Special Report 1050
January 2004

Nitrates and Groundwater:
Why Should We Be Concerned with Our Current Fertilizer Practices?

OREGON STATE UNIVERSITY
AGRICULTURAL EXPERIMENT STATION

For additional copies of this publication, write

John S. Selker
Department of Bioengineering
Oregon State University
116 Gilmore Hall
Corvallis, OR 97331

Phone: 541-737-6304
Fax: 541-737-2082

Agricultural Experiment Station
Oregon State University
Special Report 1050
January 2004

Nitrates and Groundwater:
Why Should We Be Concerned with Our Current Fertilizer Practices?

Jeff Feaga, former graduate research assistant, bioengineering;
Richard Dick, professor, crop and soil science;
Michael Louie, former graduate research assistant, bioengineering; and
John Selker, professor, bioengineering; Oregon State University.

Funding for this research provided by the Oregon Department of Agriculture, Salem.

Nitrates and Groundwater: Why Should We Be Concerned With Our Current Fertilizer Practices?

Jeff Feaga, Richard Dick, Michael Louie, John Selker

Introduction

The general understanding of our water resources and their vulnerability to contamination has improved in recent decades. Much of this contamination originates from non-point sources, from activities carried out over large areas rather than from a single source, such as a pipe outfall. Chemicals originating from non-point sources enter our streams, lakes, and groundwater through processes such as runoff and percolation, and have proved to be a large contributor of contamination. Non-point source pollution is typically associated with agricultural activities and is difficult to regulate and control. Agricultural scientists, supported by many years of research, cooperation with the farm community, and the technology to manage and present data, are now able to measure some of the environmental impacts of chemical loss from agricultural operations. Understanding the scope and depth of the problem is the first step toward addressing agricultural contamination.

Currently, agricultural production, profit and competitiveness are of utmost importance in Oregon and across the United States. The methods of farming currently in use are very effective at maximizing these economic measures, but do not generally account for degradation of soil and water resources. Frequently, the most serious agricultural contamination problems with respect to water resources stem from loss of excess nutrients. Nutrients and their correct use and application have become a widespread issue following the separation of crop and animal production, a trend that began 50 years ago when commercial fertilizers became available (Dinnes et al., 2002). Nitrogen (N) fertilizer is necessary for the competitive production of crops, but in excess, nitrates (NO_3^-) can be toxic to infants (Weisenburger 1993) and infirm people. Nitrate can adversely affect aquatic habitats by over-stimulating primary production in surface water, causing anoxic conditions and eutrophication. Voters and lawmakers concerned about the environment understand this and have put ever-increasing pressure on growers and ranchers to control their environmental impacts while continuing to supply ample and low-cost food.

This publication describes the challenges faced by the western Oregon grower concerning NO_3^- leaching losses to shallow groundwater aquifers. This paper describes 1) the conditions that make western Oregon a particularly vulnerable environment to NO_3^- leaching and contamination; 2) the incentives for western Oregon growers to undertake a careful nutrient management plan; and 3) the options for best management practices (BMP's) available to growers, including:

- winter cover crops
- soil testing
- fertilizer and manure chemical analysis
- maintenance of irrigation systems.

Nutrient Contamination

A Mediterranean climate with seasonally high water tables combined with intensive agriculture makes the Willamette Valley a particularly vulnerable location for nitrate (NO_3^-) contamination (Owens 1990). According to the United States Geological Survey (1998), 9 percent of wells in the Willamette Valley exceed the U.S. Environmental Protection Agency's (EPA) 10 ppm drinking water standard for N in the nitrate compound (NO_3^-–N). A study of 281 domestic drinking water wells in Lane County showed that 22 percent of the wells exceeded the same standard (Penhallegon 1994). In a 2000-2001 study of 476 wells in the southern Willamette Valley, 35 wells exceeded the drinking water standard, with 21 percent of the total wells exceeding 7 ppm NO_3^-–N (Department of Environmental Quality 2002). Other studies have shown high concentrations of NO_3^-–N within water draining from experimental fields planted in row crops, such as corn, broccoli, and snap beans (Sattell et al. 1999).

Nitrate and ammonium (NH_4^+) are the only plant-available forms of N. Other forms of N in the environment can be transformed to NO_3^- through several natural processes; NH_4^+, for example, is oxidized by soil bacteria into NO_3^- in aerated soils. Because the top few feet of most agricultural soils are well aerated during the growing season, the majority of NH_4^+ in applied fertilizers is quickly converted to NO_3^- by oxidation. Decaying organic N in plants undergoes a biological conversion called mineralization, the transformation of organic N to inorganic plant-available forms. In most natural systems, N is limited and is cycled through its various chemical forms without significant loss to aquifers. In agricultural systems, the need to remove the N limitation on production results in accumulated free NO_3^-. Nitrate is easily leached with moving water because it has a negative charge and therefore does not bond to soil particles. The most critical time for NO_3^- leaching is the beginning of the winter rains when soluble NO_3^- remaining after harvest is transported from the upper soil with percolating rainwater.

During Oregon's dry summers, careful irrigation practices ensure that NO_3^-, NH_4^+, or ammonia (NH_3) applied during the spring and early summer remains in the soil root zone throughout the growing season. The quantity of N removed in harvest is almost always less than the quantity of N fertilizer applied. Typically, the quantity of N removed during harvest is around 30–70 percent of the total quantity of N made available to the plant by fertilizer applications, mineralization of organic matter in the soil, and dissolved in irrigation or rainwater (Hermanson et al. 2000).

If N efficiencies can be estimated, why can't a cookbook approach be used to ensure that crops are being fertilized at a rate to maximize efficiency and minimize N available to leaching? In reality, natural processes and seasonal variation make exact N balances difficult to achieve (Table 1). Nitrogen not removed with the harvest either remains as NO_3^- in the soil, in the remaining plant residue, immobilized in soil organic matter, is lost to the atmosphere as ammonia (NH_3), or is lost as elemental nitrogen (N_2) and nitrous oxide (N_2O) after denitrification. With the onset of the rainy season, soil and fertilizer N unused by the summer crop is susceptible to leaching to the shallow water table. Beyond the depths of cover crop roots, biological activity slows down, though it is possible that denitrification can take place in anaerobic zones and may be an important process in some soil systems in western Oregon (R.P. Dick, 2003, personal communication). Deep NO_3^- not included in denitrification processes will be lost to the groundwater.

Table 1. *Average N removal efficiencies for some common crop types in the Willamette Valley. The amount of N removed from the field is usually small compared to the amount added.*

Calculating the N efficiency of a crop is not an easy task. Why?

When accounting for N in a balance, the easiest inputs to consider are the fertilizer additions.

With a crop analysis we could easily make the calculation:

$$\frac{\textbf{N in the mature crop}}{\textbf{N applied as fertilizer}} = \textbf{Fertilizer recovery; NOT overall N efficiency}$$

This calculation is not really the N uptake efficiency for the crop because it does not account for all N inputs, which are difficult to measure.

To calculate the **overall N efficiency**, it is necessary to account for other N inputs in the equation.

$$\frac{\textbf{N in the mature crop:}}{\textbf{fertilizer N + residual inorganic N + mineralized organic N + N irrigation/rain}}$$

Other N inputs can be significant. Often, half of plant-available N comes from sources other than applied fertilizer. N provided from mineralization of last years' crop residue can be substantial. In fact, crops such as broccoli, cauliflower, grass for seed, and hops leave more N in the crop residue than is removed from the field during harvest.

An oversimplified, theoretical N efficiency for corn, a crop with large N requirements and low N efficiency, would look more like this (example extracted from Hermanson et al. 2000):

$$\frac{\textbf{max corn N accumulation 225 lb/acre}}{\textbf{225 lb/acre N from fertilizer + \sim 225 lb/acre N supplied by other sources}} = \textbf{50 percent N efficiency}$$

The 225 lb/acre not used by the crop is stored in the soil, denitrified, or is leached into groundwater. More N processes take place than meets the eye!

Nitrate-N concentration in groundwater is a function of the quantity of water recharging the aquifer and the rate of N loss from the surface. Climates receiving much rainfall would be expected to dilute N inputs and therefore have lower NO_3^--N concentrations in groundwater. Table 2 gives the steady-state groundwater NO_3^--N concentration for aquifers with an array of N and water input rates. To use Table 2, make an estimate of the total annual aquifer recharge of water in equivalent depth (height of water). The average rainfall in the Willamette Valley is around 45 inches, but only about 30 inches of water truly infiltrates into the ground and recharges the aquifer because of other processes such as evaporation, surface runoff, and storage in the soil. A typical rate of N loss from an operation growing mint or vegetables is 80 lb/acre. Using Table 2, these values would result in a long-term groundwater NO_3^--N concentration nearing 12 ppm. Even in the wet Willamette Valley we can expect long-term groundwater concentrations to exceed the EPA drinking water standard. Drier climates east of the Cascades or in California's Central Valley would expect much higher long-term concentrations. Existing data support these simple calculations.

Table 2. *Theoretical steady-state NO_3^--N concentrations calculated for an aquifer with variable quantities of recharge and N loading. Nitrate -N concentrations are highest in areas with little recharge and large leaching losses. Values assume the entire land area collecting recharge water receives the same management. Example is for NO_3^--N concentration in the Willamette Valley and is explained in the text.*

Expected long-term shallow aquifer NO_3^-- N concentrations (ppm) under variable rainfall conditions and N inputs

N loss	Percolation to groundwater (inches/year)					
lb/acre	5	10	15	20	30	40
20	18	9	6	4	3	2
40	35	18	12	9	6	4
60	53	27	18	13	9	7
80	71	35	24	18	12	9
100	88	44	29	22	15	11
150	133	66	44	33	22	17
200	177	88	59	44	29	22
250	221	111	74	55	37	28
300	265	133	88	66	44	33
400	354	177	118	88	59	44

Nitrate leaching potential is most directly controlled by the amount of NO_3^- fertilizer remaining in the soil after the growing season. Excess residual soil N after harvest indicates that either 1) fertilizer is applied at rates exceeding recommended amounts to reach maximum yield; 2) fertilizer was added at the wrong time of the growth cycle; 3) the method of application is not efficiently supplying the growing plants with N; 4) excessive organic N is being mineralized into inorganic NO_3^-. Of course, a poor yield at harvest will ensure that significant quantities of NO_3^- remain in the soil.

Quantifying Leaching Under Willamette Valley Crops

A cooperative effort has been undertaken by Oregon growers, the Oregon State University (OSU) Extension Service, the Oregon Department of Environmental Quality and the Oregon Department of Agriculture to understand the process of NO_3^- leaching. Nitrate leaching studies have been completed throughout Lane County and at OSU's North Willamette Research and Extension Center (NWREC). The goal of these studies was to assess the characteristics of NO_3^- leaching within the Willamette Valley and research practical and economically feasible options for management. These long-term studies show that Oregon agriculture contributes large amounts of nutrients to groundwater, but very effective methods exist to treat the problem.

Passive Capillary Wick Samplers

A unique sampling device was used to quantify NO_3^- leaching throughout the Willamette Valley. Termed PCAPS for Passive Capillary Samplers, the lysimeters are capable of quantifying the volume and chemical content of water percolating to groundwater. PCAPS use fiberglass wicks that equilibrate to the surrounding soil's water pressure. The samplers are capable of intercepting draining soil water solutions from a known area below soils with pressures ranging from 0.0 m to 0.8 m. As a result of this design, PCAPS can collect water moving through the soil over a range of conditions from saturated to draining and approaching field capacity. The PCAPS surface panel collects water from a horizontal plane with an area of 3 ft^2 (0.28 m^2). The method of installation ensured that the soil column above the PCAPS was not disturbed, thus retaining original hydraulic characteristics above the lysimeters (Figure 1). The samplers were drained by applying a vacuum through the sample tubing from the surface.

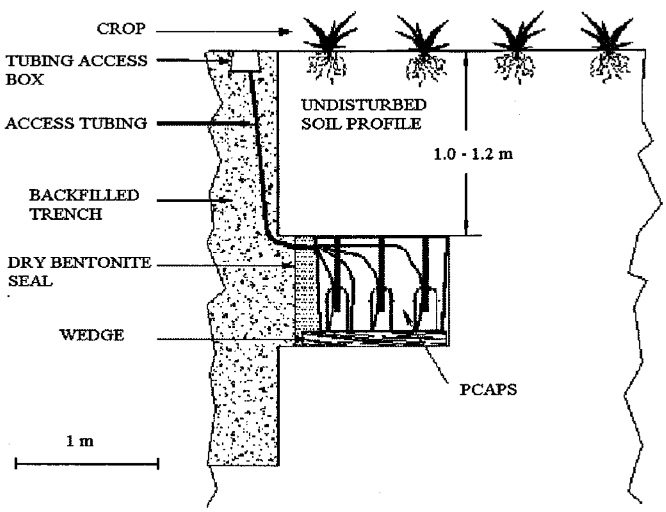

Figure 1*. PCAPS sampling unit. Samplers were installed laterally from the trench to minimize soil disturbance above the lysimeters (picture modified from Brandi-Dohrn, 1993).*

Two different PCAPS designs were used throughout the study. The PCAPS used in the controlled experiments at the NWREC were built with fiberglass and a stainless-steel top panel. Three 1-gal (3.78 L) bottles collected the water. This relatively small capacity required frequent pumping. The PCAPS models used in Lane County were either similar to those at the NWREC or were built out of high density polyurethane (HDPE). The Lane County PCAPS had a 15.9 gal (60 L) capacity. The PCAPS built of HDPE eliminated the use of a separate collection vessel altogether. The large capacity of the Lane County samplers enabled the units to be sampled monthly, even when precipitation events during the period were frequent or large. More details on the installation and operation of the PCAPS are given in Brandi-Dohrn et al. (1997) and Louie et al. (2000b).

Concentration data collected over the 5-year study were averaged with respect to flow. Flow-weighted averaging is an appropriate method to represent the average concentration over multiple sampling events, or when more than one sampler is measuring an event. To find a flow-weighted average for a 5-year period, for example, the total mass of NO_3^- collected divided by the total volume of water collected would be the 5-year flow-weighted average. Flow-weighted averages are better than simply averaging monthly NO_3^--N concentrations because the method can prevent misleading data caused when sampling events that collect small volumes have very high concentrations.

Leaching Under Field Conditions

In Lane County, 21 privately owned and operated commercial agricultural fields were assessed for their contribution of NO_3^- to shallow groundwater. Growers volunteered to take part in the study and made all crop and nutrient management decisions. Two PCAPS lysimeters were installed on each of the fields planted with row vegetables, mint, certified organic vegetable crops, orchards, or blueberries. The 4 years of water quality data collected under the vegetable crops and 5 years of data under mint crops are the focus of this analysis. The data collections began in November 1993 and continued until November 1997 and July 1998 for the vegetable fields and mint fields, respectively. PCAPS were installed at depths ranging from 3.3 to 3.9 ft (1.0 to 1.2 m) below the field surface. In addition to PCAPS, alternative smaller groundwater sampling tools called suction cup samplers were used to make a point measurement at the estimated winter water table depth of 4.9–9.8 ft (1.5–3 m). Suction cup samplers operate differently than PCAPS samplers because the user must apply suction that exceeds the water-holding pressure of the soil. These devices are best used near the water table, where PCAPS cannot be employed (Brandi-Dohrn et al. 1996).

Monthly flow-weighted NO_3^--N concentrations under fields planted in row crops (vegetable annuals) are shown in Figure 2. Nitrate-N concentrations below mint show similar trends (Figure 3). From monthly NO_3^--N averages, we can determine NO_3^- leaching potential throughout the year. Concentrations were highest in the summer when crops were fertilized and less water was available for dilution. At the onset of winter rains, the soil profile was flushed and most of the NO_3^- left after harvest is moved past sampler depth. Concentrations also decreased during this time due to the high volumes of water diluting the NO_3^--N. Even during late winter, NO_3^--N concentrations on average were near to or higher than the EPA 10-ppm standard for drinking water.

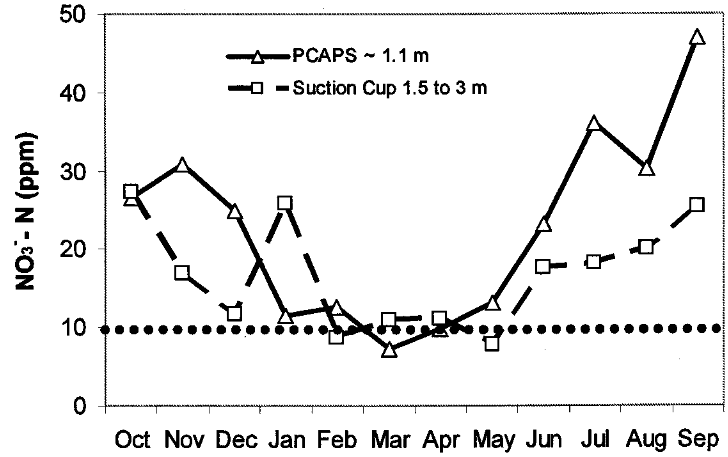

Figure 2. *Measured monthly flow-weighted average NO_3^--N concentrations below six Lane County vegetable fields during the 4-year study period. Shown are the concentrations measured by PCAPS as well as suction cup samplers. The dotted line indicates the EPA 10-ppm NO_3^--N drinking water standard.*

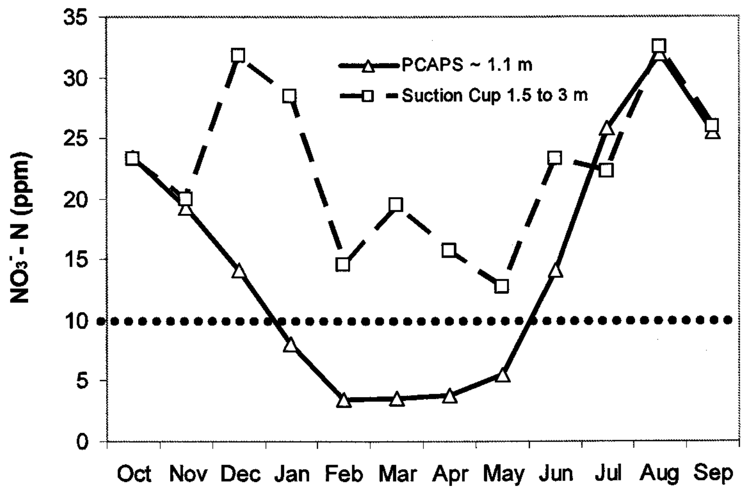

Figure 3. *Measured monthly average NO_3^--N concentrations below five Lane County mint fields during the 5-year study period. Shown are the concentrations measured by PCAPS as well as suction cup samplers. The dotted line indicates the EPA 10-ppm NO_3^--N drinking water standard.*

Flow-weighted NO_3^--N concentrations over the entire study period showed that the average recharge concentration exceeded the EPA NO_3^--N drinking water standard for most of the fields (Figures 4 and 5). The data indicated NO_3^--N concentrations in underlying aquifers may rise in the future. In regions of the Willamette Valley where high-N-input crops are being intensively grown over large contiguous areas, aquifers used for drinking water supply can be expected to approach or exceed the 10-ppm drinking water standard over time unless nutrient management practices are modified.

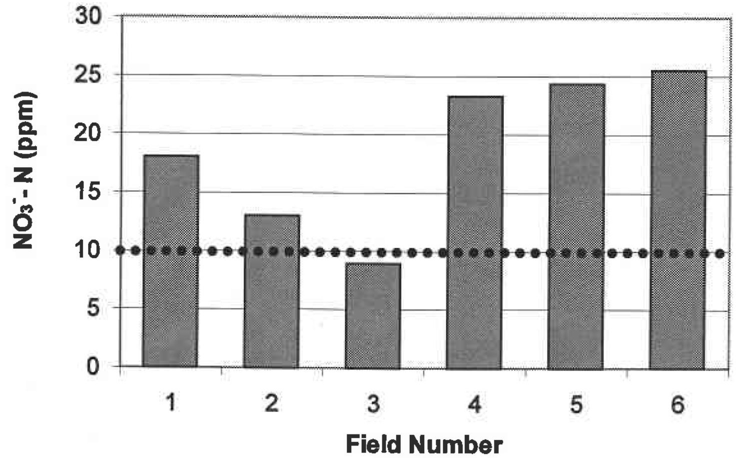

Figure 4. *Flow-weighted NO_3^--N concentrations for six fields planted to row crops during the entire 4-year study period. The dotted line indicates the EPA 10-ppm NO_3^--N drinking water standard.*

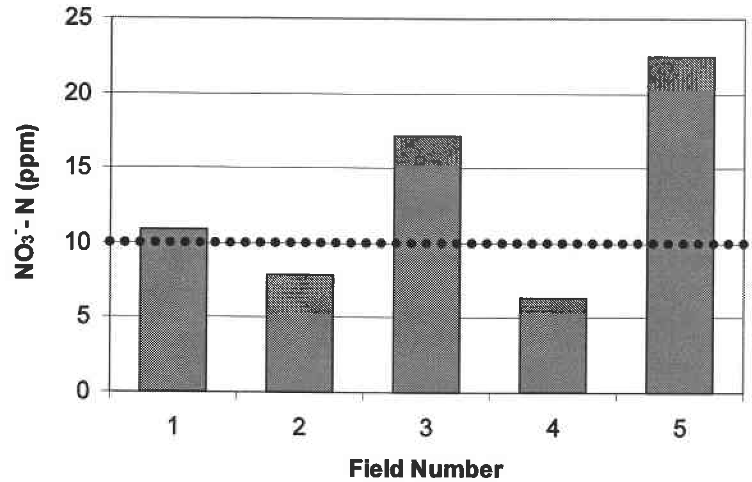

Figure 5. *Flow-weighted NO_3^--N concentrations for five fields planted to mint during the entire 5-year study period. The dotted line indicates the EPA 10-ppm NO_3^--N drinking water standard.*

The ability of Lane County PCAPS to make an accurate estimate of the real volume of water percolating to groundwater was determined by Louie et al. (2000b). The analysis was made by comparing collected water volumes from PCAPS to expected volumes calculated from a water balance. Results indicated that Lane County PCAPS overestimated the volume of water entering the ground by 25 percent. If we take this into account, we are able to make a good estimate of total mass of NO_3^--N lost to groundwater (total mass NO_3^--N is the estimated water volume multiplied by the concentration of NO_3^--N).

Average N fertilizer application rates were 200 lb/acre for row crops and 250 lb/acre for mint. Average losses of NO_3^--N mass per acre were calculated for each of the study years and are shown in Figures 6 and 7. Average annual mass losses for each crop type were 93 and 82 lb/acre from conventional vegetable and mint fields, respectively. In monetary terms, such losses of N would equate to \$3,300–\$3,700 for each 100-acre field if N is estimated to cost \$0.40/lb. It is important to note that a fraction of the NO_3^--N leached from this soil system may have originated as mineralization of organic matter. Soils are like a bank with respect to N fertilizers; sometimes N is applied and "saved" in the soil, while at other times N is "withdrawn" through mineralization. Whether or not the soil is gaining or losing N depends on many factors, including cultivation history, temperature, water content, and the carbon-to-N ratio within the soil.

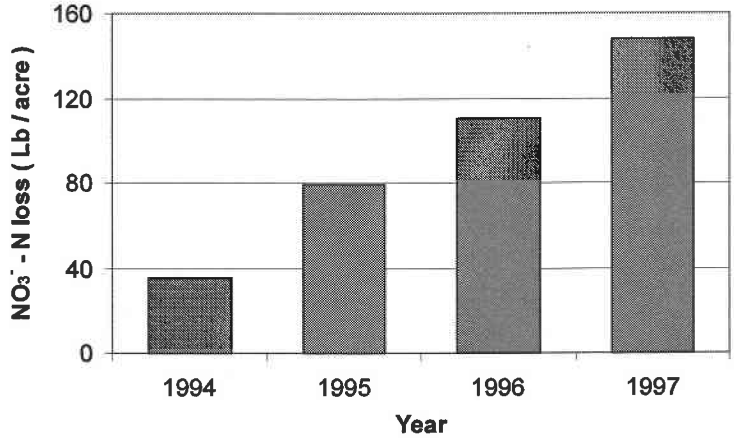

Figure 6. *Average NO_3^--N mass leaching rate from vegetable fields during each of the study years. Water years are used (October of previous year to September of posted year) as they correspond to breaks in the growing season and encompass an entire winter's precipitation. Note: October 1993 is not represented.*

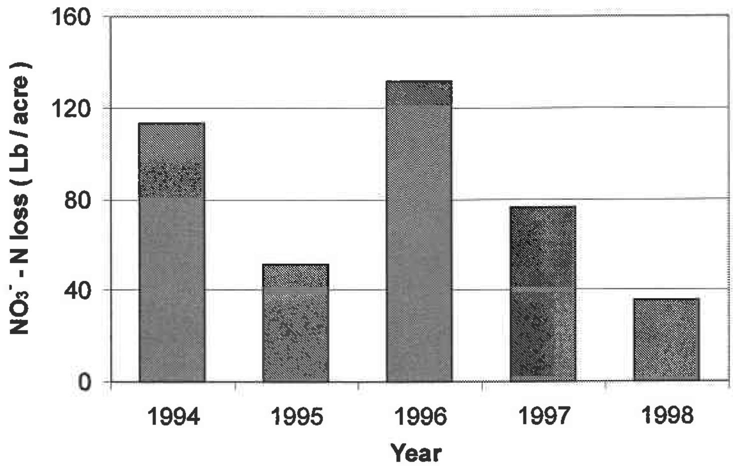

Figure 7. *Average NO_3^--N mass leaching rate from mint fields during each of the study years. Water years are used (Oct.–Sept.) as they correspond roughly to breaks in the growing season and encompass an entire winter's precipitation. Note: October 1993 and August and September 1998 are not represented.*

Incentives for Growers

At this point, we have described the NO_3^- leaching problem and have seen some convincing field evidence of high NO_3^--N concentrations in western Oregon. We are fortunate in western Oregon because practical and effective solutions to reduce the problem do exist! Still, one of the most important hurdles of the NO_3^--contamination problem remains: what are the incentives for growers to change management practices? The most important and widespread incentive is the grower's own desire to be a conscientious steward of his or her soil and water resources. At the same time, the general consumer in western Oregon would prefer growers to deliver their product with minimal environmental impacts, and are often willing to pay a premium for responsibly grown products (Kurki and Matheson 2001). Some may believe that simply reducing fertilizer use will result in a larger profit margin. However, the risk of using too little fertilizer and having a poor yield does exist, so reducing fertilizer inputs requires careful planning. Nonetheless, reducing N fertilizer inputs can amount to significant savings for the grower (Table 3).

Table 3. *Estimated reductions in operating costs as a result of 25-percent reductions in N on a 100-acre plot.*

Crop	N Rate	Costs (N at $0.40/lb)		
	lb/acre	**Full N rate**	**25% less N**	**Savings**
Corn/mint	225	$9,000	$6,750	$2,250
Snap beans	135	$5,400	$4,050	$1,350
Ryegrass or tall fescue	135	$5,400	$4,050	$1,350
Broccoli	280	$11,200	$8,400	$2,800

There are reasons to undertake a nutrient management plan besides fertilizer cost savings and reduced environmental impacts. Often the methods of instituting a good management plan for nutrients will improve other aspects of growing high-quality crops at lower costs. For example, it has long been known that winter cover crops that are disked into the ground before spring planting protect the soil surface, add organic matter, smother weeds, and improve soil tilth (Sattell et al. 1998). Cover crops maintain organic matter content, reduce erosion on slopes, and impede the formation of hard pan layers due to raindrop effects on bare earth. These effects will improve infiltration and water-holding capacity during the dry months of summer when irrigation is required. Besides improving soil quality, cover crops scavenge excess N left in the soil after fall harvest, reducing NO_3^- leaching to groundwater (Brandi-Dohrn et al. 1997).

Periodically conducting a comprehensive soil-sampling survey has many benefits. Estimates can be made of N content, other nutrients such as phosphorus (P) and potassium (K), and other important soil traits such as pH. These tests will be helpful in determining inputs of lime and possible changes in the chemical ratios of your typical fertilizer mix that may be needed to increase productivity. Having a complete understanding of nutrient content and availability within commercial fertilizers and organic fertilizers (animal manures and compost) is imperative to maximize crop production and minimize leaching losses.

Controlled Leaching Experiments–Cover Cropping

A controlled experiment studying the transport of agrochemicals has been ongoing for a decade at OSU's NWREC. The North Willamette lysimeter experiments began in 1992 and are still operating. These experiments predate the Lane County experiments previously described. Using controlled experiments enables researchers to assess the effect field management and weather conditions have on NO_3^- leaching. Similar to the Lane County results, the study revealed the vulnerability of Oregon's groundwater to NO_3^- contamination, especially under fields left fallow during the winter. The study made a clear case for the effectiveness of cover crops to reduce groundwater contamination.

Twenty-six PCAPS lysimeters were installed carefully at a depth of 3.9 ft (1.2 m) in seven separate 30- by 60-ft (9 by 18 m) plots. The cropping systems analyzed for leaching potential included summer row vegetables left fallow during winter (C plots) or summer row vegetables planted with a cover crop during the winter (H plots). Subplots within each cropping system were termed N0, N1, and N2 for no additions of fertilizer, half the recommended amount to maximize yields for a particular crop, and the recommended fertilizer amount, respectively.

Sweet corn, snap beans, or broccoli were planted during the summer growing season. For the first 8 years, cereal rye or Celia triticale, a hybrid of wheat and rye, were planted as a cover crop on half the plots during the winter months. A mixture of common vetch and triticale was used as a cover crop starting in winter 2000. Common vetch is a legume and commonly contains as much as 50–120 lb of N/acre (56–135 kg of N/ha) (Sattell et al. 1998). Nitrogen application rates were 225 lb/acre for corn, 135 lb/acre for beans, and 280 lb/acre for broccoli on the fully fertilized N2 plots. Figure 8 shows the 8-year flow-weighted average concentration of NO_3^--N in water collected by PCAPS below the various NWREC treatments during years using cereal cover crops. At the recommended rate of fertilization, NO_3^--N concentrations exceeded the drinking water standard for both fallow and cover cropped systems (Figure 8).

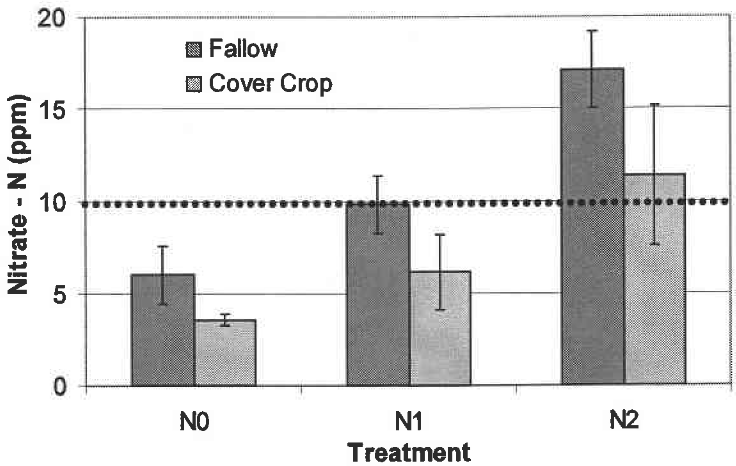

Figure 8. *NO_3^--N concentration in shallow groundwater at the North Willamette Research and Extension Center for the first eight seasons using cereal cover crops. Crops were fertilized at three different rates: N0 received none, N1 half, and N2 the recommended agronomic rate to maximize crop yield. The dotted line indicates the EPA 10-ppm drinking water standard. Error bars show the standard deviation.*

Using measured concentrations and amount of water collected during PCAPS sampling, the mass of N lost to groundwater can be quantified. These N losses, expressed in lb/acre/year (Figure 9) can be compared directly to fertilizer applications. For fields receiving the recommended fertilizer rate (N2), 25 percent of all applied N was leached to groundwater and unavailable for plant use. For the plots at the NWREC, cover-cropped plots reduced the NO_3^- contribution to groundwater by 40 percent over the fallow fields during the 8-year period using cereal cover crops.

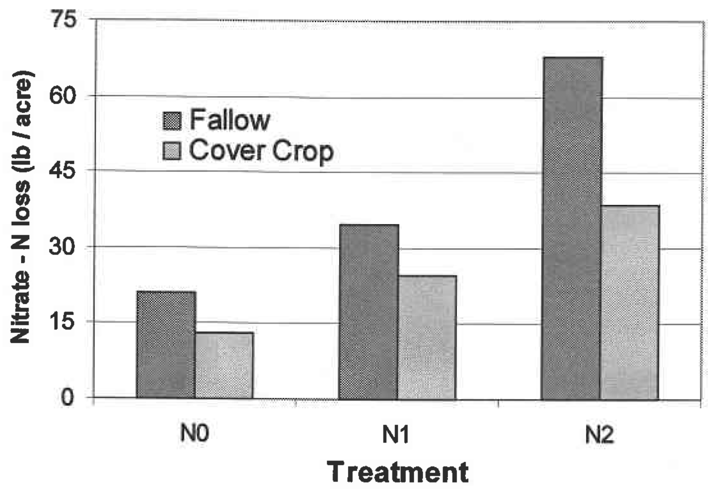

Figure 9. *Average NO_3^--N mass leaching rate for plots at the North Willamette Research and Extension Center during the first eight seasons using cereal rye cover crops. Crops were fertilized at three different rates, N0 received none: N1 half, and N2 the recommended agronomic rate to maximize crop yield.*

Sampling using the PCAPS gave NO_3^--N concentrations in soil water at a depth of 3.9 ft (1.2 m). To more precisely describe N content throughout the soil profile, a soil sampling plan was designed. The data were collected in May of 2001. At the time of sampling, the common vetch/triticale mix cover crop was decomposing at the soil surface after being tilled back into the ground 2 weeks before. Two holes were augured at each of the NWREC subplots about 4.9 ft (1.5 m) from the buried PCAPS samplers, and each of the 3.9-ft (1.2 m) holes was divided into six increments composed of 20 cm of soil depth. The soil from each of the units was extracted in the lab to determine the NO_3^--N concentration.

As expected, the magnitude of NO_3^--N concentrations correlated with fertilizer inputs. Regardless of magnitude, however, the shape of the NO_3^--N distribution within the soil profile was dependent on winter cover-crop treatment (Figure 10). The cover-cropped fields had much higher concentrations near the ground surface, an indication that the cover crop had successfully scavenged nutrients from the soil during the preceding winter months. During the time of sampling, much of this organic material seemed to cause N mineralization, as there were elevated levels of NO_3^- in the upper soil column. The fallow fields showed a NO_3^- plume moving through the soil profile at an average depth of 2.6 ft (80 cm). From tracer tests completed and analyzed at the same time as the NO_3^- analysis, we know that this NO_3^- plume originated as post-harvest NO_3^- remaining in the soil after the fall 2000 corn harvest. The NO_3^- under the cover-cropped plots was available to the following summer crop, but the NO_3^- at deeper depths below winter fallow plots would largely be below the vegetable rooting zone.

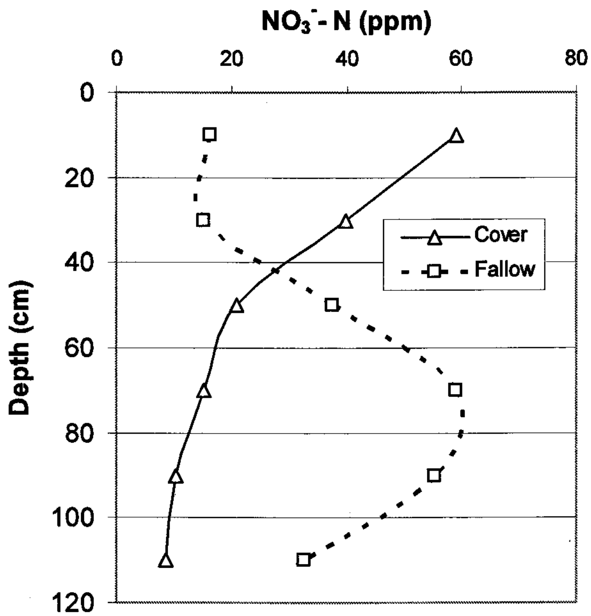

Figure 10. *NO_3^--N concentration profile in soil water at the North Willamette Research and Extension Center. Values are the average concentrations from the entire pool of N0, N1, and N2 fallow and cover-cropped plots. Crops were fertilized at the OSU-recommended level.*

Other Management Practices for Reducing NO_3^- Leaching

There are still other ways to minimize the leaching of NO_3^- to groundwater. Be assured that efforts to reduce NO_3^- leaching are also good for business: growers want to understand their soil and remedy any fertility problems to streamline their farming operation. We will discuss the following management options:

- Soil testing
- Fertilizer and manure chemical analysis
- Stem nitrate tests for peppermint
- Maintenance of irrigation systems

Soil Testing

It is in the best interest of growers to periodically sample the upper layers of their soil and send the sample off to a laboratory for chemical analysis. Fertilizer applications can be fine-tuned to crop needs, reducing costs and groundwater contamination. The OSU central analytical laboratories suggest completing this process about every 3 years for perennial crops and yearly before planting annuals (OSU Extension 2000). Included in a standard analysis is the determination of the correct mix and amount of fertilizer, as well as pH and liming requirements. Testing available N, P, and K in the soil is an effective way to reduce the possibility of over-fertilizing. With this analysis, an appropriate N-P-K mix can be bought, eliminating unneeded additions. Physical analyses of soil properties can be an important consideration to assess NO_3^- leaching potential.

A physical analysis will provide a particle size distribution, water retention characteristics, and the hydraulic conductivity of the soil. Water retention, the relationship between soil pressure and the amount of water in the soil, should be considered when preparing an irrigation schedule specific to a particular crop and soil type. With the test results, a grower can estimate the water content of the soil by measuring soil pressure, eliminating the need for guessing whether the crop is receiving sufficient water or has been over-irrigated.

Different soil sampling methods are used to prepare for each laboratory analysis. If you only require a nutrient analysis and/or particle size analysis, you can easily and quickly sample with an auger or a shovel. If you would like to have bulk density and/or water retention determined as well as nutrient analysis/particle size, then a coring device must be used to maintain soil structure. A good soil core can provide a wealth of information, especially if you are irrigating your crops.

To represent an entire field, it is important to take subsamples throughout the field and mix them into one representative sample. Field areas with different drainage and slope can cause differences in soil quality, so these places should be sampled separately. Management history can greatly affect soil nutrient content. If you are going to change the crop or add new acreage to an existing field, sampling is in order. For more specific sampling procedures and strategies concerning subsampling, mixing, and handling, see the OSU Extension Service pamphlet (Gardner and Hart 2000).

Post-harvest NO_3^- testing is an effective way to ensure that the summer crop is using all or nearly all of the fertilizer applications during growth. The post-harvest NO_3^- test analyzes for NO_3^- left in the soil profile after the crop harvest. It is important that sample collection for this test take place during the season between rapid plant growth (corresponding with rapid N uptake) and the rainy leaching season. In general, large quantities of NO_3^- remaining in the soil after a high-yield harvest indicate that the summer crop did not require the entire N application and that future application rates could likely be reduced.

Interpretation of a post-harvest NO_3^- test depends on the type of growing operation and fertilizer type used. Much work regarding post-harvest NO_3^- testing has been completed for dairy operations that require manure disposal and growing operations that use organic fertilizers as the predominant nutrient source. Operations using manure are most likely to exceed recommended nutrient agronomic rates due to timing of applications and mineralization. Sullivan and Cogger (2002) provide a useful interpretation guide for using the post-harvest NO_3^- test for operations using manure.

Operations using commercial fertilizers may also use the post-harvest NO_3^- test, but results must be interpreted differently because detailed chemical analyses provided with the fertilizer allow much lower amounts of residual NO_3^- to be left in the profile compared to operations using manure. The test is still very effective at gauging nutrient application to plant requirements, especially if the test is done yearly so that application rates can be adjusted using the results.

Nutrient Content of Fertilizer Versus Manure

The post-harvest NO_3^- test has begun to expose us to the differences between commercial fertilizers and organic fertilizers such as manure and compost. When buying commercially prepared fertilizers, growers have the convenience of knowing exactly what they are applying on their field. By following the chemical analysis of the product and with the help of soil sampling, it is possible to fine-tune fertilizer applications in response to plant requirements. Manure, on the other hand, does not come with a chemical analysis, and the minority of growers who use organic fertilizers instead of commercial fertilizers must rely on intuition and experience to gauge their fertilizer rates. In the case of manure, mineralization rates and thus N availability are hard to predict without a periodic analysis of the nutrient content in the material. In addition, manure is often diluted with water to different degrees, making applications at recommended agronomic rates highly dependent on water content. To properly fertilize with manure it is important to consider the points outlined in Table 4.

***Table 4.** Important considerations when using organic fertilizer.*

Fertilizing with manure	
Manure Analysis	
	Water content
	Nitrogen content–organic, ammonium, NO_3^- portion
Application	
	Percentage of the manure will mineralize during the current season
	Account for mineralized N from previous applications
	Application method–are there going to be ammonia losses?

One of the most important things to consider when using manure is that organic fertilizers mineralize slowly. In fact, some manure will actually supply more plant-available N two or three seasons after application than was supplied during the initial season. Consequently, it is easy for growers to supply N in rates well above the estimated plant requirement.

In the previously discussed Lane County study, two additional fields planted in certified organic vegetables were used to assess NO_3^- leaching contributions from organic growing operations. As with the mint and conventional vegetable fields, two PCAPS were installed per field. After the first two seasons, it was clear that NO_3^--N concentrations were very high. It was determined that poultry manure was applied in amounts well above recommended agronomic rates. After an estimation of N content and mineralization rates of the manure, applications were reduced. The management changes enacted in February 1996 resulted in apparent reductions in NO_3^--N concentration during the latter half of the study (Figure 11).

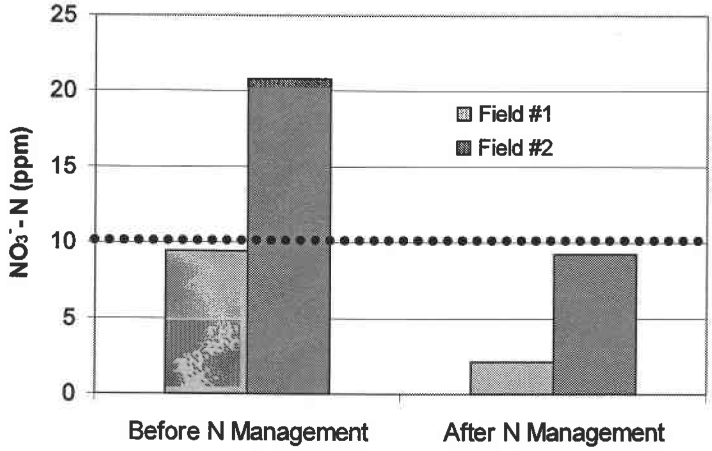

Figure 11. *Flow-weighted NO_3^--N concentrations for two fields planted in organically grown vegetables during the entire 4-year study period. After revising manure application rates according to plant requirements, a considerable decrease in NO_3^--N concentration was observed. The dotted line indicates the EPA 10-ppm NO_3^--N drinking water standard.*

Stem NO_3^- Tests for Peppermint

Due to the relatively high economic value and large N requirements of mint, it is a high-risk crop for NO_3^- leaching. Optimum fertilization rates for peppermint range between 180 and 300 lb N/acre, depending on the region. An N application rate of between 200 and 225 lb/acre is recommended for western Oregon. Christensen et al. (2003) showed that no increase in mint oil yield was achieved after N rates were increased from 225 to 320 lb/acre. Fertilizer applications should be distributed at about 30 lb/acre after harvest to stimulate roots, 40 lb/acre after spring flaming, and the remaining 130 lb/acre when the post-flame crop is growing in June (Jackson et al. 2000). Fertilization in excess of these amounts will not result in more plant growth because the crop has variable N uptake rates according to its stage of growth (Sullivan et al. 1999).

When using fertigation, a weekly stem tissue NO_3^- test is a management option. Developed about 30 years ago, the stem NO_3^- test uses a correlation between oil yields and NO_3^- concentration within the mint stem. Stem samples are taken throughout the period of fastest growth to ensure that NO_3^- concentrations within the mint stem do not fall below the critical values determined by the measured correlation. Using results from the stem NO_3^- test, N application rates can be matched to plant requirements. More information on the stem NO_3^- test is given in Brown (1982) and Smesrud and Selker (1998). See Sullivan et al. (1999) and Christiansen et al. (1998) for a description of N requirements and application schedules for mint and other crops.

Irrigation System Maintenance

Often, a good opportunity to reduce N losses from a growing operation is to ensure that irrigation systems are properly maintained and that fields are not over-irrigated. Applying excess water will force the grower to use more fertilizer than necessary. An appropriate irrigation schedule assures that water does not percolate past the root zone of the growing plants. Application rates are controlled by the potential evapotranspiration and growing stage of the crop. In the case that too much water is added, plant-available NO_3^- will be washed out of reach of the plant roots. Should this occur, the grower will either need to make an additional application of fertilizer or risk a poor harvest.

The effects of an improperly maintained irrigation system on NO_3^- leaching potential are similar to over-irrigation. An improperly maintained irrigation system will not distribute water evenly throughout the field. Uneven irrigation can set off a chain of events that effectively cause the grower to require additional fertilizer applications. Consider an irrigation system that applies water excessively to certain parts of the field and deficiently in others. Portions of the field receiving the bulk of this water will have higher NO_3^- leaching rates. Other parts of the field will be under-watered. In response, the grower will increase the irrigation amount to ensure that the drier areas are receiving enough water. Now the leaching potential in the wetter areas will further increase. Nitrogen-deficient plants in the over-irrigated areas will require additional fertilizer, assuming that the grower is able to realize the problem in time to counteract the deficiency. Crops in the drier areas of the field will have a N surplus.

An effectively managed irrigation scheme considers the following:

- **Operating pressure -** Each system has an acceptable range of operating pressures. Deviation from this leads to poor uniformity of application.

- **Nozzles -** Ensure that nozzles are of a consistent make and diameter and are not worn. Periodically (at least every 4 years) replacing all the nozzles at once is recommended to maintain uniform application.

- **Dual nozzle sprinklers -** If using a standard 40- by 60-ft sprinkler spacing design, dual nozzle emitters should be used as they are known to give more uniform coverage.

- **Soil water monitoring -** The goal of a fine-tuned irrigation system is to maintain soil water levels so that the growing crop can effectively use water without waste and minimize the leaching of nutrients. With the aid of soil water monitoring, irrigation schedules can be adjusted to ensure that soil water content in the root zone is maintained in an appropriate range. Technologies that are becoming less expensive can use changes in soil moisture levels to relay information to turn on and operate irrigation equipment.

- **Schedule irrigation based on expected ET -** Irrigation requirements vary throughout the year as potential evapotranspiration (ET) rates change with the weather. After determining the soil's available water capacity, the rooting depth of the growing crop, and the degree to which the soil can dry between irrigation events, an irrigation schedule can be developed. Assuming a constant discharge throughout the system during the entire year (check nozzles and monitor the pressure!), set times of irrigation events can be adjusted as ET rates change to apply an irrigation depth that will recharge the water-holding capacity of the soil. Monthly irrigation schedules should be validated by soil water monitoring to ensure that plant requirements are being met.

Fortunately, replacing the sprinkler nozzles on irrigation equipment is an inexpensive and often the most successful way to improve spray uniformity. The pressure distribution of a system with old or mismatched sprinkler nozzles can vary greatly from the same system after nozzle replacement (Figure 12). Pressure distribution and spray uniformity were improved with this small amount of work.

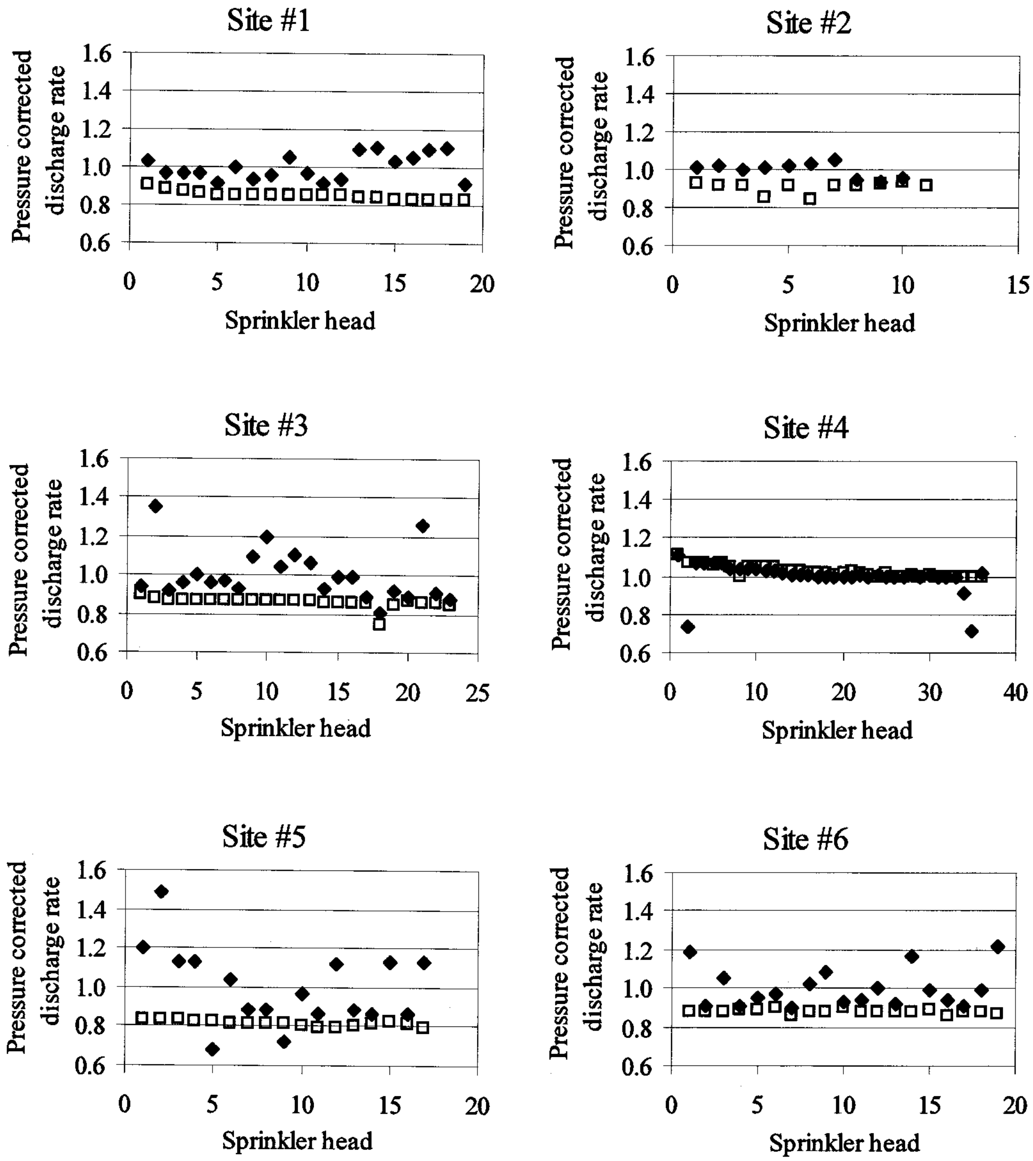

Figure 12. *Sprinkler discharge rates before and after nozzle replacement. Solid diamonds show discharge rates before nozzle replacement while the hollow squares show post-replacement discharge rates. More uniform application was achieved using replaced nozzles, likely reducing field susceptibility to* NO_3^- *leaching. Figure from Louie and Selker (2000a).*

Several Extension publications discuss methods to streamline irrigation operations. The *Western Oregon Irrigation Guides* (EM 8713, Smesrud et al. 2000) provide worksheets to calculate irrigation set times based on potential evapotranspiration for 16 different commonly grown crops. *Soil Water Monitoring and Measurement* (PNW 475, Ley et al. 1994) is a helpful guide to understanding soil water potential. Sprinkler head maintenance and its relationship to application uniformity is discussed in Louie and Selker (2000a). The post-harvest water requirements of mint are presented in Smesrud and Selker (1999). A great online source for publications and information concerning many aspects of agriculture and the environment is the Oregon State University Extension and Experiment Station Communications Web site (http://eesc.oregonstate.edu).

Conclusions

Nitrate contamination of groundwater is an issue that is impossible for growers in Oregon and around the country to ignore. As our increasing population becomes ever more dependent on groundwater for domestic use, protecting this resource is imperative. The first step to address the NO_3^- leaching problem is to become aware of the risk. Table 5 is a general list to check when assessing the potential for N leaching from the farm. There are many effective nutrient management plans that have reduced N loss from both experimental and privately owned growing operations.

Table 5. *Key issues to consider when assessing the potential for NO_3^--N leaching.*

Nitrate leaching potential
Amount of residual nitrogen left after harvest
▲ Amount: nitrogen application in excess of crop recommendations
▲ Timing: nitrogen applications stop assimilating nitrogen for growth
▲ Uniformity: inefficient nitrogen application methods
Irrigation practices
▲ Non-uniform irrigation due to incorrect operating pressures and/or worn or mismatched nozzles
▲ Over-irrigation in response to excessively dry or poor production areas
▲ High background nitrates in irrigation water
Mineralization of organic materials
▲ Untimely decay of nitrogen-rich dry matter or manure
Landscape and climate
▲ Rainfall exceeds potential evapotranspiration for extended periods
▲ Rainfall while fields are not covered in standing crop
▲ Additional water saturates field from other areas (overland flow)

Many management options to reduce susceptibility to NO_3^- leaching can be implemented with little cost and may even reduce operational costs in the long term. Maintaining irrigation systems, determining nutrient needs through soil sampling, and using cover crops may increase yields, reduce N losses, and decrease water use, enabling more irrigated acreage. Researchers continue to work in the field and cooperate with growers, a relationship that has provided and will continue to provide improvements for managing non-point source nutrient contamination. Using OSU Extension located in the county is a helpful resource to keep up on current information that can assist growers in managing a sustainable, productive, and profitable business. With cooperation, groundwater and soil resources will be conserved for years to come.

References

Brandi-Dohrn, F.M. 1993. Field evaluation of passive capillary samplers in monitoring the leaching of agrochemicals. M.S. Thesis, Oregon State University, Corvallis.

Brandi-Dohrn, F.M., R.P. Dick, M. Hess, S.M. Kauffman, D.D. Hemphill, and J.S. Selker. 1997. Nitrate leaching under a cereal rye cover crop. J. Environ. Qual 26:181-188.

Brandi-Dohrn, F.M., R.P. Dick, M.Hess, and J.S. Selker. 1996. Suction cup sampler bias in leaching characterization of an undisturbed field soil. Water Resour. Res. 32:1173-1182.

Brown, B. 1982. Nitrogen tissue test procedures for peppermint. Proceedings: 33rd Annual NW Fertilizer Conference, Boise, ID.

Christensen, N.W., J.M. Hart, M.E. Mellbye, and G.A. Gingrich. 2003. Soil nitrogen dynamics in peppermint fields. Proceedings, Western Nutrient Management Conference, Vol. 5:71-76. March 6-7, 2003. Salt Lake City, UT. Potash & -Phosphate Institute, Brookings, SD.

Department of Environmental Quality, 2002. "Southern Willamette Valley Groundwater Assessment." CD-ROM. Oregon Department of Environmental Quality, Groundwater Section, Water Quality Division, Portland.

Dinnes, D.L., D.L. Karlen, D.B. Jaynes, T.C. Kaspar, J.L. Hatfield, T.S. Colvin, and C.A. Carbardella. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. Agron. J. 94:153-171.

Gardner, E.H., and J. Hart. 2000. Soil sampling for home gardens and small acreages. Oregon State University Extension Publication EC 628.

Hermanson, R., W. Pan, C. Perillo, R. Stevens, and C. Stockle. 2000. Nitrogen use by crops and the fate of nitrogen in the soil and vadose zone–a literature search. Washington State University and Washington Department of Ecology. Publication No. 00-10-015.

Jackson, T.L., E.H. Gardner, and T.A. Doerge. 2000. Peppermint. Western Oregon–West of Cascades. Fertilizer Guide, Oregon State University Extension Publication FG 15.

Kurki, A., and N. Matheson. 2001. "Green" markets for farm products. Appropriate Technology Transfer for Rural Areas publication (http://attra.ncat.org/attra-pub/greenmarkets.html).

Ley, T.W., R.G. Stevens, R.R. Topielec, and W.H. Neibling. 1994. Soil water monitoring and measurement. Pacific Northwest Extension Publication 475.Washington State University.

Louie, M.J., and J.S. Selker. 2000*a*. Sprinkler head maintenance effects on water application uniformity. ASCE Journal of Irrigation and Drainage 126:142-148.

Louie, M.J., P.M. Shelby, J.S. Smesrud, L.O. Gatchell, and J.S. Selker. 2000*b*. Field evaluation of passive capillary samplers for estimating groundwater recharge. Water Resources Research 36:2407-2416.

Owens, L.B. 1990. Nitrate-nitrogen concentrations in percolate from lysimeters planted to a legume-grass mixture. J. Environ. Qual. 19:131-135.

Penhallegon, R.H. 1994. Private well testing results for Lane County, Oregon. OSU Lane County Extension Report, March.

Sattell, R., R. Dick, D. Hemphill, J. Selker, F. Brandi-Dohrn, H. Minshew, M. Hess, J. Sandeno, and S. Kaufman. 1999. Nitrogen scavenging: using cover crops to reduce nitrate leaching in western Oregon. Oregon State University Extension Publication EM 8728.

Sattell, R., R. Dick, J. Luna, D. McGrath and E. Peachey. 1998. Common vetch. Oregon State University Extension Publication EM 8695.

Smesrud, J.K., M. Hess, and J.S. Selker. 2000. Western Oregon irrigation guides. Oregon State University Extension Publication 8713.

Smesrud, J.K., and J.S. Selker. 1998. Field sampling considerations for the stem nitrate test in peppermint. Commun. Soil Sci. Plant Anal., 29(19 & 20):3073-3091.

Smesrud, J.K., and J.S. Selker. 1999. Post-harvest water requirements of peppermint. Communications in Soil Science and Plant Analysis 30:1657-1666.

Sullivan, D.M., and C.G. Cogger. 2002. Post-harvest soil nitrate testing for nitrogen management in manured cropping systems in western Oregon and Washington. Oregon State University Extension Publication. EM 8832-E, Corvallis, OR.Available only online (http://eesc.orst.edu/agcomwebfile/edmat/EM8832-E.pdf).

Sullivan, D.M., J.M. Hart, and N.W. Christensen. 1999. Nitrogen uptake and utilization by Pacific Northwest crops. Pacific Northwest Extension Publication 513. Corvallis, OR.

United States Geological Survey. 1998. Water quality in the Willamette Basin, Oregon, 1991–1995. Circular 1161. United States Department of the Interior. Portland, OR.

Weisenburger, D.D. 1993. Human health effects of agrochemical use. Human Pathology 24(6):571-576.