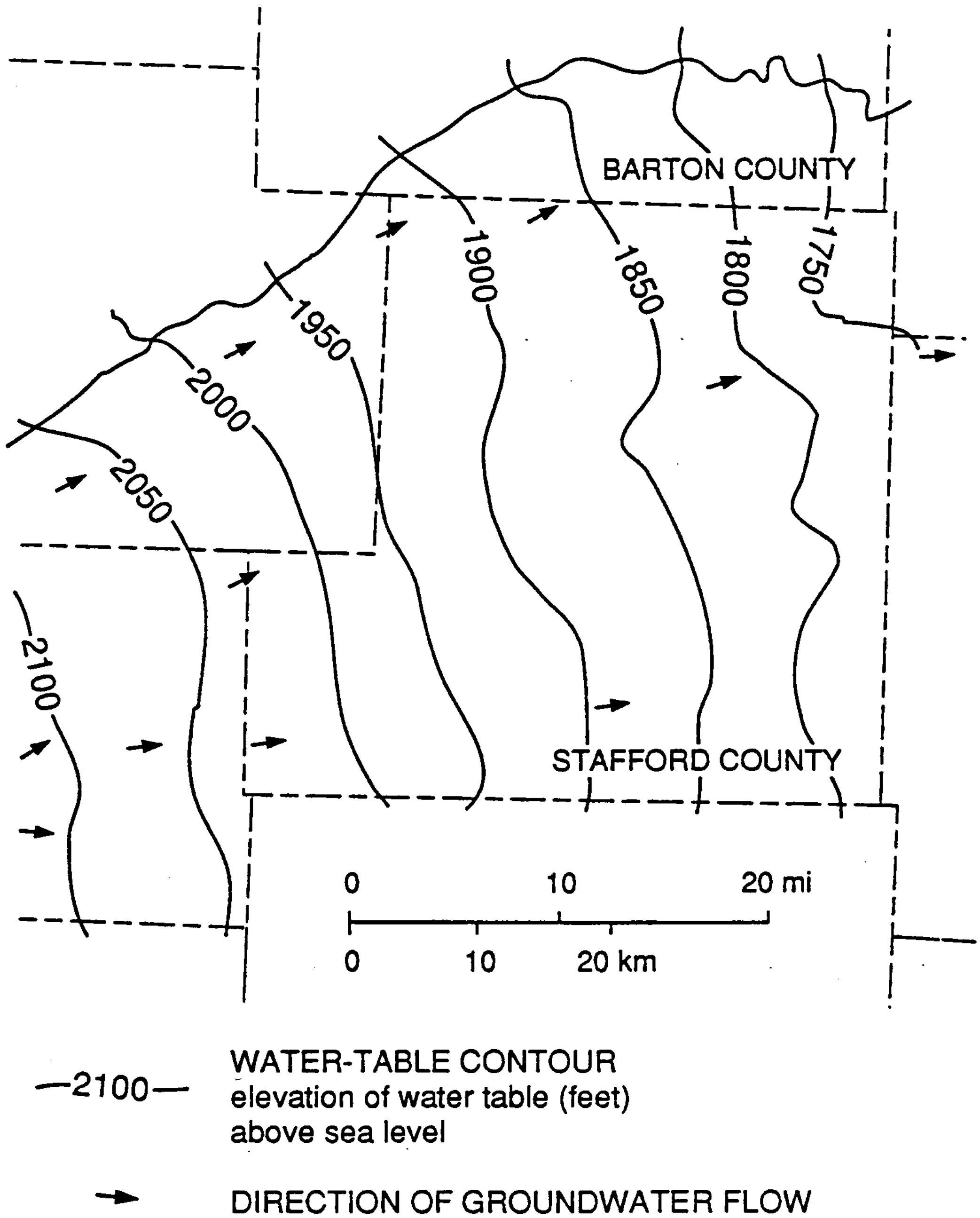


Figure 9. Elevation of water table, January 1980, and direction of ground-water flow (adapted from Stullken et al., 1987).

The aquifer has been experiencing some nitrate contamination as well as salt-water intrusion from the Permian bedrock below (Whittemore *et al.*, 1987).

B. Factors Affecting Ground-Water Nitrate Concentrations

The potential for ground-water contamination with nitrate may be related to a variety of hydrologic, land use, and stratigraphic variables. To identify those variables which affect nitrate concentrations in the study area, seven variables (depth to water, depth of well, depth of well below water table, land use, irrigation well density, soil type, and stratigraphy) were selected for evaluation.

Hydrologic Variables

Depth to water represents the approximate distance that nitrate must travel through the unsaturated zone to reach the water table. Generally, the greater the depth to water, the longer it takes for contaminants to reach the water table. Also, a thicker unsaturated zone may increase the likelihood of dissipation. Well depth and well depth below water table also are measures of the distance that nitrate must travel before entering a well. Nitrate entering an aquifer at the water table may be diluted or dispersed with depth. Therefore nitrate concentrations were expected to be lower at greater depths.

Land Use Variables

The three land uses compared were irrigated cropland, non-irrigated cropland (dryland farming), and uncultivated pastureland. Wells classified in the uncultivated pastureland and non-irrigated cropland categories were located more than one mile from the nearest irrigation well to mitigate any influence irrigation wells and/or irrigated land might impose. Wells classified in the irrigated cropland category were irrigation wells and/or contained one or more irrigation wells within a one-mile radius.

Major crops grown in the area include wheat, grain sorghum, corn, soybeans, and alfalfa. Most of the crops do not require irrigation, particularly when grown in alternating strips which reduces wind erosion. Because of the high water requirements of corn, virtually all corn is irrigated. Corn also requires the most nitrogen of all the crops grown and is heavily fertilized (and often continuously cropped on irrigated land). Approximate acreage and amounts of N applied (irrigated and non-irrigated) for the crops grown in Stafford County are listed in Table 3.

Table 3. Major crops and nitrogen applied in Stafford County.

	Acres (x 1000)			lb N applied/acre/yr	
	Total	Irrigated	Non-Irrigated	Irrigated	Non-Irrigated
Corn	27	26.6	0.4	200 - 250	100 - 125
Wheat	160	15	145	70 - 120	50 - 80
Sorghum	55	10	45	120 - 160	60 - 80
Alfalfa	14	2	12	*	*
Soybeans	16	15	1	*	*

* Little or no fertilizer is applied to legumes.

Human-applied sources of nitrogen are greatest in the irrigated areas and negligible in pastureland. Therefore ground-water nitrate concentrations were expected to be highest under irrigated land and lowest under pastureland. Irrigation well density (number of irrigation wells within a one-mile radius of sampled well) also was examined to ascertain whether or not the extent of irrigation had an impact on nitrate concentrations.

Stratigraphic Variables

Different soil types affect the rate of transport of water and contaminants. The less permeable a soil is, the longer nitrate will remain near the surface of the soil profile, and the more likely it will be consumed by plants or denitrified. Soils in the study area were compared based on the least permeable horizon in the (60 inch) soil profile, which should limit leaching potential.

The three soil associations in the study area are Pratt-Carwile, Pratt-Tivoli, and Dillwyn-Tivoli. The following information about these soils was obtained from the Soil Survey of Stafford County, Kansas (USDA, 1978):

1) The Pratt-Carwile association (sand to loamy sand) is 64 percent Pratt soils, 26 percent Carwile soils, and 10 percent minor soils. Of the soils in the three associations, the Carwile has the least permeable layer (0.06 to 0.2 inches/hour) in the soil profile, which occurs in a zone between 14 and 32 inches from the land surface.

2) Pratt-Tivoli (sandy) is 59 percent Pratt soils, 33 percent Tivoli soils, and 8 percent minor soils. The permeability in the soil profile of this association is relatively uniform, ranging from 6.0 to 20 inches/hour.

3) Dillwyn-Tivoli (sandy) is 55 percent Dillwyn soils, 30 percent Tivoli soils, and 15 percent minor soils. The permeability in the Dillwyn-Tivoli profile also ranges from 6.0 to 20 inches/hour.

Because clay layers or lenses may retard the downward movement of nitrate and promote denitrification, the presence and thickness of clay layers in the unsaturated zone was examined to determine whether they affected nitrate concentrations.

C. Methods of Investigation

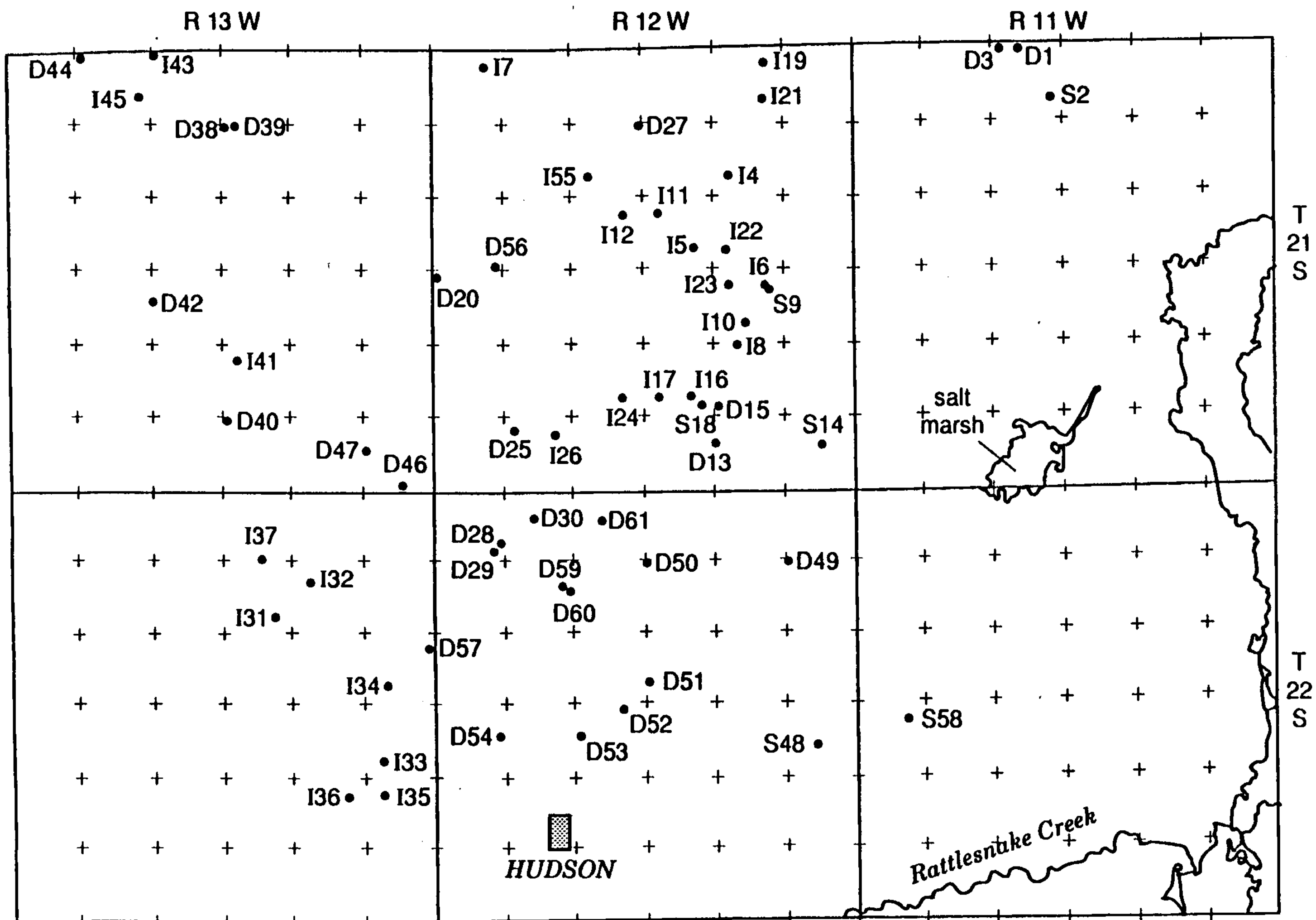
Well Selection

Wells were selected on the basis of proper well construction and permission of owners (except in a few instances when owners could not be contacted). Only wells with well logs (Water Well Records or WWC-5 forms), which contain lithologic log, grouted interval, screened interval(s), and possible sources of contamination, were selected. Since 1975, water well contractors have been required to furnish well logs to the secretary of the Kansas Department of Health and Environment, who files them with the Kansas Geological Survey. Wells that were not grouted to at least 10 feet or into the first clay zone (according to well logs) were not selected. If, upon inspection, a well head was located in a depression, the well was not sampled.

Generally, wells with possible point sources of contamination were not sampled. Irrigation wells that were chemigating were not sampled unless the injection point was safely downflow from the sampling point to ensure against contamination of the sample.

Sample Collection and Analysis

Water samples were collected from 61 wells (Figure 10) in the summer of 1990 and analyzed for nitrate-nitrogen. (These samples also were analyzed for chloride because of the salt-water intrusion problem, but chloride analysis will not be discussed herein.) In addition, 12 wells were resampled in the summer of 1991 and analyzed for nitrate-nitrogen and ^{15}N, an isotope of nitrogen, in order to determine the source of nitrate with more certainty.



I - Irrigation well   D - Domestic well   S - Stock well   + Section corners

Figure 10. Sampled wells with identification numbers.

Samples were collected in clean polyethylene bottles, which were rinsed at least three times with sample water prior to collection, and placed immediately in a cooler with ice. Samples from domestic wells were taken from points as close to the wells as possible and before storage or pressure tanks to minimize any effects of plumbing or storage. Hydrants were turned on several minutes before sample collection to ensure that water fresh from the aquifer was obtained. Samples from irrigation wells were taken after systems had been running for a considerable amount of time. Stock wells (wind mills) generally were pumping continuously.

Samples were analyzed for nitrate-nitrogen within 24 hours of collection using a Hach Portable Colorimeter (Model DR/1A) at the laboratory of the Big Bend Ground-Water Management District (GMD5). The analysis is a modification of the cadmium reduction method using gentisic acid in place of 1-naphthylamine. The chemistry is described in the Hach Water Analysis Handbook (1989). The test registers both nitrate and nitrite in the water. Because nitrite concentrations in ground water usually are negligible compared to nitrate, the concentration of nitrate-N plus nitrite-N is approximately equal to the nitrate-N concentration.

To verify results, duplicate samples were taken from about 10 percent of the wells. These duplicate samples were acid preserved and kept on ice until delivery to the Analytical Services Section of the Kansas Geological Survey, where they were analyzed for nitrate using the ultraviolet spectrophotometric screening method (418 A) described in Standard Methods (APHA, 1985). Sample bottles for the duplicates contained 1 milliliter (mL) of redistilled 6 N hydrochloric acid (HCl) per 100 mL of sample to preserve samples and prevent interferences from hydroxide and carbonate species. Using a Technicon Auto Analyzer II System, the UV screening method has been found to yield analytical values which are within three percent of those obtained by the cadmium reduction method for ground-water samples not subject to contamination by large amounts of organic matter; and the UV method has direct application to a wider range of nitrate concentrations (Larry Hathaway, personal communication, 1991). Table 4 compares concentrations obtained from the Hach kit and from the UV screening method.

Table 4. Comparison between Hach kit and UV screening values.

	NO_3-N concentration (mg/L)	
Well Number	Hach kit	UV screening
I5	8.0	7.4
S18	5.7	5.6
D30	1.7	1.4
I37	1.7	0.5
D56	5.9	6.3
D59	7.2	7.2
D60	5.7	5.2

Samples for ^{15}N were obtained by the same methods as the nitrate samples. These were kept chilled and sent to the Department of Environmental Sciences at the University of Virginia, where they were analyzed using the method described by Macko *et al.* (1987).

Data Analysis

Map overlays were generated using the GIS, ARC/INFO (ESRI, 1987); and non-parametric statistical tests were performed to determine relationships between nitrate concentrations and the factors suspecting of affecting them. All statistical tests were conducted at the 95 percent level of confidence using SAS/STAT software (SAS Institute Inc., 1991, hereafter cited as SAS).

D. Results

Well locations, characteristics, nitrate-nitrogen concentrations and ^{15}N results are listed in Table 5. Nitrate-N concentrations ranged from 0.1 to 23.0 mg/L, with a mean of 5.4 and median of 5.1 mg/L. The MCL of 10 mg/L was exceeded in five wells, two of which supply water for human consumption.

Table 5. Well locations, characteristics, and results.

Well	Location T R Sec	NO_3-N (mg/L)	Depth (ft)	DTW (ft)	DBWT (ft)	IWD	^{15}N
D1	211104BA	14.2	42	21	21	5	9.99
S2	211104DAC	6.5	58	16	42	1	.
D3	211104BB	8.5	85	33	52	6	.
I4	211211C	6.0	109	21	88	6	.
I5	211215D	8.0	115	15	100	6	.
I6	211223A	8.1	140	37	103	5	6.31
I7	211206A	0.7	115	30	85	1	.
I8	211226AB	5.1	136	18	118	5	.
S9	211223ADB	23.0	81	21	60	5	11.10
I10	211223C	4.5	140	33	107	5	.
I11	211215B	11.1	115	10	105	5	9.91
I12	211216A	3.3	131	26	105	6	.
D13	211235BBC	8.8	90	18	72	3	4.67
S14	211236ACC	0.8	49	5	44	0	.
D15	211226CC	10.5	90	22	68	4	.
I16	211227D	8.7	120	15	105	5	8.28
I17	211227C	8.1	101	18	83	5	.
S18	211227DD	5.7	90	17	73	4	8.30
I19	211202A	5.0	123	25	98	6	.
D20	211219BBB	5.4	74	20	54	5	6.88
I21	211202D	4.2	108	30	78	7	.
I22	211214C	5.9	100	24	76	6	8.91
I23	211223B	7.0	142	23	119	6	.
I24	211228D	6.0	102	21	81	5	13.24
D25	211232BBD	5.5	94	21	73	4	.
I26	211232A	1.1	115	21	94	2	.

(continued)

Well	Location T R Sec	NO_3-N (mg/L)	Depth (ft)	DTW (ft)	DBWT (ft)	IWD	^{15}N
D27	211209AAA	3.0	70	25	45	2	.
D28	221206DDA	0.1	89	19	70	0	.
D29	221206DD	0.2	80	16	64	0	.
D30	221205BDD	1.7	80	22	58	0	.
I31	221310D	1.3	92	15	77	3	.
I32	221311B	1.5	100	17	83	5	.
I33	221324C	5.9	96	22	74	6	.
I34	221313AC	4.8	93	15	78	4	.
I35	221325B	8.5	90	23	67	6	.
I36	221326A`	4.7	85	.	.	6	.
I37	221303DCC	1.7	85	11	74	4	.
D38	211310BBB	1.6	90	32	58	3	.
D39	211310BBA	3.4	56	18	38	4	.
D40	211334BBB	4.6	65	20	45	5	.
I41	211327B	1.1	85	15	70	4	.
D42	211221BCC	3.4	67	22	63	0	.
I43	211304BBB	6.0	86	19	67	4	.
D44	211305BBB	4.3	80	25	55	6	.
I45	211305DA	5.0	108	14	94	4	.
D46	211336DCC	5.8	65	15	50	3	.
D47	211336BCC	4.7	60	16	44	0	.
S48	221224CAA	2.5	118	32	86	0	.
D49	221212BBB	6.8	70	18	52	0	.
D50	221210BBB	5.2	92	18	74	0	.
D51	221215CBC	2.8	83	16	67	0	.
D52	221221ABA	3.0	93	23	70	0	.
D53	221221BCC	3.9	100	25	75	0	.
D54	221319ADD	4.9	95	23	72	1	5.28
I55	211209C	10.9	85	8	77	5	.
D56	211218DDD	5.9	80	26	54	6	.
D57	221313AAD	7.6	80	22	58	3	12.02
S58	221119A	1.2	52	11	41	0	.
D59	221208AD	7.2	92	19	73	0	.
D60	221208DDA	5.7	125	28	97	0	.
D61	221204BDD	5.3	80	21	59	0	.

DTW = Depth to water
DBWT = Depth below water table
IWD = Irrigation well density

Hydrologic Variables

Depth of sampled wells ranged from 42 to 142 feet. Depth to water and depth below water table ranged from 5 to 37 and from 21 to 119 feet, respectively. Figure 11 illustrates the relationship (or lack of relationship) between nitrate-N concentrations and these variables. Correlation analyses were performed on these three variables using the CORR procedure (SAS) and no significant correlation was found based on Spearman correlation coefficients. Nevertheless, it is worth noting that the shallowest well sampled (D1) had a nitrate concentration greater than the MCL.

Land Use Variables

Mean, median, and ranges of nitrate-N concentrations for the three land uses, irrigated cropland (IC), non-irrigated cropland (NIC), and uncultivated pastureland (P), are listed in Table 6. Figure 12 illustrates the ranges and quartiles using box plots, and Figure 13 shows nitrate-N concentrations of sampled wells on a general land use map.

The highest concentration, the highest mean and median concentrations, and all occurrences of concentrations greater than the MCL occurred in irrigated cropland areas. The median value is probably a better indicator of central tendency than the mean because it is not as heavily influenced by outlier values. The lowest mean and median concentrations occurred under pastureland. Also, all concentrations from the pastureland were less than 3 mg/L, a value proposed as separating background levels from levels influenced by human activities (Madison and Brunett, 1984).

Statistical analyses were performed using the NPAR1WAY procedure (SAS) in order to determine whether or not nitrate-nitrogen concentrations below the three

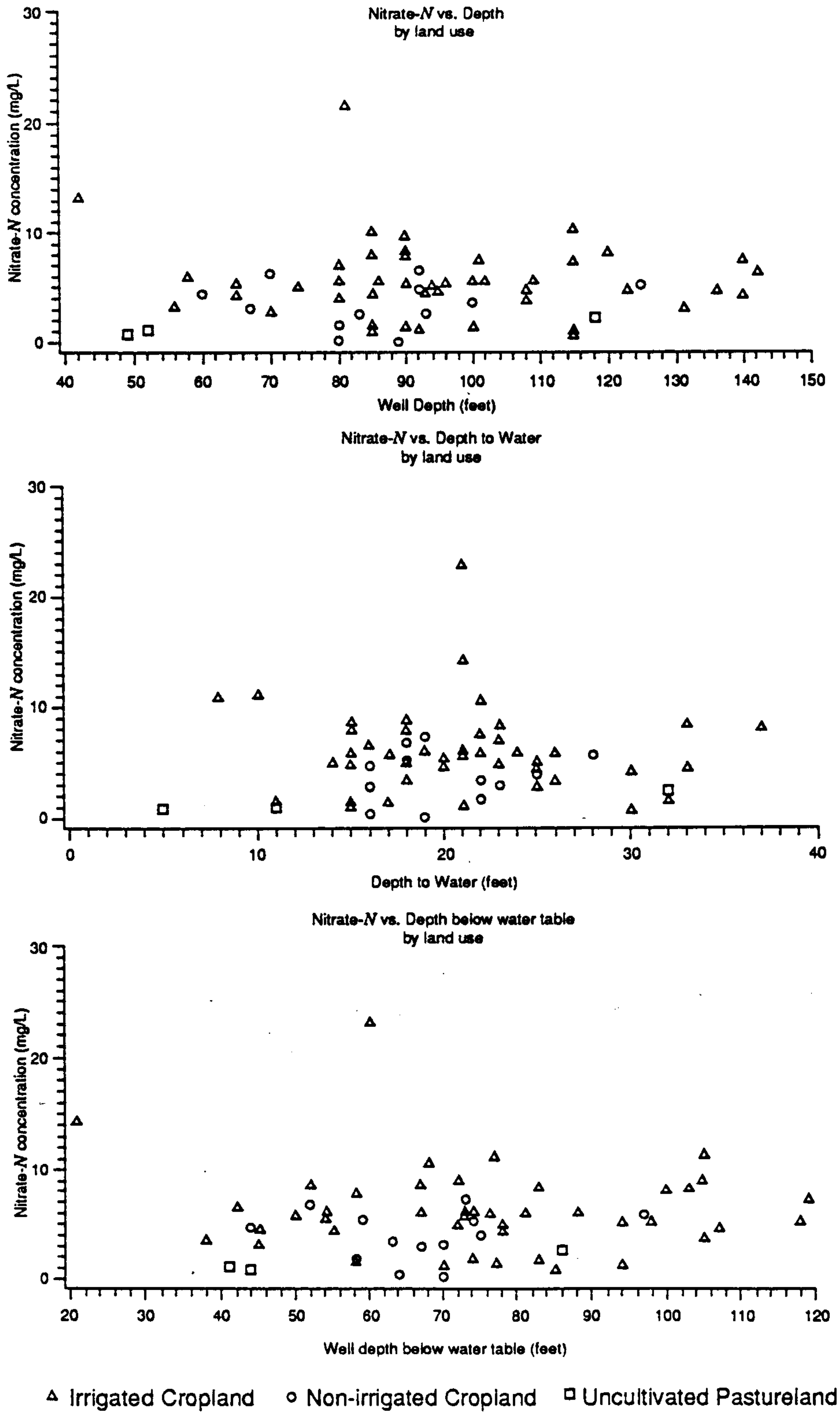


Figure 11. Nitrate - nitrogen concentrations vs. hydrologic variables.

Table 6. Nitrate - nitrogen concentrations under different land uses.

		NO_3 - *N* Concentration (mg/L)		
Land use	No. of Wells	Range	Mean	Median
IC	45	0.7 - 23.0	6.1	5.7
NIC	13	0.1 - 7.2	3.8	3.9
P	3	0.8 - 2.5	1.5	1.2

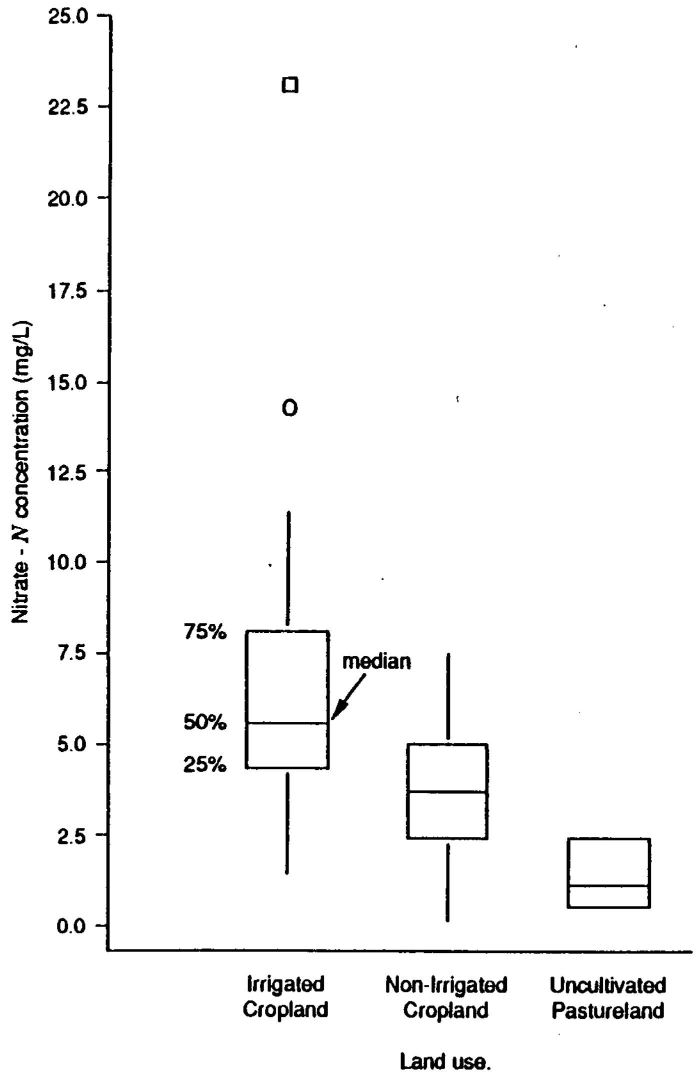


Figure 12. Quartiles and ranges of nitrate-nitrogen concentrations under different land uses.

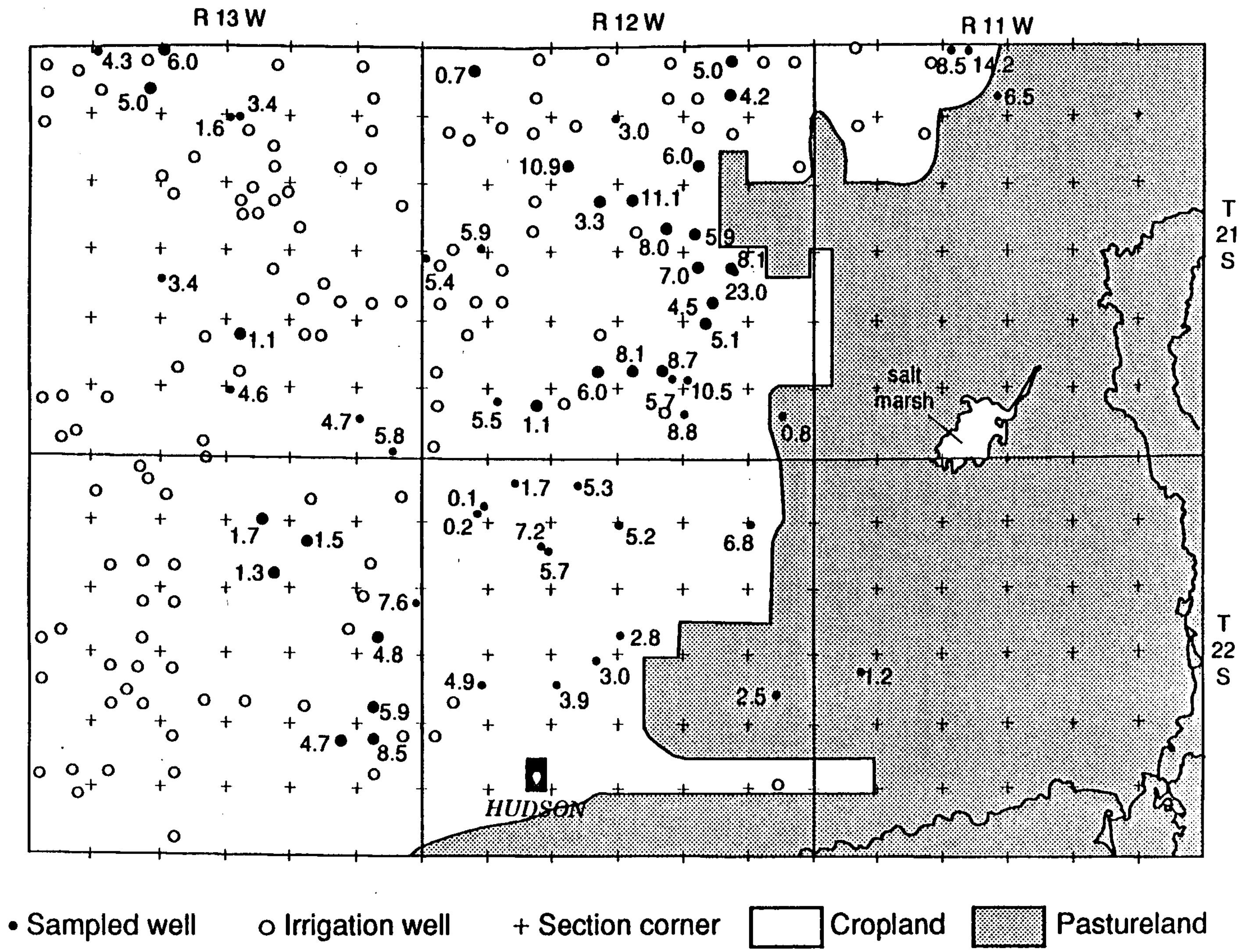


Figure 13. General land use map showing nitrate - nitrogen concentrations (mg/L) of sampled wells.

land uses were significantly different. First, using a Kruskal-Wallis test (chi square approximation), nitrate-N concentrations were found to be significantly different (α = 0.0088) under at least one of the land uses. Next, a number of combinations of land use variables were compared using the Mann-Whitney test. Concentrations were found to be significantly higher under irrigated cropland when compared with 1) non-irrigated cropland (α = 0.0367), 2) pastureland (α = 0.0161), and 3) all non-irrigated land (α = 0.0057). Also, concentrations were significantly lower under pastureland when compared with cropland (α = 0.0213).

The influence of irrigation well density on nitrate concentrations also was examined. Three densities (zero to two, three to four, and five or more irrigation wells per mile radius) were compared, and median concentrations were 3.0, 5.2 and 6.0 mg/L for these respective densities. Box plots are shown in Figure 14. Using the Mann-Whitney test, concentrations were found to be significantly different, highest at the high well density (α = 0.0006) and lowest at the low well density (α = 0.0006).

It is worth noting that the lowest nitrate-nitrogen concentration found in any irrigation well and one of the lowest in the entire study (0.7 mg/L) was from the only well in an irrigated field planted to alfalfa (I7).

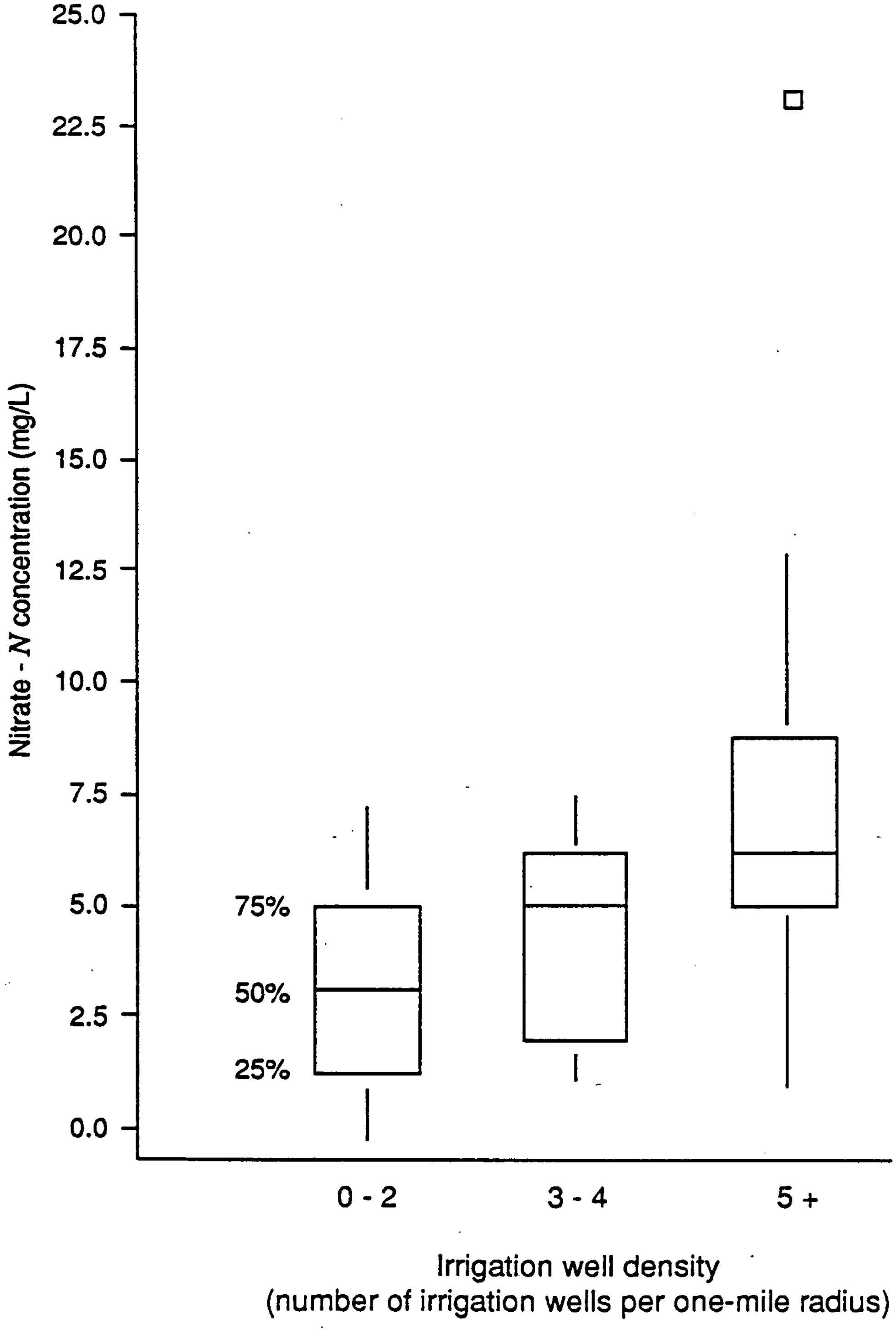


Figure 14. Quartiles and ranges of nitrate - nitrogen concentrations under different irrigation well densities.

Stratigraphic Variables

Mean, median, and ranges of nitrate-N concentrations from the three soil associations, Pratt-Carwile (PC), Pratt-Tivoli (PT), and Dillwyn-Tivoli (DT), are listed in Table 7, and box plots are shown in Figure 15. Figure 16 shows nitrate-N concentrations of sampled wells on a general soils map.

Using a Kruskal-Wallis test, concentrations were found to be significantly different ($\alpha = 0.0203$) under at least one of the soils. Because Dillwyn-Tivoli was virtually all pastureland, it was suspected that land use was responsible for low concentrations under this soil. Therefore, concentrations under the other two soil types (which have similar land uses) were compared with a Mann-Whitney test. Concentrations were significantly higher ($\alpha = .0200$) under the Pratt-Tivoli compared with the Pratt-Carwile.

Stratigraphy will be discussed in the following section.

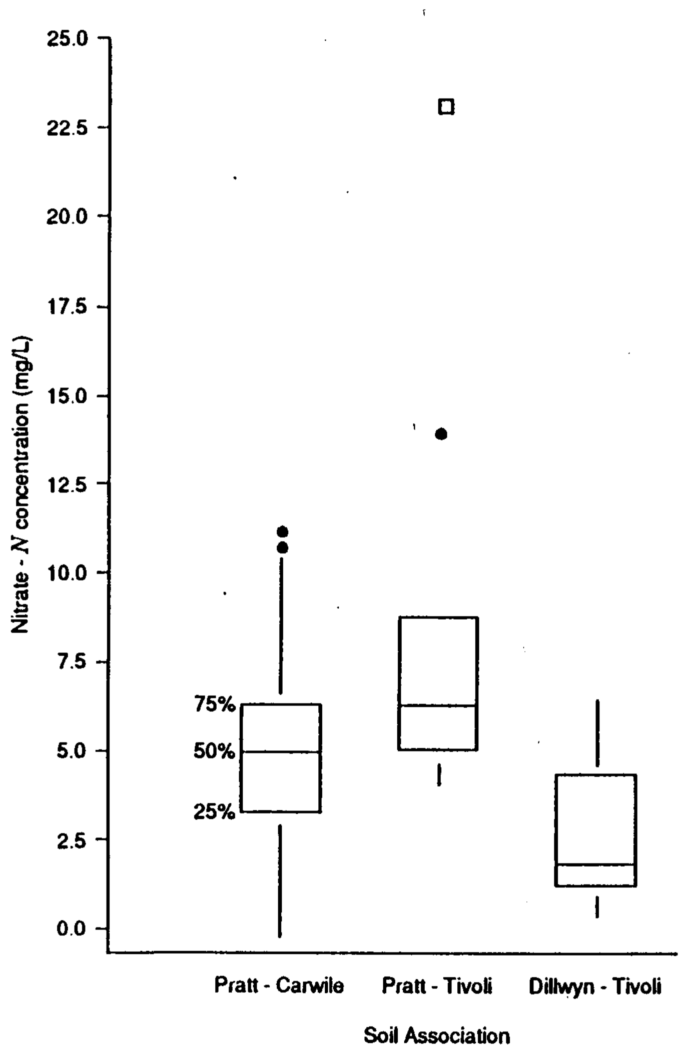


Table 7. Nitrate - nitrogen concentrations under different soil associations.

Soil	No. of Wells	NO_3 - *N* Concentration (mg/L) Range	Mean	Median
PC	46	0.1 - 11.1	4.9	5.0
PT	11	4.2 - 23.0	8.4	6.0
DT	4	0.8 - 6.5	2.8	1.8

Figure 15. Quartiles and ranges of nitrate - nitrogen concentrations under different soils.

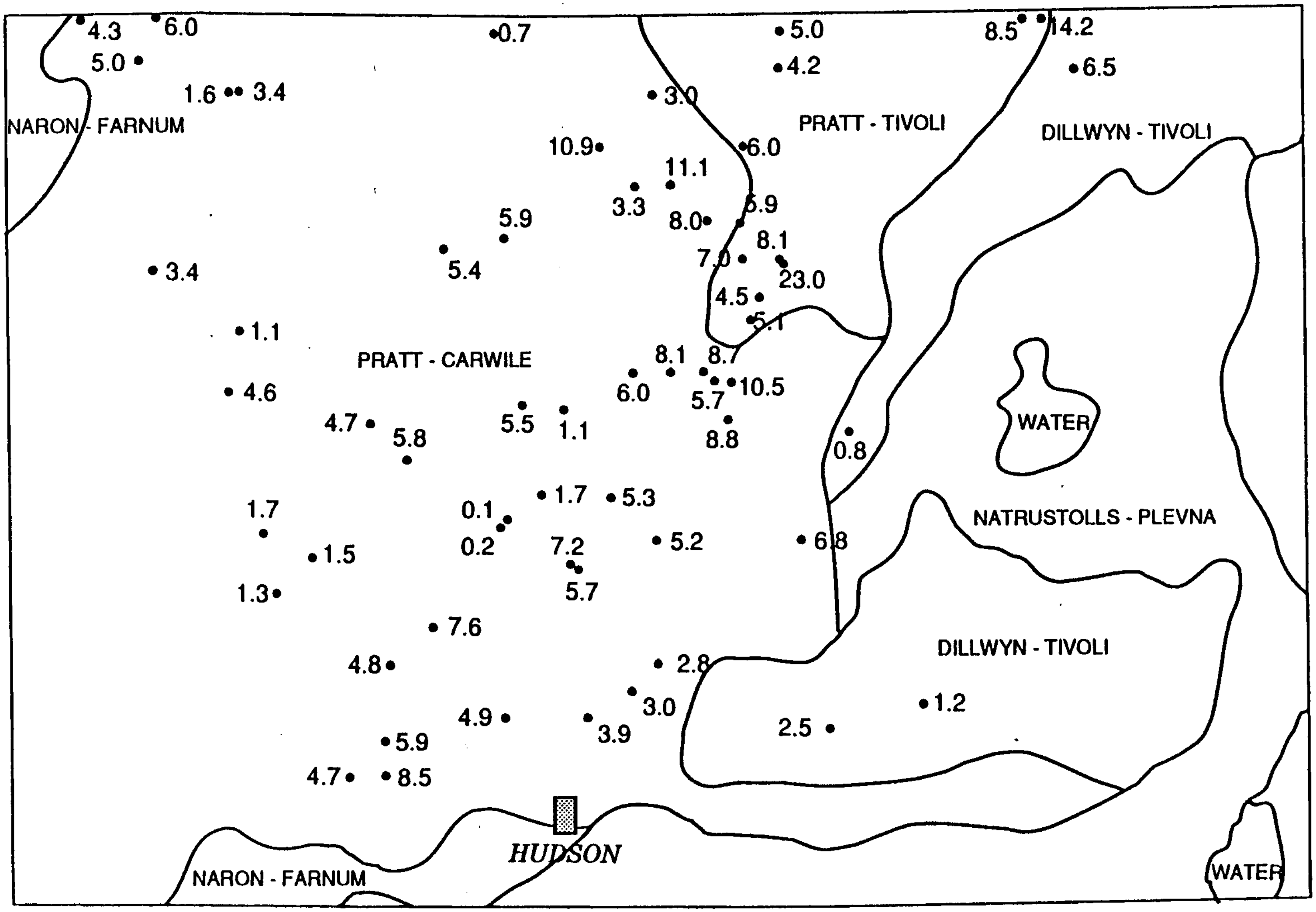


Figure 16. General soils map showing nitrate - nitrogen concentrations (mg/L) of sampled wells.

E. Discussion

Land Use Variables

Of the variables studied, land use variables had the strongest correlation with ground-water nitrate concentrations. Low nitrate-N concentrations (< 3 mg/L) under pastureland suggest that ground-water quality has been affected minimally by human activities. The concentration of 3 mg/L has been proposed as a break point between human and natural nitrate sources (Madison and Brunett, 1984). Higher concentrations under cropland imply that crop production practices have increased the amount of nitrate entering the aquifer below.

Cultivation of the virgin prairie accounts for some of the increased amount of nitrogen available for leaching under cropland. Nitrogen is used very efficiently in grasslands; uptake by plants and microorganisms generally exceeds the mineralization potential of the systems. Therefore, virtually all of the mineral nitrogen produced is immobilized in living organisms (Clark and Rosswall, 1981).

Cultivation enhances mineralization of organic nitrogen and nitrification of ammonium ions. Many authors have observed large amounts of nitrate available for leaching after the plowing of grasslands (see section D of Literature Review). Therefore, substantial nitrate leaching is likely to occur after a grassland is plowed, potentially enough to be a major source of nitrate pollution of an aquifer (Cameron and Wild, 1984).

While cultivation increases nitrate leaching potential, addition of nitrogen fertilizers undoubtedly aggravates the situation. With current agricultural practices, nitrogen use efficiencies well below 50 percent are not uncommon. Therefore, considerable amounts of unused fertilizer are available for leaching.

The results of this study indicate that the practice of irrigation has had the greatest impact on ground-water nitrate concentrations. Higher concentrations under irrigated land may be explained by reasons stated previously, particularly 1) almost twice as much fertilizer is applied to irrigated crops compared with dryland crops, and 2) the larger amount of water applied enhances the transport of nitrate.

The influence of irrigation on water quality is further evinced by the fact that nitrate concentrations were higher where irrigation well densities were greater. Apparently the large amounts of fertilizer N and water applied have resulted in significant quantities of nitrate leaching to the ground water.

Concentrations above the MCL of 10 mg/L NO_3-N already are occurring in irrigated areas. The number of wells contaminated and the nitrate concentrations are likely to increase if present fertilization rates continue and there is more time for nitrate to move into the ground water. Therefore, to prevent continuing increases in nitrate concentrations, it is essential that fertilizer and irrigation water are managed efficiently. Again, it may take decades for remedial action to improve water quality. But any management practice which results in greater efficiency of nitrogen use by a crop (and therefore less nitrate getting below the root zone) lessens the amount of nitrate that could potentially end up in the ground water.

A logical starting point would be to examine the amount of fertilizer (and irrigation water) applied. Generally, 200 lb N/acre or more is recommended for irrigated corn. However research has shown that under good management, even on sandy soils, the optimum is about 150 lb/acre. Perhaps fertilizer recommendations by testing services and Extension offices should be reexamined.

Other methods of improving N use efficiency on sandy soils have been discussed previously (see section F of Literature Review) and include the following suggestions:

1) Evaluate all sources of nitrogen, including residual soil nitrogen and nitrate in irrigation water, when considering N addition.

2) Limit preplant applications of N to avoid early season leaching.

3) Use split applications of nitrogen if possible, or consider using nitrification inhibitors or delayed released N products.

4) If irrigation is practiced, base water applications on crop uptake or evapotranspiration, and fertigate using a number of small additions.

Because continuous cropping of corn uses more fertilizer and water than any other land use in the area, and because this practice represents such a prominent threat to ground-water quality, alternatives to this practice should be considered and encouraged. Alternatives which may increase nitrogen use efficiency (many of which are practiced to some extent in the area) include: growing crops that require less water and fertilizer, using rotations including legumes, maintaining cover crops and/or growing green manure crops, integrating livestock and crop production to recycle nutrients, and reseeding marginal cropland to grassland.

Alternatives to continuous cropping are discussed in more detail in section G of Literature Review. To repeat, some of the practices mentioned may not be economically feasible at this point in time, but many farmers are finding that net returns increase when they adopt low-input methods.

It is encouraging that the lowest nitrate-N concentration found in any irrigation well and one of the lowest in the entire study (0.7 mg/L) was from an irrigation well in a well established alfalfa field. This finding suggests that alfalfa may in fact be acting as a scavenger of nitrate below the root zone of other crops. It may take a year or more to develop a good stand of alfalfa with an extensive root structure, but growing alfalfa in a rotation should minimize the amount of nitrate leaching to ground water. Usually alfalfa is grown in a field for at least three years.

Stratigraphic Variables

Upon inspection of aerial photos and maps generated using the geographical information system, ARC/INFO, it was determined that soil type and land use were not independent of one another. In particular, virtually all the area with Dillwyn-Tivoli soil is pastureland, and it was suspected that land use was responsible for low concentrations under this soil. Therefore, concentrations under the other two soils were compared. Using a Mann-Whitney test concentrations were found to be significantly higher ($\alpha = 0.0200$) under the Pratt-Tivoli (PT) compared with the Pratt-Carwile (PC).

However, upon further inspection it was determined that all wells sampled in the PT soil were from irrigated cropland, and it was suspected that lower concentrations under the PC may have been influenced by wells in non-irrigated land. Concentrations under the two soils were compared again, using only samples from wells in irrigated cropland areas. Still, concentrations were lower under the PC (Table 8), supporting the hypothesis that nitrate concentrations would be lower under the soil with the least permeable horizon in the soil profile.

Table 8. Nitrate-nitrogen concentrations from irrigated cropland under different soils associations.

		NO_3-N concentration (mg/L)		
Soil	N	Range	Mean	Median
PC	33	0.7 - 11.1	5.3	5.1
PT	11	4.2 - 23.0	8.4	6.0

Because of the sandy soils and shallow water table, it is somewhat surprising that nitrate concentrations were not higher. In areas of Nebraska with similar characteristics and farming practices, nitrate-N concentrations in ground water typically exceed and usually are well above 10 mg/L (Spalding and Kitchen, 1988). One possible explanation could be that leaching nitrate has been slowed or denitrified by clay layers and/or lenses in the study area. Well logs were examined to see if nitrate concentrations were related to the presence or absence of clay layers.

According to well logs, wells with low concentrations indeed had significant clay layers. However, virtually all well logs revealed significant clay layers. Most logs reported at least 10 feet of clay and many more than 30 feet. It is probable that the clay layers have retarded the downward movement of nitrate and/or resulted in denitrification, which would explain why ground-water nitrate concentrations were not higher.

A possible correlation between nitrate concentrations and stratigraphy could be that clays were more sandy in the high-nitrate wells. Logs of wells with higher nitrate concentrations listed more "sandy clay" and logs of low-nitrate wells listed more "clay". But the degree of detail and accuracy on well logs varies tremendously, and one driller's "sandy clay" might be another driller's "clay". It had been planned to constuct one or more transects through the study area to get a better idea of the stratigraphy, but because of the lack of detailed information and the questionable accuracy of the information, this plan was abandoned.

Hydrologic Variables

An unexpected result was the lack of correlation between nitrate concentrations and the hydrologic variables examined. In addition to the variables already mentioned, screened interval of wells was inspected (including distance from water table to top of screen), but no correlation was discovered. Perhaps sampling from different depths at paired-well sites would have revealed more correlation, however no functional paired-well sites were available. Concentrations from two wells (D59 and D60) located in close proximity in non-irrigated cropland suggested that concentrations may decrease with depth in that area. Also, it is worth noting that the shallowest well sampled (D1) had a nitrate concentration greater than the MCL, indicating that concentrations potentially may be higher at shallow depths.

One condition that may account for the lack of correlation with depth is that the boreholes of virtually all wells in the study area are gravel packed from the bottom of the grout to the bottom of the well. This could allow shallow ground water to move down the outside of the casing, mix with deeper water, and enter a well. Heavy pumping (as by irrigation wells) could exacerbate this mixing phenomenon. According to Anderson (1987): "Water from the water table containing elevated nitrate concentrations may flow down the steep hydraulic gradient of the cone of depression surrounding a high capacity pumping well, thereby increasing the amount of nitrate at greater depth." Such processes may be responsible for elevated concentrations in deeper irrigation wells.

If shallow ground water is contaminated, it would be advantageous to prevent it from mixing with deeper water. Mixing of shallow and deeper water through the gravel pack could be attenuated by grouting through clay layers. Mixing induced by steep hydraulic gradients from cones of depression could be reduced by irrigating less or using low pressure drip irrigation instead of high pressure sprinkler systems. There is presently a moratorium on new irrigation wells in the area.

Point Sources

Because of the wide range of nitrate concentrations and the heterogeneity in the concentrations over short areal distances, it was suspected that some point-source contamination had occurred. Although wells with possible point sources of contamination generally were not sampled, it would be difficult or impossible to be sure that point-source contamination had not occurred at a site, especially in the past. For example: 1) virtually every homestead (and therefore every domestic well) has possible sources such as areas of livestock confinement and septic systems; 2) it is probable that fertilizer has been mixed or stored near most or all of the domestic and irrigation wells (therefore spills may have occurred); and 3) stock wells are frequented by livestock, which defecate and urinate while they drink.

Other potential sources of nitrate in the study area include unplugged abandoned wells and test holes, poorly or improperly constructed wells, and sinkholes, through which contaminants from the land surface could enter the aquifer directly. Many old dug wells exist which are open to the surface, and it is not uncommon to find unplugged abandoned wells or testholes. It is impossible to know what has been put in sinkholes. Keller and Smith (1967) quoted a Missouri farmer who said, "sinkholes are the best places to feed hogs because there is no problem of disposal of manure or feed residues." In addition to these potential sources, on some chemigating irrigation wells the point of injection is upflow from the check valve, making backsiphoning of chemicals possible.

To reduce the potential for point-source contamination, chemicals should not be stored or mixed near wells, areas of livestock confinement should not be located near wells (and vice versa), and proper well construction and plugging should be enforced. Regulations for drilling and plugging wells in Kansas are contained in K.S.A. 82a-1201 to 82a-1215, but are not well enforced at this time.

Nitrogen Isotopes

Nitrogen isotopes were used to distinguish between sources of nitrate in ground water. The two stable isotopes of nitrogen are ^{14}N and ^{15}N; over 99 percent is ^{14}N. Terminology and theory associated with ^{15}N tests are described by Kreitler (1975). Basically, the more enriched the ^{15}N in a sample is relative to a standard, the higher its $\delta^{15}N$ ("delta ^{15}N" or "del ^{15}N") value. The symbol δ designates the relative difference in concentration with units of permil or parts per thousand. For simplicity, in this report $\delta^{15}N$ will simply be referred to as ^{15}N.

Figure 17 illustrates ^{15}N ranges of major potential sources of nitrogen in ground and surface waters. In identifying sources of nitrate contamination of ground water, there is general agreement that nitrate derived from fertilizer or mineralization of organic nitrogen in cultivated soils has an ^{15}N range of about +2 to +8, and that nitrate from decomposition of animals wastes has ^{15}N values greater than +10 or +12 (Bouwer, 1987, and references therein; Kreitler, 1975).

As expected, ^{15}N values from wells I6 (6.31), D13 (4.67), D20 (6.88), and D54 (5.28) indicated that fertilizer nitrogen (possibly accompanied by organic nitrogen released by cultivation) was the source of nitrogen. These wells are located in cropland areas and no other evident sources of nitrogen existed. Although nitrate-N concentrations were elevated relative to background concentrations, none of these exceeded the MCL of 10 mg/L.

^{15}N results for wells D1 (9.99) and S9 (11.01), which had the highest nitrate-N concentrations in the study, indicated that animal wastes were the main source of contamination in these wells. D1 has intermittently used livestock pens located about

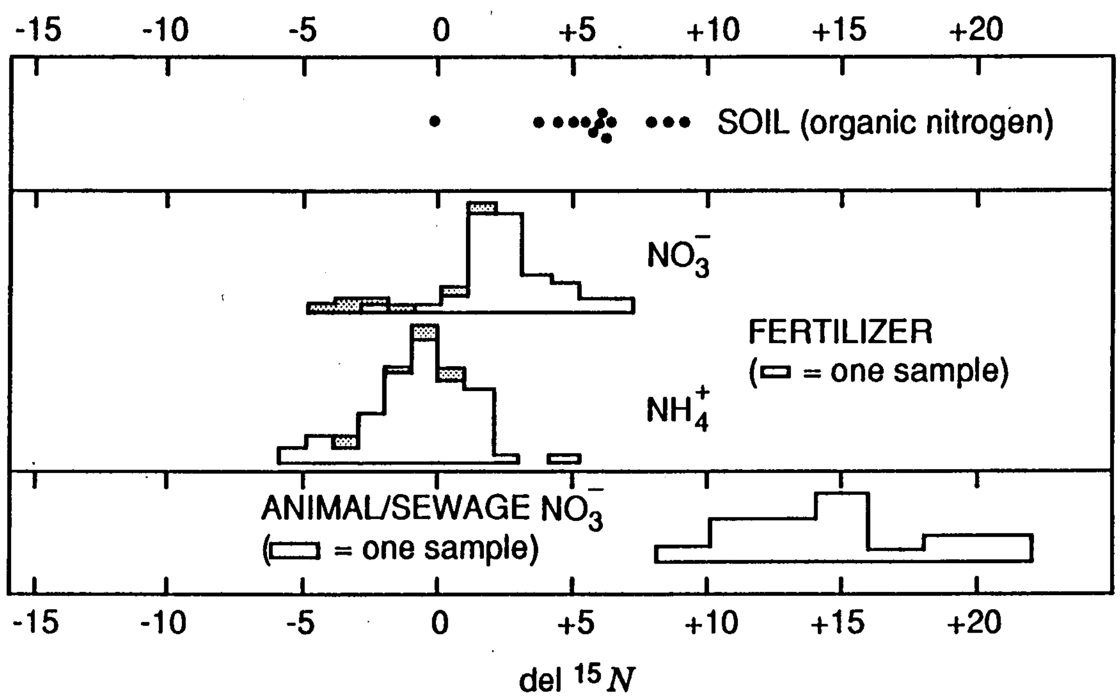


Figure 17. Ranges of ^{15}N values for major potential sources of nitrogen in ground and surface water (adapted from Heaton, 1986).

25 feet to the east, and S9 is a stock well that is visited by cattle on an intermittent basis. Animal wastes from livestock apparently are resulting in elevated nitrate concentrations in these wells. The high concentration in the shallow domestic well (D1) points out the risk of locating livestock pens near such a well or vice versa. Incidentally, the owner has discussed moving the pens farther away from the well.

Well D57 (12.02) also had an ^{15}N value in the animal waste range. The NO_3-N concentration in this well was 7.6 mg/L, which is higher than the mean and median concentrations in the study area, but not extremely high. It is likely that the concentration has been elevated by livestock around the farmstead. Old livestock pens are located upgradient from the well. Also, a major sinkhole exists less than one-half mile to the west. The sinkhole is located in a field grazed by cattle. It is possible that contamination from many years of animal wastes being washed down the sinkhole has reached the well.

^{15}N values for wells I11 (9.91), I16 (8.28), S18 (8.30), and I22 (8.91) are slightly above the fertilizer range. These wells are located in irrigated areas and it was suspected that ^{15}N values would be clearly in the fertilizer range. Because significant clay layers exist at all these sites, denitrification may occur in the vicinities. Denitrification results in a residual NO_3^- enriched in ^{15}N (Gormly and Spalding, 1979; Kreitler, 1975). Therefore, ^{15}N values slightly above the fertilizer range may be the result of partial denitrification of nitrate from fertilizer.

Values in this range also may indicate two or more sources of nitrogen. Animal wastes from cattle grazing on corn stubble may have contributed enough nitrogen to raise the ^{15}N values slightly out of the fertilizer range. According to the farmers surveyed, manure had not been applied as fertilizer.

Figure 18 illustrates that there is a slight correlation between nitrate-N concentrations and ^{15}N values (Spearman correlation coefficient (r_s) = 0.308). Although not statistically significant, it appears that higher nitrate concentrations tend to have animal wastes as the primary source of nitrogen. In fact, all wells sampled for ^{15}N which had NO_3-N concentrations greater than 10 mg/L had ^{15}N values in the animal waste range.

In summary, elevated nitrate-N concentrations appear to be occurring as a result of fertilizer use and animal wastes. Regionally, fertilizer use has resulted in nitrate entering ground water. While concentrations greater than 10 mg/L do not seem to be widespread now, the number of wells contaminated and the nitrate concentrations are likely to increase if present fertilization rates continue and there is more time for nitrate to move into ground water. Locally, animal wastes can be more of a problem than fertilizer, particularly when livestock are concentrated near a well, constituting a potential point source.

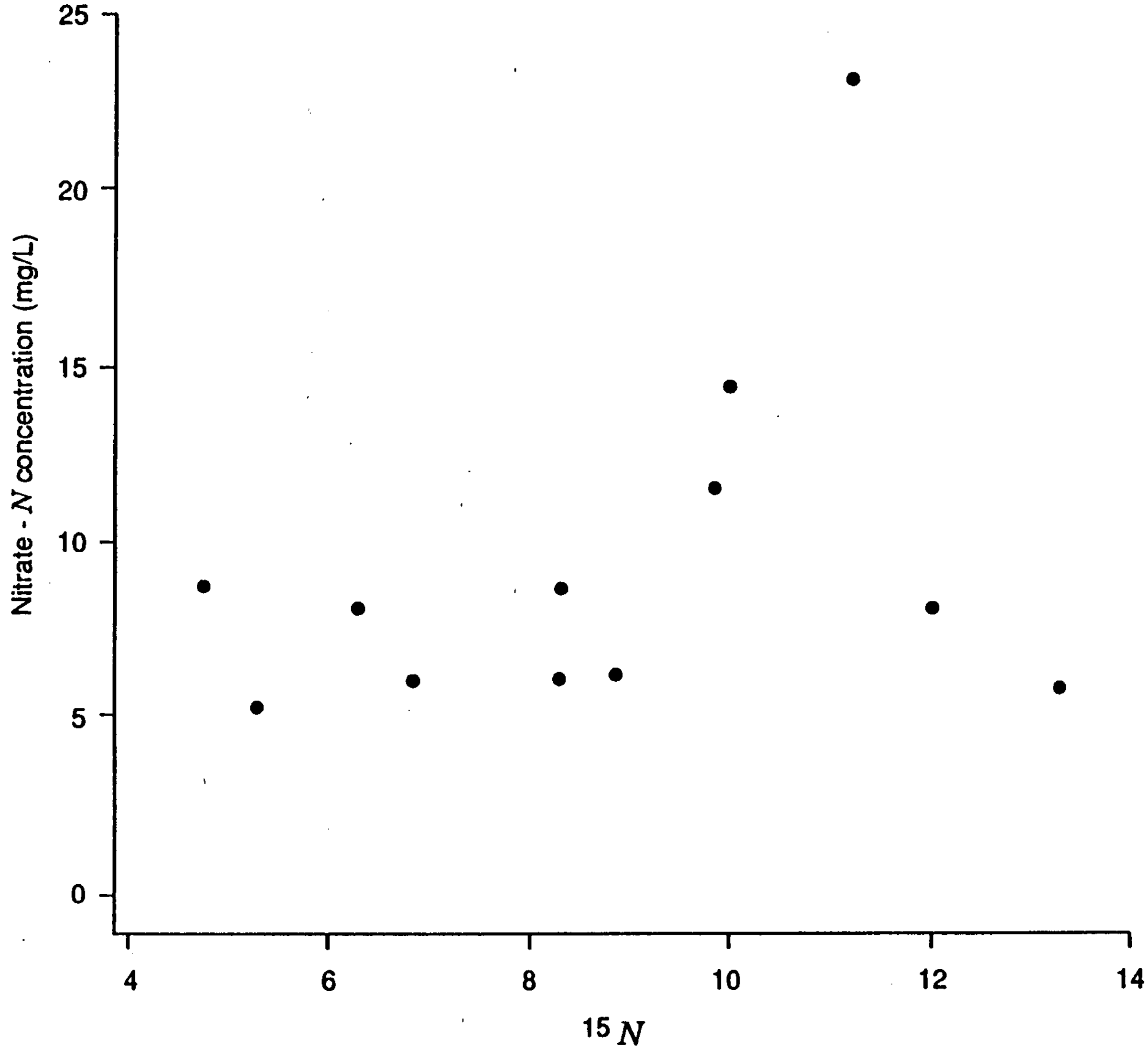


Figure 18. Nitrate - nitrogen concentrations vs.^{15}N values.

CONCLUSIONS

1. Elevated nitrate-nitrogen concentrations are occurring in the ground water in northern Stafford County, Kansas. Presently, concentrations greater than the MCL of 10 mg/L are not widespread.

2. Of the variables examined, land use variables had the strongest correlation with NO_3^-. Nitrate-nitrogen concentrations were significantly different under the three major land uses. Mean and median concentrations were highest under irrigated cropland areas, intermediate under non-irrigated cropland, and lowest under uncultivated pastureland. Low concentrations under pastureland suggest that ground water has been affected minimally by human activities. Cultivation and fertilization are primarily responsible for higher concentrations under cropland.

3. The apparent impact of irrigation on ground-water quality can be explained by two fundamental reasons: 1) almost twice as much fertilizer is applied to irrigated crops compared with dryland crops, and 2) the larger amount of water applied enhances the downward transport of nitrate. Continuous cropping of corn uses more fertilizer and more water than any other land use in the area.

4. The influence of irrigation on ground-water quality is further manifested by the fact that nitrate concentrations were higher where irrigation well densities were greater. Apparently the large amounts of fertilizer nitrogen and water applied have resulted in significant quantities of nitrate leaching to the ground water. The number of wells contaminated and the nitrate concentrations are likely to increase if present fertilizer rates continue and there is more time for nitrate to move into the ground water.

5. An encouraging finding was that the lowest nitrate-N concentration found in any irrigation well and one of the lowest in the entire study (0.7 mg/L) was from an irrigation well in an alfalfa field. Alfalfa may in fact be acting as a scavenger of nitrate below the root zone of other crops.

6. Nitrate-nitrogen concentrations were significantly lower under the Pratt-Carwile compared with the Pratt-Tivoli soil, supporting the hypothesis that concentrations would be lower under the soil with the least permeable horizon in the soil profile.

7. While statistically significant differences in nitrate concentrations were evident under the different land uses and different soil types, these variables are not completely independent of one another and both influence nitrate concentrations.

8. Virtually all well logs revealed significant clay layers. Most logs reported at least 10 feet, and many more than 30 feet of clay. It is likely that the clay layers (or lenses) have retarded the downward movement of nitrate and resulted in dentrification, which would explain why nitrate concentrations were not higher in this shallow aquifer under sandy soils.

9. No significant correlation was discovered between nitrate-N concentrations and any of the hydrologic (depth) variables examined, however the shallowest well sampled had a concentration greater than the MCL. One condition that may account for the lack of correlation with depth is that the boreholes of virtually all wells in the study area are gravel packed from the bottom of the grout to the bottom of the well, allowing shallow and deeper water to mix. Heavy pumping (as by irrigation wells) could exacerbate the mixing.

10. Many potential point sources of contamination exist in the study area, including areas of livestock confinement, areas of chemical mixing and storage, unplugged abandoned wells and testholes, poorly constructed wells, and sinkholes.

11. Locally, animal wastes can be more of a problem than fertilizer. Animal wastes can result in ground-water nitrate-N concentrations greater than the MCL, particularly when livestock are concentrated near a well, constituting a potential point source.

12. Unlike some other regions, digging deeper wells is not a solution to the problem of nitrate contamination of ground water in northern Stafford County. Elevated concentrations of nitrate and chloride (caused by salt-water intrusion from the Permian bedrock) already are occurring in deeper wells. Continuing increases in nitrate concentrations must be prevented to protect this valuable aquifer.

RECOMMENDATIONS / FUTURE RESEARCH

Included in this section are: 1) recommendations to be considered for preventing further nitrate contamination, and 2) suggestions for future research. The economic feasibility of all recommendations has not been determined and requires further consideration.

To prevent continuing increases in ground-water nitrate concentrations, it is essential that fertilizer nitrogen and irrigation water are managed efficiently. The farmers, their families and offspring are the ones who drink the water and they are concerned about protecting it. Farmers need to be educated about: 1) adverse environmental and economic consequences of overuse of fertilizer and irrigation water, and 2) existing and newly researched management practices which improve nitrogen use efficiency.

The amount of fertilizer applied is probably the most important variable affecting nitrate leaching in cropland areas, and perhaps fertilizer recommendations should be reexamined. On irrigated corn in the study area, an application rate of at least 200 lb N/acre is normally recommended and applied. Research elsewhere has shown that with good management, even on sandy soils, the optimum rate is about 150 lb N/acre. Employing such techniques as split applications of fertilizer, use of nitrification or urease inhibitors, and timely irrigations may lower the optimum rate. All existing sources, including residual soil nitrogen and nitrate in irrigation water, should be taken into account when N rates are considered.

Irrigating less should reduce the amount and rate of nitrate leaching and leave applied nitrogen available to plants for a longer time. Possibly, using low pressure drip irrigation would be advantageous, resulting in lower evaporation, water use, and energy consumption than the conventional high pressure sprinkler systems. Perhaps more research on techniques for increasing nitrogen use efficiency could be conducted at Sandyland Experiment Field (a Kansas Agricultural Experiment Station located in Stafford County), and results distributed to farmers. Also, more research into the development of field techniques to measure soil moisture and nutrient content would be advantageous. Such techniques would help farmers tailor nitrogen and water applications to crop needs.

Because continuous cropping of corn represents such a threat to ground-water quality, alternatives to this practice should be considered and encouraged. Alternatives which may increase nitrogen use efficiency (many of which are practiced to some extent in the area) include: growing crops that require less fertilizer and water, using rotations including legumes, maintaining cover crops and/or growing green manure crops, integrating livestock and crop production to recycle nutrients, and reseeding marginal cropland to pastureland. Alfalfa, used in longer-term rotations, offers distinct potential for scavenging nitrate below the root zone of other crops. Once again, research is needed to discover the viability of these alternatives, and the results must be made available to farmers.

Because land use and soil type variables were not completely independent of each other, in order to distinguish between the two, future studies might analyze cores from different soils where historical land use data are available. Comparing amounts of nitrate below the rooting zone under similar land uses would give a better indication of leaching potential under different soils, and vice versa. Also, more research is needed on denitrification and flow through the unsaturated zone.

Point-source contamination can be reduced if wells are not located near areas of livestock confinement or areas of chemical mixing or storage. Also, proper well construction and plugging (K.S.A. 82a-1201 to 82a-1215) should be enforced to reduce the number of direct pathways from the land surface to the aquifer. Grouting through clay layers would lessen the amount of mixing between shallow and deeper ground water.

The data obtained from this research can be used as a space in time or baseline reference. For future assessment, a system of functional observation wells would facilitate better monitoring of ground-water quality. Sampling from different depths from well-defined and well-constructed observation wells (particularly during the non-irrigating season) would give a better idea of the vertical distribution of contaminants. More frequent sampling (perhaps monthly) would help detect seasonal fluctuations and trends.

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