ELEVEN YEAR STUDY OF NITRATE LEACHING UNDER VEGETABLE PRODUCTION WITH COVER CROPS

Under review for publication in the Journal of Environmental Quality

Jeffrey B. Feaga
Department of Bioengineering
Oregon State University
116 Gilmore Hall
Corvallis, OR 97331

Richard P. Dick
Department of Crop and Soil Science
Oregon State University
109 Crop Science Building
Corvallis, OR 97331

Delbert D. Hemphill
North Willamette Experiment Station
Oregon State University
15210 NE Miley Road
Aurora, OR 97002-9543

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

Abbreviation List:

PCAPS	- Passive Capillary Samplers
NWREC	- North Willamette Research and Extension Center
C	- Fallow crop treatment
H	- Cover crop treatment
N0	- Control subplot receiving no N fertilizer
N1	- Subplot receiving intermediate N fertilizer applications
N2	- Subplot receiving full N fertilizer applications

Corresponding Author Information:

John S. Selker
Department of Bioengineering
Oregon State University
116 Gilmore Hall
Corvallis, OR 97331
Phone number – (541)737- 6304

ABSTRACT

The high winter precipitation in the Willamette Valley of Oregon leaches residual nitrate (NO_3^-). Shallow groundwater was sampled for 11 years from summer vegetables with and without winter cover crops using a randomized complete-block split plot design with three N fertilizer application rates (N0 for no fertilizer, N1 for intermediate and N2 for the full recommended N inputs). The fall-seeded cover crops included cereal rye (*Secale cereale* L var. Wheeler*)*, triticale (*Tritcosecale X* L. var. Celia), or common vetch (*Vicia Sativa*) / triticale mix cover crops during winter. Twenty-six 0.26 m^2 passive capillary samplers (PCAPS) continuously sampled water flux at a depth of 1.2 meters.

Eleven-year flow-weighted average NO_3^--N concentrations (mg L^{-1}) for fallow and cover cropped plots were 16.7 and 11.9; 9.9 and 6.4; and 7.0 and 4.1 for N2, N1 and N0 plots, respectively. Annual average NO_3^--N mass losses (kg ha^{-1}) for fallow and cover cropped plots were 76.3 and 45.9, 40.0 and 30.2, and 29.0 and 17.3 for N2, N1 and N0 plots, respectively. Analysis of variance indicated that cover crops, N fertilization rate, and year had significant effects on NO_3^--N concentration and mass losses (P-value < 0.0001). The common vetch / triticale mix cover crop treatment used the last three seasons had a significant effect on NO_3^--N concentration and mass losses (P-value < 0.0001); however annual results during this period were highly variable. This long-term study demonstrates the effectiveness of nutrient and cover crop management to regulate groundwater NO_3^--N concentrations.

INTRODUCTION

Nitrate (NO_3^-) contamination of groundwater by agricultural practices is a national concern. In the United States Midwestern Corn Belt, agriculture dominates land use and a majority of the population relies on groundwater for drinking (Klocke et al., 1999). Nitrate leaching in Mid-Atlantic and Southern states has been intensely researched due to high density farm operations using intensive row cropping practices, the prevalence of highly permeable sandy coastal plain soils, and the need to regulate nutrient inputs to water courses exhibiting eutrophic conditions (Staver and Brinsfield, 1998; Ritter et al., 1998). Many of these studies have measured and quantified NO_3^--N concentrations in soil water percolating to depths below the root zone and into aquifers. As a result of substantial nitrogen (N) inputs, shallow groundwater aquifers in agricultural areas can contain substantial quantities of NO_3^- and often exceed the EPA 10 mg L^{-1} drinking water standard set for N in the NO_3^- compound, or NO_3^--N (Brandi-Dohrn et al., 1997; Meisinger et al., 1991; Staver and Brinsfield, 1998).

Nitrate leaching processes and the methods of N management are regional. In Western Oregon's Willamette Valley, a Mediterranean (dry summer maritime) climate with nearly 100 cm of rain falling between the months of October and April can make for conditions particularly conducive to NO_3^- leaching. The United States Geological Survey (1998) in a 1993 study found that nine percent of 70 domestic wells in the Willamette Valley exceed the EPA 10 mg L^{-1} drinking water standard for NO_3^--N. A study in Marion County where our study was conducted showed that 28 of the 82 tested wells exceeded the EPA limit (Petit, 1988). In a 2000-2001 study of 476 wells in the Southern Willamette Valley, 35 wells exceeded the drinking water standard, with 21% of the total wells exceeding 7 ppm NO_3^--N (DEQ, 2002).

The Willamette Valley has extensive cultivation of irrigated peppermint and row vegetables, which have high N requirements and low N efficiency. Often, significant amounts of plant available N remain in the soil profile after harvest. With the onset of the rainy season in October or November, soluble NO_3^- is quickly lost and plant residues left on the surface are quickly mineralized. Rainfall characteristics and mild winter temperatures make winter cover crops a valuable best management practice (BMP) to reduce N loss from row crop systems in western Oregon (Brandi-Dohrn et al., 1997; Burket et al., 1997).

Additions of NO_3^- in aquifer recharge water do not necessarily have an immediate effect on deep groundwater aquifer concentration, such as in wells. Owens et al. (1985) applied a Bromide (Br^-) (as a surrogate for NO_3^-) tracer to two Ohio pastures and found that up to 104 weeks were needed to reach peak concentrations within nearby groundwater springs. For aquifers at risk of NO_3^- contamination, land managers are beginning to realize that the delayed effect of N inputs to raise groundwater NO_3^-- N concentrations obligates that action be taken to develop BMP's before there is a problem with drinking water. Some of the most typical strategies include: determining the timing, rate, and method of N applications, accounting for and managing mineralization rates of crop residue during noncropping periods, using diversified crop rotations, and using various tillage practices (Dinnes, 2002).

The quantity of inorganic N available for leaching has generally been found to be more dependent on cropping and fertilizer application history than fertilizer applications of the current year (Macdonald et al., 1989; Martinez and Guiraud, 1990). Long-term use of cover crops can change the timing of plant available N supply because of uptake and subsequent mineralization. Successful growing operations often rotate crops and management in response to changing demand, therefore studies of systems supporting a stable monoculture may be unrealistic for some regions. Within the context of rotational cropping, few NO_3^- leaching studies have been operated for periods long enough to accurately measure the effect of field management changes on NO_3^-- N concentration in leachate. The relation to NO_3^- leaching from environmental factors such as rainfall timing, amount and intensity is hard to discern during short studies. Experiments with controlled precipitation are of limited relevance to real world processes.

Finding the most appropriate methods for measuring management effects on NO_3^- content within mobile soil water has been a challenge for researchers. Deep well testing is not an ideal method due to the time lag of the groundwater response and other groundwater inputs diluting the NO_3^- and making it difficult to identify the NO_3^- source (Owens et al., 1985; Owens and Edwards, 1992). Sampling methods in the upper vadose zone are the most capable of timely detection of NO_3^- management effects, but present their own difficulties. Many studies use destructive sampling such as coring. Such methods, particularly with repetition, can change infiltration and drainage characteristics of the soil and disrupt the hydrology of long term study sites. Most sampling devices are incapable of measuring both soil water flux and soil water quality. Zero tension pan lysimeters require positive pore water pressures before water collection can occur. This characteristic leads to lateral flow away from the sampler with collection efficiencies ranging from 10 to 58% (Jemison and Fox, 1992). Suction cup samplers require high negative pressures for operation, making estimates of chemical mass impossible because the volume of soil from which water is extracted is uncertain. In addition, suction cup samplers and soil cores do not well represent water flowing along preferential flow paths (Brandi-Dohrn et al., 1996b).

Passive capillary wick samplers have much higher collection efficiencies than pan lysimeters, and are able to sample matrix and preferential water (Boll et al., 1991; Brandi-Dohrn et al., 1996b). Brandi-Dohrn et al. (1996b) showed that Br^- concentration measured by PCAPS differed from concentrations measured using suction cup samplers during the rising and falling limb of the tracer's breakthrough curve. This was due to the PCAPS sampling of flux concentrations while suction cup samplers obtain matrix concentrations.

Cereal Cover Crops

The use of winter cover crops is a strategy that has potential as a BMP for N as well as soil fertility and conservation. Winter cover crops that are incorporated into the ground before spring planting add organic matter, smother weeds and improve soil tilth (Sattell et al., 1998). Cover crops can reduce erosion on slopes and impede the formation of crust layers due to raindrop effects on bare earth, improving infiltration and water-holding capacity. Besides improving soil quality, cover crops scavenge residual N in the soil after fall harvest, reducing NO_3^- leaching to groundwater (Meisinger et al., 1991; Brandi-Dohrn et al., 1997; Staver and Brinsfield, 1998; McCracken et al., 1994). Researchers have observed varying effectiveness for cover crops to assimilate residual soil NO_3^- and decrease NO_3^-- N concentrations within soil water. In an N_{15} lysimeter study in France an Italian rye grass cover crop reduced NO_3 leaching from 110 kg N ha^{-1} under bare fallow to 40 kg N ha^{-1} (Martinez and Guiraud, 1990). Nitrate -N concentrations in the soil water were reduced from 48 to 25 mg L^{-1}. In a cover crop study using a corn/rye rotation on the Atlantic Coastal plain of Maryland, NO_3^--N concentrations measured by 6 foot deep observation wells were reduced from 17 mg L^{-1} to 12 mg L^{-1} (Meisinger et al., 1990).

There are several desired characteristics of winter cover crops used for managing residual soil NO_3^-. The cover crop must be easy to establish and grow adequately in cooler fall temperatures in order to establish a root network. After being killed in the spring to prepare for planting, the cover crop would ideally make N available to the growing plant through mineralization. In theory, this additional plant available N could supply a considerable portion of the summer crop's N requirements and fertilizer additions could be reduced. The most common and effective cover crops used for N scavenging are cereal crops such as ryegrass and other forage crops which can typically accumulate between 25 and 50 kg $ha^{-1}yr^{-1}$ of N (Wagger and Mengel, 1988; Shennan, 1992; Shipley et al., 1992; Ditch et al., 1993).

Despite the effectiveness of cereal crops to accumulate N, research findings question the ability of disked cereal rye residue to provide available N to the summer crop. Brandi-Dohrn (1997) found that inorganic N contents measured for three consecutive Septembers under cereal rye plots were not significantly different, suggesting that the cereal rye was not contributing to the plant-available N pool through mineralization. On the same experimental plots, Burket (1997) measured crop yields harvested from plots managed under fallow treatment, cereal rye and clover. Consistent with other studies such as McCracken et al. (1989), Mitchell and Teel (1977) and Raimbault et al. (1991), Burket found no yield improvements for corn grown in cereal cover plots versus fallow plots, suggesting that mineralization was not enhancing crop growth. These observations could be a result of high C:N ratios in cereal rye residue, or possibly phytotoxic compounds released in the decomposing cereal rye residue (Raimbault et al., 1991).

Leguminous Cover Crops

Leguminous winter cover crops such as crimson clover, winter pea, and vetch are appealing because while scavenging NO_3^- from the previous crop, additional N may be supplied to the system by fixation of atmospheric N (N_2). Leguminous cover crops can fix N_2 to varying degrees depending on the type of legume, growing region, and accumulated biomass. Leguminous crops are more effective at supplying mineralized N to the growing crop due to greater N concentrations in the biomass (Sainju et al., 1997). Nonetheless, it is common for mineralization to lag behind the period of rapid plant uptake, as was observed with a hairy vetch cover mineralizing after corn silking (after rapid uptake). This observation may be due to dry conditions slowing mineralization rates (Brown et al., 1993).

Studies have shown that most winter legume covers do not scavenge soil NO_3^- as efficiently as cereal crops. McCracken et al., (1994) found that rye reduced NO_3^- leaching by 94% compared with 48% using hairy vetch. To explain the apparent inability of typical leguminous covers to scavenge NO_3^-, Sainju et al. (1998) measured the densities and length of rye, hairy vetch, and crimson clover. Rye had a greater root density and length earlier in the winter than did the leguminous crops. A positive correlation was made between root count and crop biomass and N uptake. A negative correlation was established between root count and NO_3^--N concentration in the soil. Because of temperature, rye crops resume growth earlier in the spring than vetch (McCracken et al., 1994). Meisinger et al. (1991) hypothesized that legumes may achieve N requirements through fixation rather than soil water uptake, making legumes less effective at scavenging residual NO_3^-.

The use of cereal / legume bicultures as winter cover crops is a promising alternative to using monocultures. Bicultures can utilize the scavenging ability of a cereal crop, while the legume decreases the C:N ratio of the residue (Ranells and Wagger, 1997). Sullivan et al., (1991) found that rye had higher concentrations of N grown with hairy vetch than grown without. The moderate C:N ratio associated with bicultures can prevent early mineralization of a legume biculture, and prevent immobilization, which is a risk with rye monoculture (Ranells and Wagger, 1997).

The objectives of this study were to use observations over eleven growing seasons in Western Oregon to: 1) estimate the concentration and mass flux of NO_3^- below the root zone following corn, broccoli, and snap beans grown with and without a winter cover crop 2) Describe the relationship of NO_3^- leaching to rainfall patterns and climatic conditions 3) Determine NO_3^- leaching characteristics under common vetch / triticale mix winter cover crops.

METHODS

Site Description

The study site was at the North Willamette Research and Extension Center (NWREC) located near Aurora, Oregon (45° 17' N and 122° 45' W), at 46 m elevation above sea level. The Willamette Valley has a Mediterranean climate characterized by wet winters and dry summers. A meteorological station has been operated at the NWREC site since 1963. The Pacific Northwest Cooperative Agricultural Weather Network has maintained the meteorological station since October 1, 1998. Weather records from 1963 to 1990 give an annual average precipitation total of 103.6 cm (40.8 inches) (Oregon Climate Service, 2003). Data are arranged according to months of the water year, which begins in October and ends in September of the posted year. The months included in a water year more closely coincide with the timing of an agricultural growing year. During the dry, sunny summer months, potential evapotranspiration (ET) far exceeds rainfall. Precipitation totals for the years of study are summarized in Table 1, showing the driest year had 1/3 the rainfall of the wettest.

Soils at the 0.98 hectare study site are slightly sloped towards the south (<3%). The soils are of glaciolacustrine genesis and are classified as a Woodburn variant loam with a small strip of Willamette variant loam bisecting the field. Description of organic carbon, pH, bulk density, particle size distribution, saturated hydraulic conductivity and moisture retention characteristics for the NWREC study plot are described in Brandi-Dohrn (1996a). Soil bulk density measurements were repeated in 2001.

Field management with respect to soil tillage remained the same over the 11 year study period. There was evidence of burrowing rodents at the site, most commonly in the border areas between the experimental plots. Efforts were made to control the rodents with varying success throughout the study. The rodents may have changed conductivity and bulk density values both spatially and temporally. The southeast corner of the field had a slight depression and often became ponded in the winter. Soil sampling here showed a compacted layer at 0.7 m depth with low hydraulic conductivity.

Experimental Design

Prior to the initiation of the cover crop studies, the site had been under continuous wheat production and winter fallow for seven years. Starting in 1989, the experimental design changed to a randomized complete block split plot, with cover crop system as main plot and N fertilizer rate as the subplot. The main plot treatments followed summer crops as conventional winter fallow (called C plots) or as a fall planted cover crop (called H plots). The field was divided into 40 plots with dimensions of 18 m by 9 m. Eight of the plots had lysimeters installed in 1992. Each plot was divided into three subplots, two with dimensions of 9 m by 6 m and the control measuring 18 m by 3 m. Nitrogen fertilizer treatments at the sub-plot level were managed as N0, N1, or N2 which represented no addition of fertilizer, an intermediate rate, and the Oregon State University Extension Service recommended amount to achieve maximum yield, respectively.

Summer vegetables were irrigated using a hand move sprinkling system. Irrigation sets took place once per week. Water was applied for variable set times according to the time of the year; however a quantitative model of evapotranspiration was not used to fine tune irrigation amounts. Irrigation procedures were consistently managed by the same person throughout the entire study.

Summer vegetable and winter cover crop type changed throughout the experiment and included sweet corn (*Zea mays* L. cv. Jubilee), broccoli (*Brassica oleracea* L. Botrytis Group cv. Gem), and snap beans (*Phaseolus vulgaris* L. cv. Oregon 91G). Crop type and planting and harvesting schedules are summarized in Table 2. Cover crops included cereal rye (*Secale cereale* L var. Wheeler), a commonly used cover crop, triticale (*Tritcosecale X* L. var. Celia), a rye / wheat hybrid, and a common vetch (*Vicia Sativa*) / triticale mix during the last three winter seasons of the study. Common vetch is a legume and commonly contains as much as 56-135 of N per hectare (Sattell et al., 1998).

For this analysis, the leaching or crop year was defined as beginning at planting of summer vegetable crops. Therefore, the leaching year includes the summer vegetable crop and the following winter cover crop as a unit. For example, the period of time from the planting of corn on the 30th of May 1996 until May 1997 was defined as 1996. Data is often subdivided according to the periods defined by the cover crop system used (cereal cover crop and common vetch / triticale mix periods).

To prepare for spring planting, soil was moldboard plowed to a depth of 30 cm. Several weeks later, soil was further worked with a disk-harrow combination and a seedbed was prepared using a spike toothed harrow and packing rollers. Fertilizer was applied two times, the first at planting and the second about one month later (Table 3). At harvest in late summer, vegetable crops were removed from 4.5 m transects of two rows within each subplot. Total plant biomass (wet and dry) and total plant N were determined for each crop from a 0.5 kg sub-sample. The remainder of the standing crop was mowed and incorporated back into the soil.

About a month after the summer crop was mowed, cover cropped plots were prepared for planting the cereal cover using a moldboard plow and disk. To prepare plots for common vetch / triticale cover crops, water was added to the soil surface to prepare a soft seed bed. Seeds were broadcast over the surface by hand. Seeding densities and fertilization rates for each vegetable and cover crop are given in Table 3.

In late March or early April the success of the cover crop was determined by taking a spatially random 1.0 m^2 sample from each of the sub-plots. A 0.5 kg sub-sample was saved from each random sample to determine total N and dry weight biomass. The cover crop was killed by mowing, allowed to decompose for several weeks, and turned into the soil with a moldboard plow to begin preparation for another summer vegetable crop. Though not mimicking a typical commercial growing operation, this management practice ensured that all N inputs were accounted for. In this analysis the assumption is made that mineralization rates for the mowed crops reached steady state by the time lysimeters were installed in the fall of 1992 (Brandi Dohrn et al., 1997). Not until the winter of 2000 were N inputs potentially modified when N fixing common vetch was introduced to the rotation.

Instrumentation

In the summer of 1992, 32 passive capillary samplers (PCAPS) were installed at the NWREC plots. Samplers represented four fallow plots (C) and four cover cropped plots (H). Each plot received four PCAPS, one each in the N1 and N2 sub-plots, and two PCAPS on opposite ends of the N0 control sub-plots. The PCAPS installation was completed to maximize statistical comparability made possible by the complete block split plot design. However, due to flooding, four of the subplots were abandoned in block one leaving only three complete replications. The current experimental design utilizes 26 samplers. Published results prior to 1997 from this field site included data from the six consistently flooded PCAPS, but these data were omitted for this analysis.

A detailed description of wick sampler design can be found in Knutson and Selker (1996) and Brandi-Dohrn et al. (1996a). Sampler installation and operation at the NWREC is detailed in Brandi-Dohrn et al. (1996a).

Sample Processing

A vacuum pump was used to sample leachate collected from the PCAPS. Samples were taken after cumulative rainfall between sampling events neared 2.5 cm, at which point the collection vessels would be reaching capacity. During late spring and summer it was not necessary to sample as frequently because potential ET rates exceed inputs from rainfall and irrigation. Brandi Dohrn (1996) determined that sampler bias between the three separate PCAPS collection vessels stabilized after the first year of operation; therefore groundwater volumes from each vessel were combined on-site. One sample was taken from these mixed volumes for analysis. Each sampling event provided one sample from each PCAPS unit. Samples were put into HDPE vials and frozen until ion analysis. A Dionex 2000i ion chromatograph with a Dionex AS4A-5C separator column and an AG4A-SC guard column was used to determine anion concentrations. Anions of interest included NO_3^-, Br^-, and Cl^-. Groundwater was sampled from each PCAPS 249 times, starting with the first collection on the 4th of November 1992 until the last on the 26th of April 2003.

Calculations and Data Analysis

PCAPS are capable of measuring both water flux and concentration of dissolved constituents. Therefore, reliable measurements can be made to calculate average concentrations weighted with respect to water flow. Flow-weighted averages can be calculated for multiple samplers and / or samples can be averaged over periods of time ranging from one sampling event to events encompassing multiple growing seasons.

The equation for flow weighting the ion concentration of multiple samplers from the same collection event is:

$$\bar{c} = \frac{\sum_{i=1}^{n} c_i V_i}{\sum_{i=1}^{n} V_i} \tag{1}$$

$\bar{c}$ = Mean flow-weighted concentration for multiple samplers
c_i = Concentration as measured by each of n samplers
V_i = Volume of percolation as measured by each of n samplers
n = Number of samplers collecting water

The equation for finding a flow-weighted average ion concentration over multiple sampling events using flow-weighted averages calculated for multiple samplers is:

$$\bar{c}(t) = \frac{\sum_{t=1}^{N} \bar{c}_t \bar{V}_t}{\sum_{t=1}^{N} \bar{V}_t} \tag{2}$$

$\bar{c}\,(t)$ = Mean flow-weighted concentration over multiple sampling events

$\bar{c}_t$ = Mean flow-weighted concentration measured for multiple samplers calculated for N sampling events
$\bar{V}_t$ = Average volume of percolation collected during each sampling event calculated for N sampling events
N = Number of sampling events

The equation for average cumulative flux of ions over *t* sampling events is:

$$M = \frac{\sum_{t=1}^{N} \frac{1}{n_t} \left(\sum_{i=1}^{n_t} c_{i,t} V_{i,t} \right)}{A_{PCAPS}} \tag{3}$$

M = Mass flux
$c_{i,t}$ = Concentration as measured by n samplers during time interval $t_{i+1} - t_i$
$V_{i,t}$ = Volume of percolation measured by n samplers during time interval $t_{i+1} - t_i$
N = Number of sampling events
n_t = Number of samplers at sampling event t
A_{PCAPS} = Surface area of PCAPS (2619.5 cm^2)

The experimental design allowed a statistical comparison using analysis of variance (ANOVA) with a general linear model as a randomized complete split-plot block design over years with winter cover crop treatment as main plots and N rate as subplots. ANOVA was made for NO_3^--N concentration and mass during years using only cereal winter cover crops (1992-1999), years using a legume / cereal mix cover crop (2000-2002), and the entire study period. A separate ANOVA analysis was also made for each of the 11 years in the study.

An important statistical assessment of a sampler and its variability is the calculation of the number of PCAPS required to estimate the annual recharge at the site. This number was generated using the mean collection confidence interval generated from the variability of the PCAPS collection efficiencies during the time periods used in a water balance (Equation 4). Where $\bar{y}$ is the mean yearly collection efficiency, n is the number of samplers, t is the t statistic with n-1 degrees of freedom and a probability of exceedance of $\alpha/2$, and S is the sample standard deviation. A α value of 0.05 was chosen to give the 95% confidence interval. The sample standard deviation was

$$\bar{y} \pm t_{\alpha/2,n-1}\left(\frac{S}{\sqrt{n}}\right) \tag{4}$$

estimated from the pooled standard deviation of the 78 values provided by the 26 samplers during the three periods in the water balance. For analysis using the t statistic to be valid, measured collection efficiencies must be independent and follow a normal distribution. It was found that the distribution appeared normal, but was not significant at the 0.05 significance level using the Filliben test for normality.

RESULTS / DISCUSSION

Variability of PCAPS

The reliability of PCAPS was validated using a water balance before an analysis on water quality was made. The hypothesis was that the collection efficiency of the PCAPS would not change or decrease during the experiment. Therefore, the relative collection efficiency of each sampler compared to the mean collection efficiency of all the samplers would not be expected to change. In other words, a sampler that collected water volumes greater than the average at the beginning of the experiment would be expected to do the same at the end of the experiment. Collected volumes from sample events # 5 through # 67 were compared to sample events # 121 through # 172, which corresponded to time periods between the Dec 3rd 1992 through April 11th 1995 and Dec 3rd 1997 through April 20th 2000, respectively. Water collected from the pool of 26 samplers during the first period was summed and ranked by the % deviation from the mean collection amount. The % deviation from the same sampler number during the second group of sample dates are plotted alongside the original rankings (Figure 1). Sample collection efficiency varied over the experiment, but the majority of samplers consistently collected greater or less than the mean amount. It appears from these results that there were not any large changes in the structure of soil or flow characteristics in the soil column over the samplers during the course of the experiment.

To determine the reliability of the PCAPS to represent the actual quantity of percolation, a water balance was calculated for three periods of the eleven year study

(Table 4). The three periods used for the analysis were the months of December through March of the winter of 1993-1994, 1999-2000, and 2001-2002. These periods were chosen because they took place during years of near average precipitation (108%, 89%, and 108% of the 30 year average, respectively), represented the beginning and end of the experiment, and did not include times when fields were often flooded.

To perform the water balance, PCAPS collected water volumes were compared to the theoretical percolation calculated as precipitation minus ET. Evapotranspiration information was obtained on a daily basis and was based on the 1982 Kimberly Penman Equation reference value (Pacific Northwest Cooperative Agricultural Weather Network Website, 2003). For simplification, change in soil storage was not considered as the three periods were during the wettest winter months and the soil profile was at moisture contents near saturation. Surface runoff and lateral subsurface flow were also not considered because of the slight 3% slopes of the field and the inability to accurately measure these parameters.

Collection efficiencies were 49%, 81% and 100% for the winters of 1993-1994, 1999-2000, and 2001-2002, respectively. The low efficiency for the first period could be due to several days of high rainfall during the last week of February 1994 that exceeded the capacity of the samplers and allowed water to bypass the lysimeters. The 100% collection efficiency realized during the last period could be attributed to our assumption that runoff was negligible. On two occasions in winter 2001, water was observed to flow from portions of the adjacent fallow field to the south east and onto the study site where it flooded plots supporting operating PCAPS. Brandi-Dohrn et al. (1996a) calculated the collection efficiency of the NWREC PCAPS units for several periods during the early stages of the experiment and found efficiency ranges from 66% to 81%. These values are comparable to the 76% average collection efficiency calculated in this water balance.

The variation in the water balance collection efficiency allowed the determination of the minimum number of samplers needed to estimate the mean annual recharge at the PCAPS field site. With a 15% bound on the mean a minimum of 20 samplers were required. A minimum of six samplers were required to estimate the mean annual recharge with a 30% bound on the mean.

Nitrate Leaching

Long term concentrations and leaching patterns

Nitrate - N concentrations and cumulative NO_3^-- N losses for N0, N1 and N2 fertilizer treatments measured by PCAPS through time are shown in Figure 2, Figure 3, and Figure 4, respectively. Differences in NO_3^-- N concentration due to fertilizer application level are apparent. Nitrate - N concentration and cumulative NO_3^--N mass were consistently higher under fallow crop rotations (C) than under cover crop treatments (H). Concentrations of $N0_3^-$- N were often greater than the EPA 10 mg L^{-1} standard set for water intended for drinking, especially for plots receiving N2 fertilizer additions.

Nitrate- N concentration varied through time, and periods of high and low NO_3^-- N leaching losses reflect the seasonal pattern of rainfall in the Willamette Valley. Nitrate - N concentrations were typically the highest during the fall and early winter. As winter approached and fall rains began, the soil profile became saturated and most of the NO_3^- left after harvest was leached below the sampling depth. Nitrate - N concentrations decreased during this time due to the high volumes of water diluting the NO_3^-- N. The highest NO_3^-- N mass flux rates in the fall and early winter period were related to periods of highest NO_3^-- N concentration but lagged in time behind them.

Water collected from unfertilized N0 plots contained NO_3^- throughout the study and patterns of fluctuating NO_3^-- N concentration and leaching losses were the same as for N1 and N2 plots. Nitrogen was present below unfertilized plots due to the reservoir of N available for mineralization contained in soil minerals and humus. Weathering and mineralization made these forms of N plant-available. More plant-available N could have been added to the system through groundwater pumped irrigation water. Finally, N could have been added to the system through atmospheric N fixation during the last three seasons using the common vetch / cereal mix cover crop. Background (N0) NO_3^-- N concentrations and mass losses were not subtracted from N1 and N2 plots for this analysis, but it is important to realize the dynamic N cycle under control plots.

Effect of cover cropping

Flow-weighted average NO_3^-- N concentrations and mass losses for each year of the study as well as periods using different cover crop treatments are summarized in Tables 5 and 6. Flow-weighted average NO_3^--N concentrations (mg L^{-1}) for fallow vs cover cropped plots over the entire study were 16.7 and 11.9; 9.9 and 6.4; and 7.0 and 4.1 for N2, N1 and N0 plots, respectively. Calculated average annual NO_3^--N mass losses (kg ha^-) for fallow vs. cover cropped plots over the entire study were 76.3 and 45.9, 40.0 and 30.2, and 29.0 and 17.3 for N2, N1 and N0 plots, respectively.

Annual flow-weighted average NO_3^-- N concentrations throughout the study for fields fertilized at recommended agronomic N rates (N2 plots) ranged from 5.0 to 23.3 mg L^{-1} and 6.7 to 24.9 mg L^{-1} for cover cropped and fallow fields, respectively. Annual average NO_3^-- N mass losses on N2 plots during this same period ranged from 21.0 to 125.7 kg ha^{-1} and 37.8 to 150.4 kg ha^{-1} for cover cropped and fallow fields, respectively. The distribution of calculated yearly flow-weighted NO_3^-- N concentrations and NO_3^-- N mass losses on N2 plots are shown in boxplot form in Figure 5.

Table 7 shows the resulting *P*-values from analysis of variance comparing the differences in flow-weighted average NO_3^-- N concentration and mass over years of the experiment using only cereal cover crops, legume / cereal mix cover crops, and the entire experiment. ANOVA results showed that cover crop treatment, N fertilizer rate, and year all had a significant effect (*P* value of ≤ 0.001) on NO_3^-- N concentration and mass during each of the different time periods. Using cover crops reduced the NO_3^-- N concentration by 29, 36, and 41% for N2, N1 and N0 plots, respectively. Reductions in yearly NO_3^-- N mass leached due to cover crops were 40, 25, and 40% for N2, N1 and N0 plots, respectively. Year also had a significant effect on variance of NO_3^-- N concentration and mass and could be explained by differences in crop type, winter rainfall conditions, and cover crop establishment during each season; however, no statistics were used to test the significance of these factors. ANOVA also showed that several significant combination effects were expressed. The strong effect of year*cover crop (*P*-value < 0.0001) indicated that the relationship between these factors were not truly linear as would be the case in an ideal complete block split plot experimental design.

Apparent was the observation that cover crop treatment significantly effected NO_3^-- N concentration and mass (as determined by yearly separated ANOVA) during every year that rainfall was less than the average (water years 1994, 2000, and 2001; corresponding to leaching years 1993, 1999, and 2000). Conversely, very rainy winters such as 1994 and 1996 did not show differences in NO_3^-- N concentration and mass due to cover crop treatment. This trend was not always the case, however, as water year 1996 had 159% of the usual rainfall, but still had a significant cover crop effect on NO_3^-- N mass losses during leaching year 1995. It is inferred from these observations that high rates of NO_3^- leaching to deeper depths would be expected during years where cover crop establishment is weak because of poor growing conditions and / or consistent rainfalls begin before crop roots are well established. Staver and Brinsfield (1998) observed improved N scavenging for cover crops planted after corn harvest due to the limited number of leaching events in early autumn.

When there is normal rainfall in early winter with below average rainfall in late winter, the bulk of NO_3^- mass left after harvest may not reach sampler depth and will over-winter in the soil profile. At these depths, NO_3^- does not undergo rapid chemical change nor can it be used by growing crops during the following summer because few vegetable roots penetrate to this depth. This situation can result in high NO_3^-- N concentration and mass losses the following winter as the residual NO_3^- of two growing seasons leach to sampling depth during one winter.

The leaching of two season's excess NO_3^- is a possible explanation for the extremely high NO_3^-- N concentration and mass losses recorded during leaching year 1994 as the previous water year (October 1993 to September 1994) received only 77% of the long-term average precipitation. This process may also explain NO_3^-- N observations in 2001 under common vetch / triticale mix cover crops and is discussed in the following section. Careful observation and statistical testing of the relationship of rainfall amount, timing, and vegetable and cover crop establishment are needed to completely understand the relationship between cover crop NO_3^- uptake and climate. These types of comparisons and correlations are difficult, however, due to the challenge of maintaining an experimental control.

Assessment of NO_3^- leaching under legume / cereal mix cover crops

The final years of the study using common vetch / triticale cover crops resulted in observed flow-weighted NO_3^-- N concentrations and mass losses that were significantly affected by cover crop treatment and N fertilization rate (ANOVA over three years, *P*-value < 0.0001) (Table 7). These results were similar to those observed under cereal cover crops, but observations of NO_3^-- N concentration and mass losses were very different each of the three years (Figure 6). Figure 7 shows average mass of NO_3^- lost during this same period. Yearly observations may reflect complicated environmental factors such as atmospheric N fixation, rainfall differences, and / or mineralization of organic matter. During 2000 and 2002, separated yearly analysis of variance shows that cover crop treatment significant effected NO_3^-- N concentration. Cover crop treatment could not explain variance in NO_3^-- N concentration or mass in 2001.

Nitrate – N concentrations during 2001 were generally high for fallow plots at all fertilizer treatments, and were the absolute highest concentrations measured during the 11 year study under cover cropped plots at all three N fertilization rates. There are several possible explanations for the high NO_3^-- N concentrations and mass losses in 2001 compared to the other years using common vetch / triticale mix cover crops. Because mineralization rates were not determined nor organic matter contents in the soil measured over time, it is impossible to positively attribute observations in 2001 to an increase in NO_3^- made available through atmospheric fixation of N by the common vetch. A probable explanation for the variable observations is the difference in rainfall patterns experienced during the last three years of the study. High concentrations and little mass loss during the year 2000 using common vetch could be explained by the extremely dry conditions in water year 2001 when only 58% of the long-term average rainfall was collected. The second year of common vetch / triticale cover crops had typical rainfall accumulations, with 108% of the long-term precipitation average. Similar to 1994, it is possible that the leaching of two season's worth of NO_3^- can explain the observations made in 2001.

Though results were variable under common vetch / triticale mix cover crops, NO_3^--N concentration and mass losses were affected by winter cover crop treatment. It is possible that the bulk of NO_3^- scavenging ability of this mix cover crop was due to the triticale portion of the cover crop mixture. Further investigation is needed to test whether cereal cover crops are more effective NO_3^- scavengers than common vetch / triticale biculture cover crops.

CONCLUSIONS

The analysis of water collected below the root zone at 1.2 meters depth indicated that the use of cover crops and N fertilizer application rates had a significant effect (*P*-value <0.0001) on NO_3^-- N concentration and mass losses over the 11 year study. Fall planted cereal cover crops used during the first eight years as well as common vetch / triticale mix cover crops planted during the last three years successfully scavenged residual NO_3^- remaining in the upper soil column after summer vegetable growth. Further investigation under legume / cereal cover crops is necessary to evaluate the relation of NO_3^- leaching to legume mineralization.

Despite the differences in average NO_3^-- N concentration and mass losses achieved using cover crops, all plots fertilized at recommended N rates were higher than the EPA's 10 mg L^{-1} drinking water standard set for NO_3^-- N. Similar NO_3^- leaching characteristics would be expected under row vegetable growing operation throughout the Willamette Valley. These results stress the importance of employing nutrient management strategies before NO_3^-- N concentrations increase in drinking water aquifers.

From the yearly variability of NO_3^-- N concentrations and mass losses, it was clear that environmental factors, especially timing and quantity of rainfall, had pronounced effects on NO_3^- leaching. Seed germination and establishment of the winter cover crop is important for successful winter scavenging. Large rain events before good cover crop root establishment can leach NO_3^- to depths unreachable by crop roots and reduce the efficiency of the cover crop to scavenge residual N contained in the soil water.

This long-term study makes a strong demonstration for the effectiveness of winter cover crop management as an option to limit NO_3^- leaching losses to groundwater. It is likely that organic matter levels would eventually increase in soils under long-term winter cereal crop rotations. Long term studies, on the order of decades, are needed to reveal the possible improvements for crop growth and the opportunity of applying N fertilizer credits from increased mineralization rates. The highly correlated response of NO_3^-- N concentration to application rates infer that nutrient management strategies must continue to achieve increases in N efficiencies through application methods and timing without compromising crop yield. With such management, fertilizer application rates could possibly be decreased and contamination of drinking water aquifers by agriculture would be reduced.

ACKNOWLEDGEMENTS

We thank Joan Sandeno for ion analysis of samples, anyone who edited this manuscript, and the Oregon Department of Agriculture who funded the preparation of this manuscript.

REFERENCES

Boll, J., J.S. Selker, B.M. Nijssen, T.S. Steenhuis, J. van Winkle, and E. Jolles. 1991. Water quality sampling under preferential flow conditions. P. 290-298. *In* R.G. Allen et al. (ed.) Lysimeters for evapotranspiration and environmental measurements. Proc. ASCE Int. Symp. Lysimetry, Honolulu, Hawaii 23-25 July 1991. Am. Soc. Civ. Eng., New York.

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

Brandi-Dohrn, F.M., R.P. Dick, M. Hess, and J.S. Selker. 1996a. Field evaluation of passive capillary samplers. Soil Sci. Soc. Am. J. 60:1705-1713.

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

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.

Brown, R.E., G.E. Varvel, and C.A. Shapiro. 1993. Residual effects of interseeded hairy vetch on soil nitrate-nitrogen levels. Soil Sci. Soc. Am. J. 57:121-124.

Burket, J.Z., D.D. Hemphill, and R.P. Dick. 1997. Winter cover crops and nitrogen management in sweet corn and broccoli rotations. HortScience 32(4):664-668.

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

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.

Ditsch, D.C., M.M. Alley, K.R. Delley and Y.Z. Lei. 1993. Effectiveness of winter rye for accumulating residual fertilizer N flowing corn. J. Soil and Water Cons. 48:125-132.

Jemison, J.M. and R.H. Fox. 1992. Estimation of zero-tension pan lysimeters collection efficiency. Soil Science 154:85-94.

Katupitiya, A., D.E. Eisenhauer, R.B. Ferguson, R.F. Spalding, F.W. Roeth, M.W. Bobier. 1997. Long-term tillage and crop rotation effects on residual nitrate in the crop root zone and nitrate accumulation in the intermediate vadose zone. Transactions of the ASAE. 40(5):1321-1327.

Klocke, N.L., D.G. Watts, J.P. Schneekloth, D.R. Davison, R.W. Todd, A.M. Parkhurst. 1999. Nitrate leaching in irrigated corn and soybean in a semi-arid climate. Transactions of the ASAE. 42(6):1621-1630.

MacDonald, A.J., D.S. Powlson, P.R. Poulton, and D.S. Jenkinson. 1989. Unused fertilizer nitrogen in arable soils – Its contribution to nitrate leaching. J. Sci. Food Agric. 46:407-419

Martinez, J., and G. Guiraud. 1990 A lysimeter study of the effects of a rye grass cover crop, during winter wheat/maize rotation, on nitrate leaching and on the following crop. J. Soil Sci. 41:5-16.

McCracken, D.V., S.J. Corak, M.S. Smith, W.W. Fry, and R.L. Blevins. 1989. Residual effects of nitrogen fertilization and winter cover cropping on nitrogen availability. Soil Sci. Soc. Am. J. 53:1459-1464.

McCracken, D.V., M.S. Smith, J.H. Grove, C.T. MacKown, and R.L. Blevins. 1994. Nitrate leaching as influenced by cover cropping and nitrogen source. Soil Sci. Soc. Am. J. 58:1476-1483.

Meisinger, J.J., P.R. Shipley, and A.M. Decker. 1990. Using winter cover crops to recycle nitrogen and reduce leaching. In J.P. Mueller and M.G. Wagger [eds.] Conservation Tillage for Agriculture in the 1990's. Spec. Bull. 90-1. N. Car. State Univ., Raleigh. pp. 3-6.

Meisinger, J.J., W.L. Hargrove, R.L. Mikkelson, Jr., J.R. Williams, and V.W. Benson. 1991. Effects of cover crops on groundwater quality. P. 57-68. In W.L. Hargrove [ed.] Cover crops for clean water. Soil Water Conserv. Soc., Ankeny, IA.

Mitchell, W.H. and M.R. Teel. 1977. Winter-annual cover crops for no-tillage corn production. Agron. J. 69:569-573.

Oregon Climate Service. 2003. Climate Data Archives. Available at http://www.ocs.orst.edu/allzone/allzone2.html. (Verified 20 June 2003).

Owens, L.B., R.W. van Keuren and W.M. Edwards. 1985. Groundwater quality changes resulting from a surface bromide application to a pasture. J. Environ. Qual. 14:543-548.

Owens, L.B., W.M. Edwards. 1992. Long-term groundwater quality changes from a one-time surface bromide application. J. Environ. Qual. 21:406-410.

Pacific Northwest Cooperative Agricultural Weather Network. 2003. Available at http://mac1.pn.usbr.gov/agrimet/index.html. (Verified 20 June 2003).

Petit, G. 1988. Assessment of Oregon's Groundwater for Agricultural Chemicals, Report to the State of Oregon (DEQ, Portland, OR).

Raimbault, B.A., T.J. Vyn, and M. Tollenaar. 1991. Corn response to cereal rye cover crop, tillage methods, and planter options. Agron. J. 83:287-290.

Ranells, N.N., and M.G. Wagger. 1997. Grass-legume bicultures as winter annual cover crops. Agron. J. 89:659-665.

Ritter, W.F., R.W. Scarborough, A.E.M. Chirnside. 1998. Winter cover crops as a best management practice for reducing nitrogen leaching. J. Contam. Hydrol. 34:1-15.

Sainju, U.M. and B.P. Singh. 1997. Winter cover crops from sustainable agricultural systems: influence on soil properties, water quality, and crop yields. HortScience 32:21-27.

Sainju, U.M., B.P. Singh and W.F. Whitehead. 1998. Cover crop root distribution and its effect on soil nitrogen cycling. Agron. J. 90:511-518.

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

Shennan, C. 1992. Cover crops, nitrogen cycling, and soil properties in semi-irrigated vegetable production systems. HortScience 27:749-754.

Shipley, P.R., J.J. Meisinger, and A.M. Decker. 1992. Conserving residual corn fertilizer nitrogen with winter cover crops. Agron. J. 84:869-876.

Staver, K.W., and R.B. Brinsfield. 1998. Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic coastal plain. Journal of Soil and Water Conservation 53(3):230-240.

Sullivan, P.G., D.J. Parrish, and J.M. Luna. 1991. Cover crop contributions to N supply and water conservation in corn production. Am. J. Altern. Agric. 6:106-113.

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

Wagger, M.G., and D.M. Mengel. 1988. The role of nonleguminous cover crops in the efficient use of water and nitrogen. pp. 115-128. *In* W.L. Hargrove [ed.] Cropping strategies for efficient use of water and nitrogen. ASA Spec. Publ. 51.

LIST OF FIGURES

Figure

LIST OF TABLES

Table

Table 1 Total yearly precipitation at the NWREC by water year (October of previous year to the September of posted year) during study period (Oregon Climate Service, 2003).

Water Year	**Rainfall (cm)**	**Relative to 30 Year Average (%)**
1993	111.5	108
1994	79.3	77
1995	132.6	128
1996	165.0	159
1997	176.3	170
1998	110.6	107
1999	130.0	125
2000	92.0	89
2001	59.7	58
2002	112.1	108
2003†	100.0	96

† Does not include last four months of water year.

Table 2 Crop type and planting and harvesting dates during the experimental period.

Leaching Year	Spring Crop	Seeding	Harvest	Winter Crop	Winter Crop Timing
1992	Sweet Corn	May 20th	Aug	Cereal Rye	Seeding late September or early October of posted year Harvest late March or early April of following year
1993	Broccoli	June 9th	Aug 30th	Cereal Rye	
1994	Sweet Corn	July 7th	Sep	Cereal Rye	
1995	Broccoli	July 11th	Aug 31st	Triticale	
1996	Sweet Corn	May 30th	Sep 5th	Triticale	
1997	Broccoli	July 3rd	Sep 16th	Triticale	
1998	Sweet Corn	June 1st	Sep 9th	Cereal Rye	
1999	Snap Beans	June 10th	Aug 17th	Triticale	
2000	Sweet Corn	May 23rd	Sep 6th	Common vetch / Triticale	
2001	Snap Beans	June 13th	Aug 29th	Common vetch / Triticale	
2002	Sweet Corn	May 14th	Aug 21st	Common vetch / Triticale	

Table 3 Seed planting and fertilizer application densities for vegetable and cover crops during the experimental period.

Crop	Seeding density (Vegetable rows 102 cm apart)	N1 Fertilization (2 applications)	N2 Fertilization (2 applications)
Corn	62,000 plants ha^{-1}	56 kg ha^{-1}	224 kg ha^{-1}
Broccoli	30 cm spacing	140 kg ha^{-1}	280 kg ha^{-1}
Snap beans	51 cm spacing	67 kg ha^{-1}	134 kg ha^{-1}
Cereal Rye	75 kg ha^{-1}	No fertilizer	No fertilizer
Triticale	75 kg ha^{-1}	No fertilizer	No fertilizer
Common Vetch / Triticale	90 kg ha^{-1} Common Vetch 20 kg ha^{-1} triticale	No fertilizer	No fertilizer

Table 4 Water balance and collection efficiency of PCAPS for three periods throughout the study.

Period **Sampling event**	**Precipitation**	**ET**	**Percolation**		**Collection**
			expected	**observed**	**efficiency**
	-----cm-----				%
# 27 - # 37	55.5	12.9	42.5	20.6	49
# 158 - # 169	48.7	9.3	39.4	31.9	81
# 196 - # 219	64.0	10.5	53.5	53.3	100

Table 5 Average NO_3^-- N concentration measured under various fertilizer treatments. Cover cropped plots are divided into the periods using cereal cover crops and leguminous cover crops.

Year (winter)	**N2**			**N1**			**N0**		
	C Plots	**H Plots**	**Δ due to cover**	**C Plots**	**H Plots**	**Δ due to cover**	**C Plots**	**H Plots**	**Δ due to cover**
	mg L^{-1}		**%**	**mg L^{-1}**		**%**	**mg L^{-1}**		**%**
1992	13.4	9.6	28	8.3	4.6	45	6.5	2.8	56
1993	22.1	11.2	49	13.3	4.3	67	6.0	2.2	63
1994	18.0	16.1	10	11.9	8.7	27	5.0	4.5	9
1995	18.2	12.2	33	11.4	9.1	21	6.0	3.7	38
1996	6.7	5.0	26	2.3	1.2	47	2.3	1.3	43
1997	15.6	15.5	0	10.0	6.2	37	5.0	4.0	20
1998	20.1	11.5	43	6.4	5.5	14	6.1	3.5	43
1999	24.9	11.1	56	17.5	8.9	49	12.9	6.3	51
2000	26.4	8.2	69	15.0	4.5	70	13.7	3.9	71
2001	21.3	23.3	-9	13.9	10.2	27	12.7	9.1	28
2002	7.0	3.8	52	4.4	3.4	24	4.4	2.0	46
1992 - 1999 Cereal	17.1	11.4	34	9.8	6.1	37	6.0	3.6	41
2000 - 2002 Legume / Cereal	16.1	13.1	19	10.0	6.9	32	9.4	5.6	41
1992 – 2002 Entire Study	16.7	11.9	29	9.9	6.4	36	7.0	4.1	41

Table 6 Average NO_3^-- N mass measured under various fertilizer treatments. Cover cropped plots are divided into the periods using cereal cover crops and leguminous cover crops.

	N2			N1			N0		
Year	**C Plots**	**H Plots**	**Δ due to cover**	**C Plots**	**H Plots**	**Δ due to cover**	**C Plots**	**H Plots**	**Δ due to cover**
	kg ha^{-1}		**%**	**kg ha^{-1}**		**%**	**kg ha^{-1}**		**%**
1992	51.3	36.2	30	32.2	13.4	58	25.5	9.2	64
1993	56.2	24.6	56	29.2	13.2	55	15.0	6.6	56
1994	107.6	89.4	17	65.9	55.8	15	25.5	26.4	-4
1995	90.0	47.5	47	49.4	46.0	7	27.9	18.8	33
1996	37.8	21.0	44	10.9	6.9	37	8.9	6.5	27
1997	38.0	34.8	8	22.6	14.8	35	11.7	8.9	24
1998	128.9	58.5	55	36.0	36.8	-2	29.9	18.0	40
1999	98.3	34.2	65	65.4	32.7	50	43.1	21.7	50
2000	40.9	10.6	74	21.0	7.5	64	22.9	6.0	74
2001	150.4	125.7	16	85.1	79.5	7	84.9	56.8	33
2002	39.9	21.9	44	22.2	25.1	-13	23.2	11.5	51
1992 - 1999 Cereal Avg.	76.0	43.3	43	39.0	27.5	29	24.0	14.6	39
2000 - 2002 Legume / Cereal Avg.	76.9	52.7	31	42.7	37.3	13	43.7	24.7	43
1992 - 2002 Entire Study	76.3	45.9	40	40.0	30.2	25	29.0	17.3	40

Table 7 Summary of analyses of variance showing the sources of effects on NO_3^-- N concentration and mass losses during key periods of the study.

Time Period	**Source of Variation**	**NO_3^--N Concentration**		**NO_3^--N Mass**	
		df	***P*-value**	**df**	***P*-value**
Cereal Cover Crop Years (1992-1999)	Year	7	< 0.0001	7	< 0.0001
	Cover crop	1	< 0.0001	1	< 0.0001
	N fert. rate	2	< 0.0001	2	< 0.0001
	Block	3	0.0919	3	0.0202
	Year * Cover crop	7	0.0114	7	0.0686
	Cover * N fert. rate	2	0.1263	2	0.0042
	Year * N fert. rate	14	0.2919	14	0.0065
Common Vetch / Cereal Mix Cover Crop Years (2000-2002)	Year	2	< 0.0001	2	< 0.0001
	Cover crop	1	< 0.0001	1	0.0010
	N fert. rate	2	< 0.0001	2	< 0.0001
	Block	3	0.4814	3	0.0317
	Year * Cover crop	2	< 0.0001	2	0.5786
	Cover * N fert. rate	2	0.6313	2	0.2630
	Year * N fert. rate	4	0.0182	4	0.0005
Entire Study Period (1992-2002)	Year	10	< 0.0001	10	< 0.0001
	Cover crop	1	< 0.0001	1	< 0.0001
	N fert. rate	2	< 0.0001	2	< 0.0001
	Block	3	0.2457	3	0.0055
	Year * Cover crop	10	< 0.0001	10	0.1600
	Cover * N fert. rate	2	0.1071	2	0.0027
	Year * N fert. rate	20	0.0584	20	< 0.0001

Figures

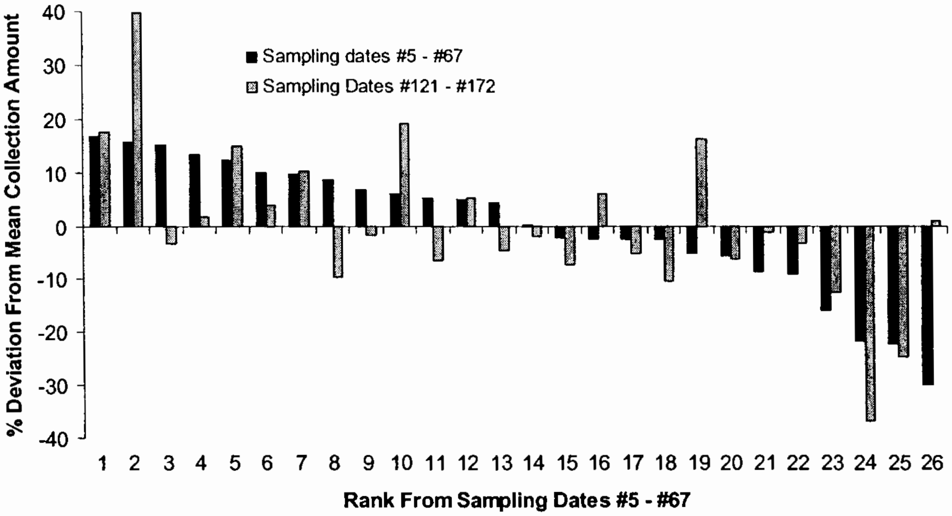

Figure 1 PCAPS collection efficiency compared to the mean. PCAPS were expected to consistently sample volumes greater or less than the mean amount.

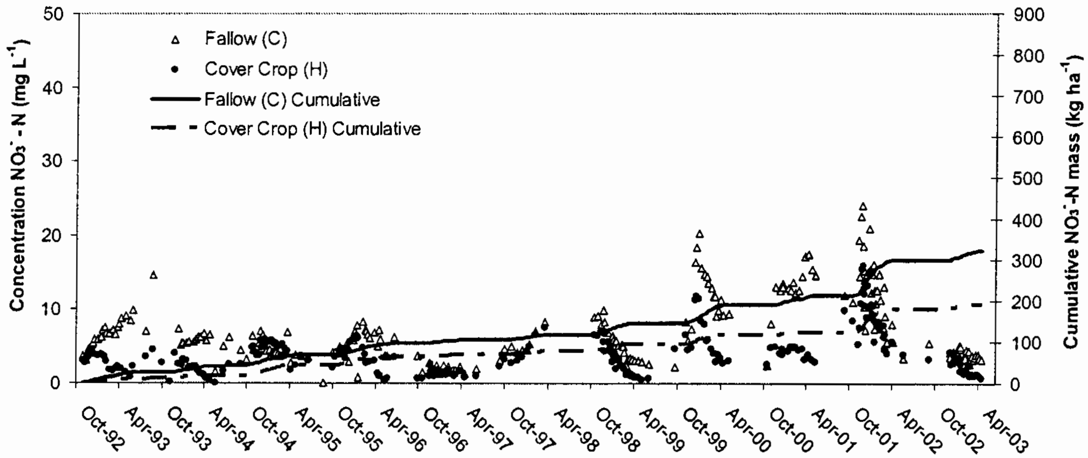

Figure 2 Flow-weighted NO_3^--N concentrations and cumulative mass leaching with time for N0 plots.

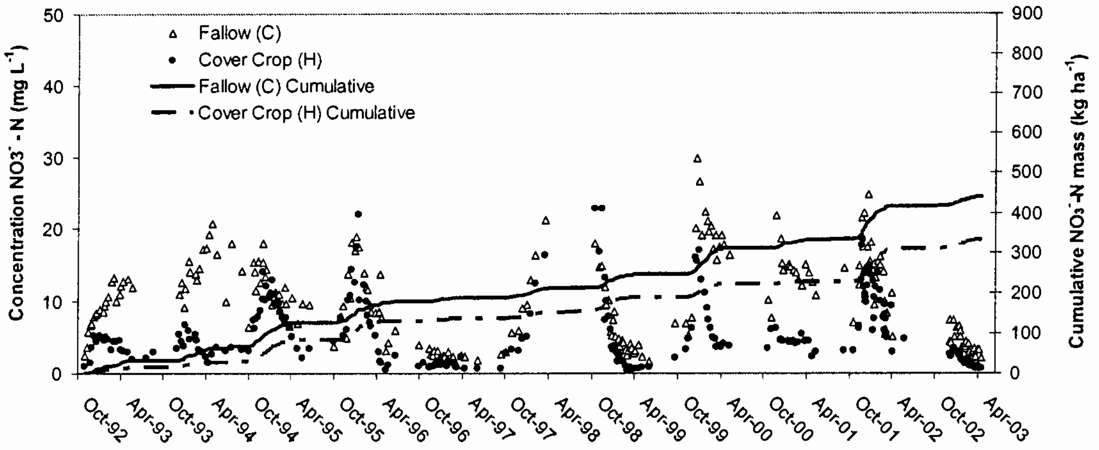

Figure 3 Flow-weighted NO_3^--N concentrations and cumulative mass leaching with time for N1 plots.

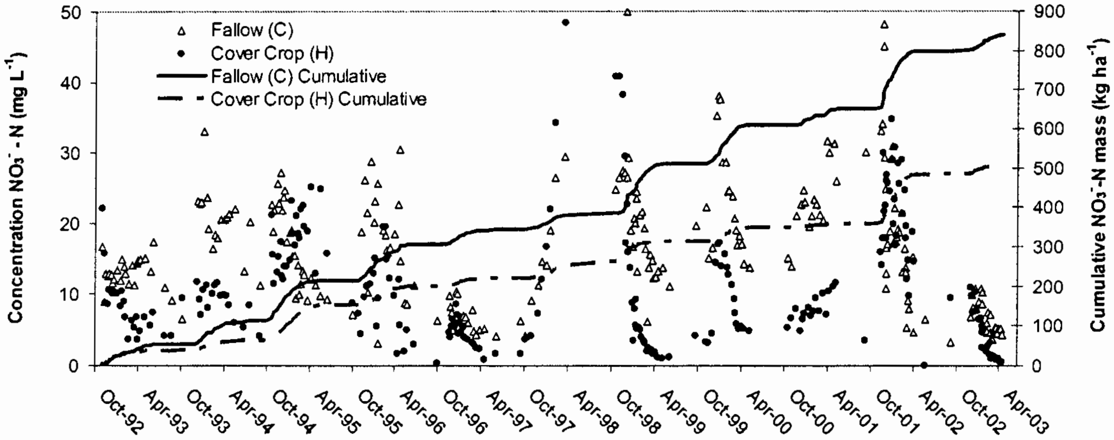

Figure 4 Flow-weighted NO_3^--N concentrations and cumulative mass leaching with time for N2 plots.

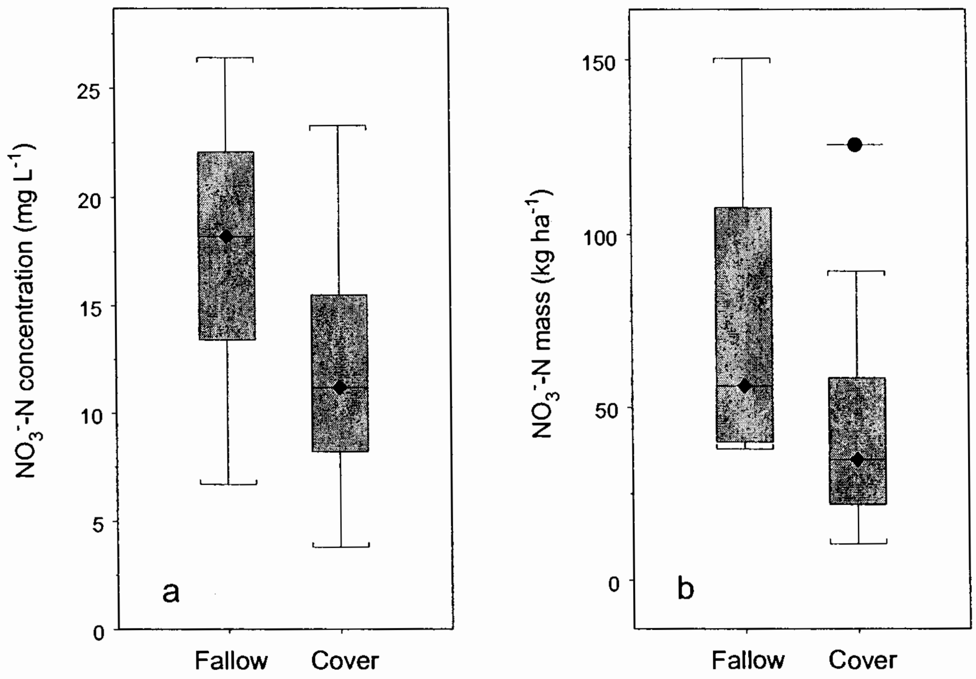

Figure 5 Range of flow-weighted average NO_3^-- N concentration (a) and mass losses measured under N2 plots throughout the entire 11 year study period, (b). Box and whisker plot shows a box with borders at the 25 and 75% quartiles and the statistical median in the center. The whiskers extend to the farthest points that are not outliers (i.e., that are within 3/2 times the interquartile range). A dot is shown for every point more than 3/2 times the interquartile range.

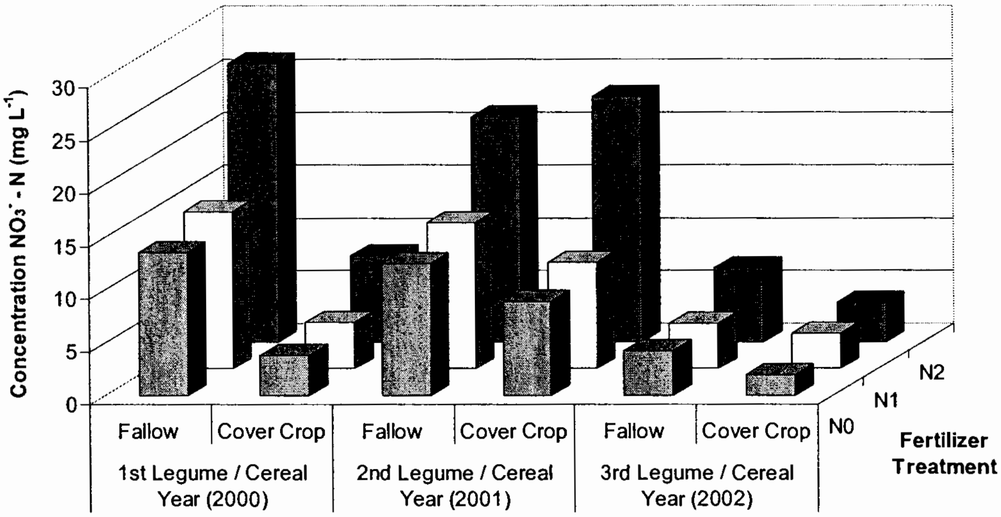

Figure 6 Flow-weighted average NO$_3^-$-N concentrations during three season using common vetch / triticale mix cover crops.

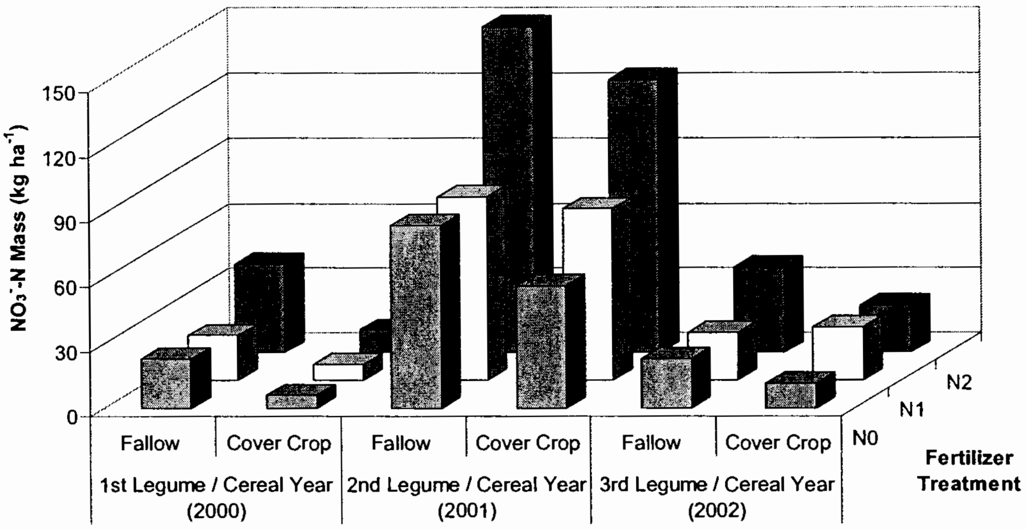

Figure 7 Average NO_3^--N mass losses during three season using common vetch / triticale mix cover crops.