

Nitrate in Wisconsin Groundwater: Sources and Concerns

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Little nitrate moves into groundwater from well-managed, non-irrigated farmland.

When nitrogen in the form of fertilizers, wastes or plant residues is applied to the land, it undergoes numerous chemical, physical and biological reactions. In its nitrate form (NO_3^-), it can move down through soil into groundwater. Nitrate can also be a factor in surface water quality problems. In sufficient concentrations, nitrate in drinking water can be toxic to infants. Scientists are also investigating possible links between nitrate and other long-term health effects, though none have yet been demonstrated.

Although nitrogen can cause environmental and health problems, it is an essential element in living matter. Nitrogen is a major component of proteins and DNA, and is indispensable in the production of food and fiber.

The main sources of nitrogen in agriculture are commercial fertilizers, livestock wastes and the residues of legume plants such as alfalfa that can “fix” nitrogen from the air and convert it to organic forms. Commercial fertilizers, in particular, are a major factor in the high productivity of modern agriculture.

This publication explains how this complex and dynamic element works in the environment, its role in agriculture, the numerous nitrate sources that can contaminate ground-

water, its impact on human and animal health, and what can be done to keep nitrate from building up to potentially harmful levels in groundwater.

The nitrogen cycle in agriculture

Figure 1 (shown on page 2) illustrates the cycling of nitrogen in agriculture. Nitrogen reacts in the soil environment in five basic ways.

Organic matter in soil is a reservoir of nitrogen. The plow layer of most Wisconsin soils contains from 500 to 5,000 pounds of nitrogen per acre. However, plants can't use the nitrogen in this organic matter until it undergoes **ammonification** (reaction 1). Microorganisms convert the nitrogen in soil organic matter—crop residues, human and animal wastes—to ammonium (NH_4^+), which plants can absorb through their roots. Farmers commonly apply ammonium forms of fertilizer to crops.

Ammonium binds tightly to soil particles and does not leach into groundwater. But in warm, well-aerated soils, bacteria rapidly convert ammonium first to nitrite and then to nitrate in a process called **nitrification** (reaction 2). Plants readily use nitrate, like ammonium. But unlike

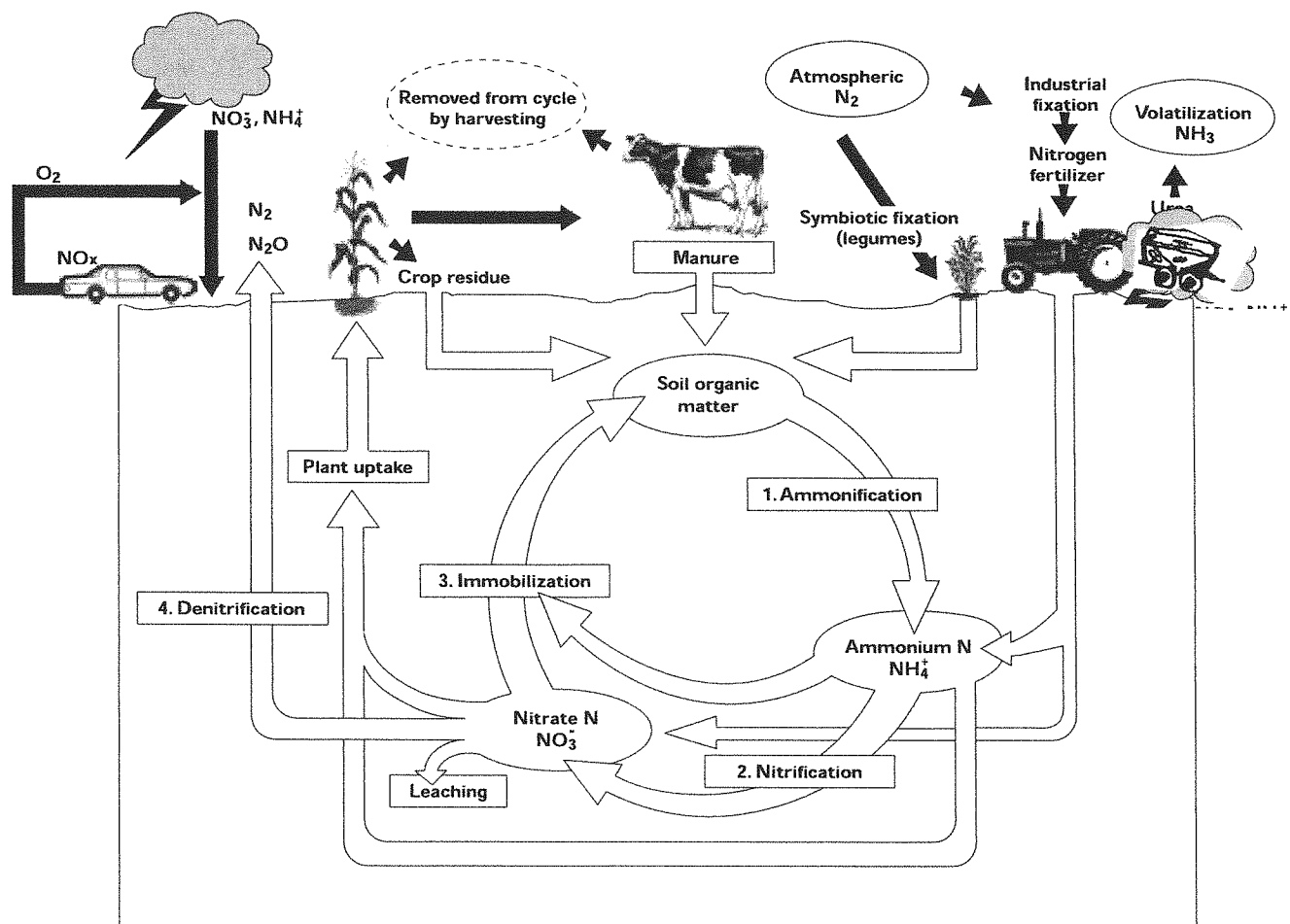


Figure 1. The nitrogen cycle.

ammonium, nitrate is highly soluble in water. Nitrate does not bind to the soil, but readily leaches through it.

Like plants, soil microorganisms also use nitrate and ammonium. When microorganisms use nitrogen for their own growth, the process is called **immobilization** (reaction 3), because the nitrogen becomes unavailable for plant growth.

When farmers add high-nitrogen residues such as legumes to the soil, more nitrogen is present than the microbial population needs, resulting in mineralization. Both mineralization (reactions 1 and 2 combined) and immobilization go on simultaneously whenever the soil is warm enough for microbial activity. Microbial growth accelerates when organic materials are added to the soil because of the additional “food” sources. Thus, legume plant residues and manures are good organic nitrogen fertilizers. If farmers add residues such as cornstalks or straw which don't contain enough nitrogen to satisfy microbial needs, the microbes

use inorganic nitrogen from the soil, causing a temporary nitrogen deficiency for the crop until microbes decompose the residues.

In warm, extremely wet surface soils where little oxygen is present, **denitrification** (reaction 4) can occur. This process, also carried out by bacteria, converts nitrate to nitrogen gas (N_2).

Biological fixation of nitrogen is an important source of usable nitrogen in Wisconsin agriculture. Fixation is the ability of certain microorganisms and plants to convert gaseous nitrogen to ammonium. Some algae in lakes and streams fix nitrogen, as do some bacteria. In agriculture, legumes such as soybeans, alfalfa and clover fix atmospheric nitrogen with the help of specialized soil bacteria called rhizobia.

Some of this organic nitrogen stays in roots and residues not removed during harvest. These residues enrich the soil with nitrogen. On most soils, corn grown following alfalfa usually does not need additional nitrogen fertilizer.

Some available nitrogen is present in precipitation. Data for Wisconsin indicate that precipitation adds about 10 pounds of nitrogen per acre per year, mainly in the form of ammonium and nitrate. While not of great importance to agriculture, this is a major source of nitrogen in nonfarm areas such as forests and lakes.

Nitrogen use in Wisconsin

Wisconsin, with its higher proportion of dairy and beef farming, does not rely as heavily on commercial fertilizer nitrogen as do surrounding corn belt states. The total nitrogen in legume crop residues contributes about 80,000 tons of *available* nitrogen to crops annually. Animal manures produced each year contain about 300,000 tons of total nitrogen. This important source of recyclable nitrogen contributes roughly 100,000 tons of nitrogen per year to crop production.

About 240,000 tons of commercial fertilizer nitrogen are added to cropland each year. Much of this fertilizer nitrogen is used on approximately 4 million acres of corn, where application rates average about 120 pounds of nitrogen per acre statewide. Commonly, farmers use higher rates of fertilizer nitrogen in southern Wisconsin where the growing season is longer. Specialty crops, although small in total acreage, often receive high rates of fertilizer nitrogen.

Adverse health and environmental impacts of nitrate

Human health

The main sources of nitrate and nitrite in the diet are vegetables and cured meats. According to the U.S. Department of Agriculture, the average adult ingests about 25 mg of nitrate-nitrogen per day in foods.

Normally, less than 10% of nitrate comes from drinking water. However, drinking water supplies contaminated by fertilizers or by nitrogenous wastes from barnyards, feedlots or septic systems can become a major source of nitrate intake.

Federal drinking water standards do not allow public water supplies to contain more than 10 mg of nitrate-nitrogen per liter.* However, many private wells in Wisconsin exceed this

level. Shallow wells and those with less than 40 feet of casing located in agricultural areas are at higher risk for nitrate contamination. Water that is high in nitrate poses a risk to infants less than six months old.

Infant nitrate poisoning has been recognized as a concern since the problem was first reported in 1945. Infants fed water or formula containing water with high nitrate levels can develop a condition called methemoglobinemia, also referred to as "blue baby syndrome." The name derives from the characteristically blue or lavender skin color of infants suffering from the syndrome. The distinctive blue color is caused by the red blood cells' inability to carry oxygen from the lungs to the rest of the body.

This condition occurs when bacteria in a baby's mouth and stomach convert nitrate to highly toxic nitrite. Although confirmed cases of infant deaths from nitrate poisoning are rare, immediate medical attention is required to prevent brain damage or death.

Methemoglobinemia generally does not affect older children or healthy adults. However, some information suggests that ingesting nitrate-contaminated drinking water during early pregnancy may increase the risk of certain birth defects. Studies conducted in Australia, Canada and New Jersey found a higher incidence of neural tube defects and cleft palates in areas where nitrate levels were elevated. Additional concerns about nitrate exposure during pregnancy have been raised because research shows nitrites may cross the placenta and potentially increase methemoglobin levels in the developing fetus.

Although scientists are unsure about the chronic health effects of nitrate, long term ingestion of water containing high nitrate levels is not recommended. Some researchers have reported finding higher stomach cancer rates in areas where drinking water nitrate levels were elevated. In addition, high nitrate levels are often accompanied by pesticide or bacterial contamination. Thus, nitrate is an important indicator of overall drinking water quality.

Animal health

While symptoms of nitrate toxicity do occur in livestock, the doses necessary to produce acute toxicity are much higher than those required for humans. Nitrate poisoning in livestock is caused more often by feed than water. Nitrate-contaminated water is usually a problem only when nitrate in the water combines with high nitrate concentrations already present in some feeds.

* Laboratories that analyze water samples report the nitrate content of water as either nitrate (NO_3^-) or nitrate-nitrogen ($\text{NO}_3\text{-N}$). Ten milligrams per liter of $\text{NO}_3\text{-N}$ is the same as 44 milligrams per liter of NO_3^- . Milligrams per liter is the same as parts per million (ppm) for water samples.

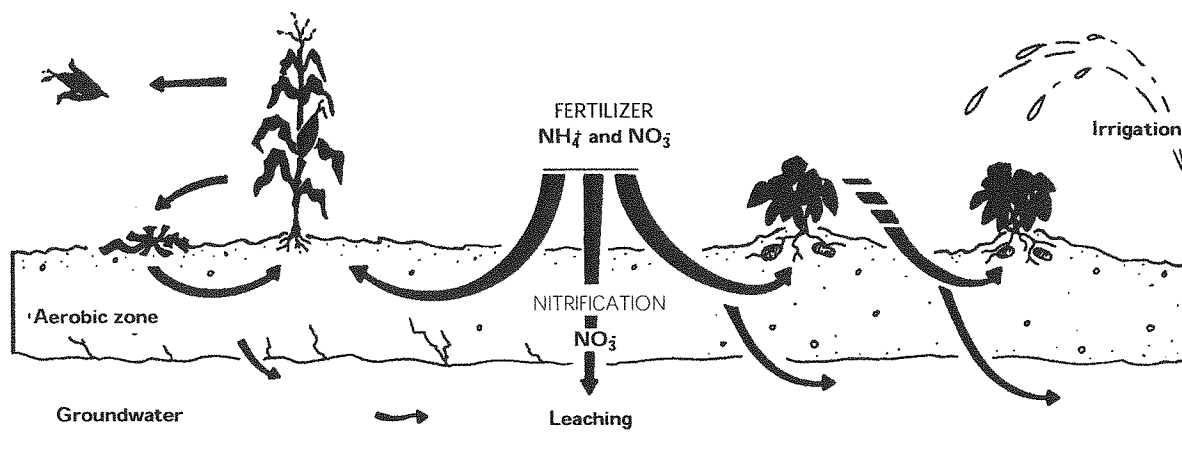


Figure 2. Unused nitrate can leach out of the soil under rain-fed agriculture (left) or irrigated agriculture (right).

While it is relatively easy to determine fatal levels of nitrate for animals, it is difficult to determine the dose that produces chronic, non-fatal symptoms, or to prove that chronic symptoms result from nitrate poisoning. Many general symptoms such as poor appetite, poor growth and even abortions are often blamed solely on nitrate. However, disease, poor nutrition and poor management may cause or worsen these symptoms.

For example, nitrate merely exacerbates poor performance on a ration low in energy or lacking essential minerals. No one has yet identified a symptom or chemical diagnosis that specifically points to chronic nitrate poisoning in animals. Chronic problems caused by nitrate alone are probably rare.

Environment

High-nitrate groundwater affects not only human and animal health, but also the environment. Nitrate-contaminated groundwater eventually becomes surface water when it reaches a discharge zone. Nitrate concentrations of 0.3 mg/liter in surface waters, particularly lakes, will support algae and weed growth. However phosphorus, rather than nitrogen, appears to be the limiting nutrient for algal growth in most of Wisconsin's waters. Over-enrichment with nutrients (eutrophication) eventually causes noxious algae blooms and dense stands of aquatic plants. This excessive growth interferes with lake recreation, and, as the weeds and algae decompose, lowers dissolved oxygen and may kill fish.

Sources of nitrate in groundwater

Experts can readily list sources of nitrate, but measuring the actual contribution of each to wells or surface waters is far more difficult. In Wisconsin, local sources of nitrate include water that percolates through septic system seepage beds and livestock holding areas. Regional sources include intensive, non-irrigated farming and irrigated agriculture. As explained earlier, the nitrate output from forest, pastures and alfalfa fields is usually low.

As shown in Figure 1, nitrate moves downward in soils along with water because it does not attach to soil solids. The amount and rate of nitrate movement is difficult to predict accurately because soils can differ widely in their properties—even within a field. Sandy (coarse-textured) soils retain less water than do fine-textured soils, which are higher in clay. Thus, the potential for rapid nitrate movement below the root zone is greater in sandy soils.

Once nitrate moves through the soil down to groundwater, it mixes slowly with the water in the aquifer. As a result, a particular water layer in the aquifer may be more contaminated than water above or below it. Because groundwater moves in such a complex fashion, the exact fate of nitrate-contaminated groundwater is hard to predict. However, it eventually discharges into a lake, stream, wetland or well.

Agriculture

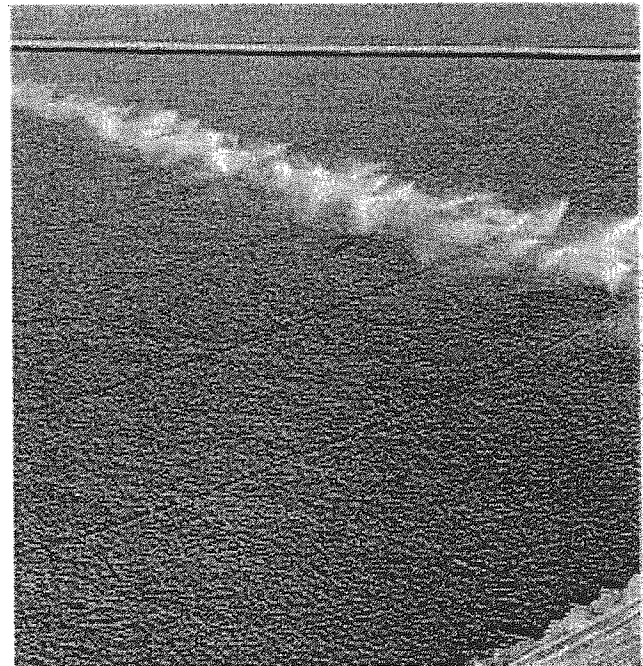
Natural grasslands and forests are roughly balanced with respect to nitrogen entering and leaving the soils. Nitrogen coming in through rain and biological fixation is approximately matched by that escaping back to the atmosphere through volatilization and denitrification; little nitrate leaches into groundwater.

When these systems are disturbed by clearing the forests and tilling and draining the soil, the natural cycle changes. The rate of decomposition of organic matter accelerates and more nitrate forms than crops can assimilate. Some of this nitrate likely reaches the groundwater. Because many aquifers recharge slowly, often over several decades, some nitrate in groundwater may be the result of agriculture in the “prefertilizer” era.

Research in the early 1900s showed that many soils no longer had enough nitrogen available to produce maximum yields, so many farmers planted legumes in their crop rotation to replenish soil nitrogen. By the end of World War II, farmers recognized that fertilizer nitrogen could replace the nitrogen found in soil, freeing prime farm land for growing corn and other high-profit grains. Since that time, nitrogen fertilizer use has increased rapidly. One reason for the increase has been fertilizer nitrogen’s low price relative to the value of the crop, especially corn. The favorable corn/fertilizer price can lead to excess nitrogen fertilizer use.

Industrial production of nitrogen fertilizers from natural gas has been common since the 1940s. The process requires considerable energy. It takes about 24 cubic feet of natural gas to produce one pound of fertilizer nitrogen—about the same amount of energy required to drive a car three miles. About 2% of the U.S. natural gas consumption goes toward manufacturing nitrogen fertilizers. In the future, nitrogen fertilizer could become an expensive commodity requiring more careful and efficient management.

Intensive farming on non-irrigated farms, such as the corn-soybean farming practiced in the Midwest, has been linked to high-nitrate drainage water. However, studies show that on most soils, if the available nitrogen in the soil is kept to about the level of nitrogen that crops actually need, the loss of nitrate is minimized. If the amount of available nitrogen is kept in balance with crop needs, other factors—such as the relatively slow movement of water through most soils and the potential for denitrification—also mitigate against serious nitrate contamination.



High-intensity agriculture on sandy soils contributes to local groundwater nitrate problems.

Irrigated agriculture

A nearly ideal situation for irrigated agriculture exists in the “golden sands” area of central Wisconsin. There, high quality groundwater is available in large volume close to the surface. The level, porous sands are easy to till and manage for high-value crops such as vegetables and potatoes. As a result, irrigated agriculture has expanded rapidly in this area. Unfortunately, these same conditions make for inefficient nitrogen management (figure 2).

The sandy soil in the “golden sands” holds little water. Growers must water crops frequently during the growing season, which can lead to leaching of water soluble components such as nitrate. Because of the unpredictable nature of weather, heavy rains may follow irrigation, making leaching problems worse. Certain crops, especially potatoes, require as much nitrogen as corn. Because the soils are low in organic matter, farmers must add most of the nitrogen crops need. Potatoes have especially shallow roots, so just a little leaching washes nitrate out of their root zone. Because the sandy soils warm rapidly and are well-aerated, nitrification is rapid. Virtually no opportunity exists for denitrification.

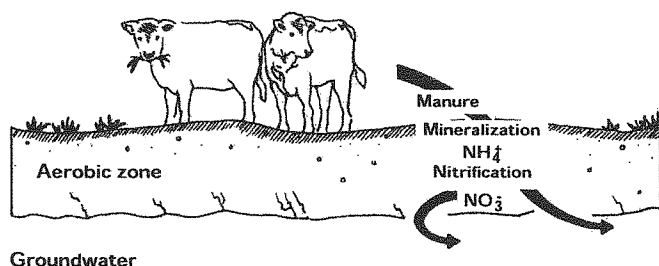


Figure 3. In some areas, animal manures are an important nitrate source.

University of Wisconsin-Madison researchers have conducted studies at the Hancock Agricultural Research Station in an attempt to use fertilizer nitrogen more efficiently. These studies showed that 50 to 100 pounds of nitrogen per acre leached from a typically managed potato field. The studies also indicated that reducing this loss is extremely difficult and costly. Compounds that slowed the nitrification process did not help. The compounds were not completely effective, and potato yields suffered because too much ammonium was in the root zone at the wrong time. Slow-release forms of nitrogen also proved to be very costly. Only when irrigation and fertilization are managed together is there a probability of consistently reducing nitrate leaching.

Livestock operations

In Wisconsin, most livestock operations are fairly small. The cattle spend time in pastures and holding areas, which can be local sources of nitrate in private wells (figure 3). The tendency of farmers to dispose of manure close to farmsteads also may overload some fields with manure nitrogen. In addition, Wisconsin studies have shown that poorly designed manure storage pits, lagoons and storage tanks can contribute significant amounts of nitrate to groundwater.

The potential for nitrate leaching from barnyards is great when they are located on sandy soils or on thin soils over creviced bedrock. In these situations, yards tend to stay porous and aerobic, allowing nitrogen to convert to nitrate and leach rapidly into groundwater.

Septic tanks

In unsewered areas, most people use septic systems to dispose of their household wastewater. The system passes waste into a tank and then into an underground disposal field. Nitrogen in the wastes remains in the ammonium and organic forms until it reaches the aerobic zone below the disposal field. There it is oxidized to nitrate and moves with water into the groundwater. Very little, if any, nitrogen is

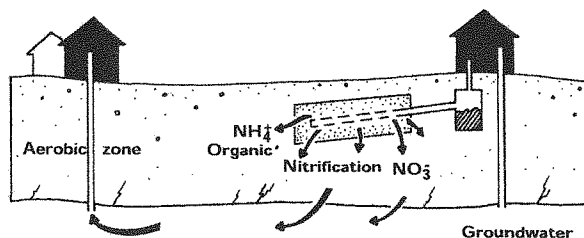


Figure 4. Septic tank systems can be a source of nitrate.

removed (figure 4). Monitoring studies show that wastewater from a disposal field that percolates down to the groundwater contains about 50 mg/liter nitrate-nitrogen. This can provide a local source of nitrate in wells. The direction and rate of groundwater movement, and the nitrate concentration in groundwater upgradient from dwellings combine to influence drinking water quality.

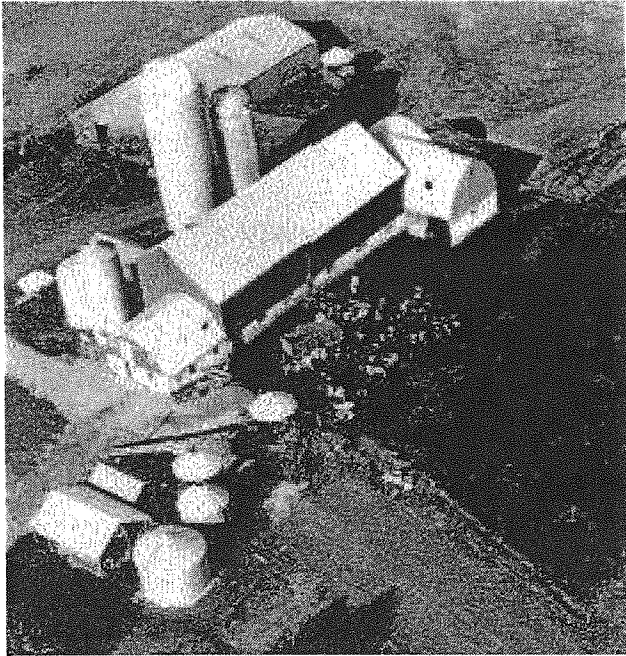
The Wisconsin Department of Industry, Labor and Human Relations (DILHR) is charged with seeing that septic systems do not contribute excessive amounts of nitrate to groundwater. The agency's administrative code ILHR 83 needs review and updating to ensure that septic systems comply with groundwater standards. Research projects at the University of Wisconsin-Stevens Point and University of Wisconsin-Madison are being conducted to address this problem.

Controlling sources of nitrate

Best management practices for agriculture

The techniques for minimizing nitrate leaching from cropland are the same as those for making sure that crops use available nitrogen as efficiently as possible. Careful matching of nitrogen application rates to crop needs can reduce nitrate leaching. However, this is a difficult task because the availability of soil organic nitrogen and crop residue nitrogen is hard to predict, and because soil, crop and weather factors influence how efficiently crops use nitrogen. Preplant and pre-sidedress soil nitrate tests can help farmers identify the optimum nitrogen rate to apply in specific fields. Claiming appropriate nitrogen credits for previous legume crops and manure additions is also essential for profitable production and water quality protection.

Better timing and placement of fertilizer nitrogen can improve efficiency. Fall application of nitrogen without use of nitrification inhibitors is an inefficient practice that farmers should avoid. In irrigated systems, careful water manage-

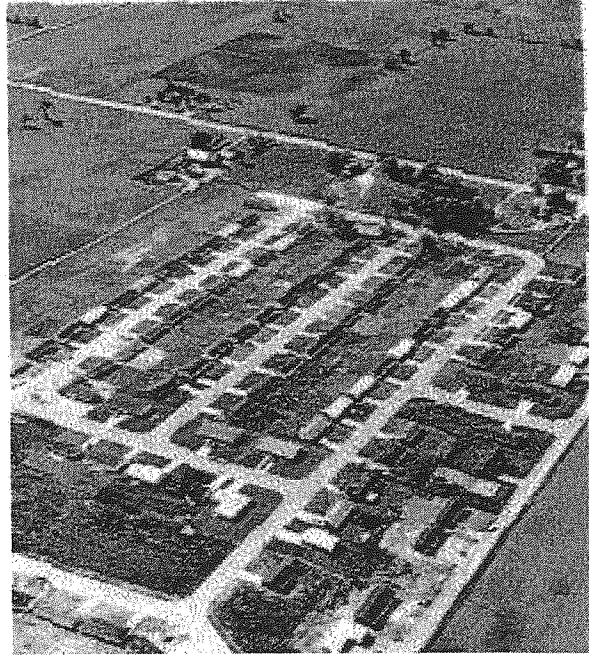


Nitrate often increases in the groundwater below livestock holding areas.

ment can decrease nitrate leaching (a good example is found in the Wisconsin Irrigation Scheduling Program, or WISP). Using chemical nitrification inhibitors to slow down the conversion of ammonium into leachable nitrate can help reduce losses from preplant-applied fertilizers on sandy soils. Delayed or sidedress nitrogen applications without inhibitors are usually equally effective in controlling nitrate leaching losses on sandy soils.

When properly managed, organic wastes such as manure and sewage sludge can act as slow-release fertilizers and reduce leaching potential. As with commercial fertilizers, growers need to manage the timing, application rate and nitrogen credits from these sources carefully. However, not nearly enough of these wastes are available to satisfy growers' fertilizer needs.

Although applying fertilizer to the leaves of plants rather than to the soil can reduce the amount of nitrate available for leaching and offers possibilities for some specialty crops, it is impractical for crops such as corn.



Cluster developments in rural areas are a source of nitrate in groundwater.

Rotating deep-rooted crops such as alfalfa with high-nitrogen-demanding crops such as corn and potatoes, or legume inter-planting may remove deep subsoil nitrate, preventing subsoil nitrate build-up and reducing leaching potential.

New technologies hold promise for future improvements in nitrogen management. Models based on production and climatic information may allow estimation of nitrate carryover and available nitrogen release from organic amendments without extensive field sampling. Farmers will be able to use these methods to improve decisions about the rate and timing of nitrogen application to maximize crop use of nitrogen, thus reducing the amount of nitrogen leaching.

Land use controls

Where nitrogen contamination of groundwater seriously threatens drinking water, government regulation is sometimes possible.

Wisconsin's 1984 groundwater law allows local governments to zone land "to encourage the protection of groundwater resources." Classifying land uses based on their threat to groundwater and zoning lands on their susceptibility to contamination is a reasonable exercise of local land use controls.

To protect groundwater, communities can take regulatory approaches that range from simple to complex. Zoning ordinances can protect groundwater by prohibiting uses that cause problems, permitting other uses only under certain conditions, limiting the intensity of development, and determining where certain uses will be permitted.

Local governments can identify and regulate land uses in areas where the soil and geologic conditions allow easy contamination of groundwater, can identify aquifers and regulate land uses on lands recharging those aquifers, and can regulate land uses in areas near existing and future public wells. Actions to protect drinking water supplies from nitrogen contamination might include zoning areas near public wells for parks or other undeveloped uses (wellhead protection), or permitting only very scattered unsewered residential development in important aquifer recharge areas. Larger lot sizes are required in some areas to sufficiently dilute nitrate from septic systems. (This practice contributes to urban sprawl and its related problems, however.) Several Wisconsin counties have prepared comprehensive groundwater protection plans designed to minimize threats to groundwater from a variety of sources.

Although local regulatory actions to protect groundwater may work well to reduce nitrate problems in developing areas, it is questionable whether such ordinances can be applied successfully to agricultural sources. Some states now delineate management areas where fertilizer application is regulated or specific practices are recommended. The Coastal Nonpoint Pollution Control Program directs the state to require nutrient management plans for activities in 25 Wisconsin counties. In addition, access to some cost-share programs may require compliance with a nutrient management plan. Problems with this approach include the enormous difficulty and expense of enforcement.

Many Wisconsin counties have enacted ordinances that regulate the design and location of manure storage facilities. Research shows that earthen pit storage facilities may contaminate groundwater. The ordinances require farmers to acquire a permit before installing a storage facility.

The permit requirement lets counties ensure that storage facilities are properly designed and located to minimize the potential for groundwater contamination. These ordinances help prevent poorly designed and located storage facilities, but they are not the answer to nitrate contamination from livestock wastes. Storing livestock waste results in millions of gallons of waste being applied to agricultural lands at one time. If farmers spread these wastes on the wrong sites at the wrong time of year, they can cause major groundwater contamination.

Perspectives

Nitrate contamination of private wells is a serious problem in Wisconsin. Even some public wells have recorded nitrate concentrations above the 10 mg/liter drinking water standard.

Often nitrate-contaminated water comes from a local source—a barnyard or septic system. People can correct these situations after they recognize the source and determine the direction of groundwater flow.

Of greater concern is the potential contamination of regional aquifers used for public water supplies. Because many sources usually contribute nitrate to these aquifers, control is difficult. Often agriculture is the most obvious source, especially in sensitive areas such as those where farmers practice irrigated agriculture on sandy soils.

Controlling regional nitrate pollution ultimately involves recognizing the many social, economic and technological factors involved. For example, the expansion of unsewered subdivisions may need to be limited and the amount of land under intensive agriculture controlled. Certainly, educational and research programs to improve the efficiency of nitrogen use on farms—from fertilizers, wastes, or legume residues—must be expanded. However, all these are major tasks requiring a large expenditure of resources and considerable time.

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