AN ABSTRACT OF THE THESIS OF

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Richard P. Dick

Winter cover crops hold potential to reduce NO_3-N leaching to groundwater by taking up excess soil NO_3-N in the fall before high leaching periods in winter. Four winter cover crops were grown in western Oregon during a 5-yr field experiment. The objectives of the experiment were to determine the effects of fertilizer rates and fall-planted cover crops on NO_3-N leaching, and to investigate the relative effects of cover crop type and sowing date on inorganic soil N concentrations in vegetable cropping systems compared to winter fallow. Data collected at the site from 1992-1997 also were used to develop a statistical model for predicting NO_3-N leaching and to evaluate the computer model Nitrate Leaching and Economical Analysis Package (NLEAP). Cereal cover crops were grown in rotation with summer crops, broccoli (*Brassica oleracea.*) and sweet corn (*Zea mays*). Fall-planted triticale significantly reduced NO_3-N concentrations compared to fallow ($P < 0.05$) in 1995 and 1996 at all three fertilizer rates. Total mean NO_3-N (kg ha^{-1}) collected under fallow treatments was 58% higher in 1995-1996 and 56% higher in 1996-1997 than under cover crop treatments at the N2 rate. Higher N fertilizer rates resulted in significantly higher NO_3-N leaching in 1995-1996 and 1996-

1997. Cover crops generally did not change inorganic soil N concentrations from year to year, while cover crop biomass production and N uptake generally declined from 1994 to 1997.

Stepwise multiple linear regression showed that a four independent variable model (log transformed fall soil NO_3-N, leachate volume, summer crop N uptake, and N fertilizer rate) best predicted NO_3-N leaching ($P < 0.001$ and $r^2 = 0.57$). Comparisons between NLEAP and observed field data for mass of NO_3-N (kg ha^{-1}) leached kg ha^{-1}, between the months of September and May from 1992 to 1997, showed NLEAP predictions were better correlated to observed data during high-rainfall years compared to dry or average-rainfall years. The model was found to be sensitive to yield estimates, but crop choice was limiting for vegetable crops and for systems that included a cover crop.

Nitrate Leaching and Model Evaluation under Winter Cover Crops

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Hudson F. Minshew

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes releases of my thesis to any reader upon request.

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I dedicate this thesis in memory of my brother Whitney Leigh Minshew. His passing taught me the value of friendship and love.

NITRATE LEACHING AND MODEL EVALUATION UNDER WINTER COVER CROPS

INTRODUCTION

Agricultural production can have significant impacts on environmental quality. Understanding the underlying principles that govern soil processes will help in reducing nonpoint source pollution and improving the efficiency of farm production. Nitrate-nitrogen (NO_3-N) is of great concern in groundwater pollution because most water systems are N limited and are ecologically disturbed when N concentrations are raised above baseline quantities. Also, NO_3-N can adversely affect human health causing "blue baby" syndrome (methemoglobinemia) in infants. Agriculture is increasingly cited by U.S. regulatory agencies as a major contributor to nonpoint source pollution of water resources. Quantifying field-scale nitrogen dynamics in cropping systems is critical for reducing the amount of NO_3-N that is lost from the root zone on an annual basis. Another reason to improve N uptake efficiency in cropping systems is economics, because costs of N fertilizer production is expected to rise with increased energy costs. Furthermore, conserving N in cropping systems is critical for developing sustainable agricultural production that will meet food demands of the 21st century while preserving ecological systems and improving water quality.

Western Oregon is susceptible to groundwater and surface water pollution when agricultural chemicals are leached through soils during wet winters. Eighty percent of the mean annual precipitation (1036-mm) falls between November and March, a period of groundwater recharge and NO_3-N leaching. Unless a fall crop is planted immediately after harvest of the summer crop, residual soil NO_3-N has a greater potential of leaching below the root zone during winter, making it inaccessible to future crops and posing a threat to groundwater quality.

This research project had two hypotheses: 1) cereal cover crops reduce NO_3-N concentrations in leachate compared to winter fallow at the intermediate and recommended fertilizer rates by capturing excess fall-soil N, and 2) cover crops affect inorganic soil N concentrations by capturing fall-soil N (cereal cover crops) or by adding mineralizable N (leguminous cover crops).

In addition to testing the two hypotheses, I had two research goals: 1) to use data collected at the site between 1992 and 1997 and develop a statistical model for predicting NO_3-N leaching, and 2) to evaluate the computer model Nitrate Leaching and Economical Analysis Package (NLEAP) for its ability to predict NO_3-N leaching from a vegetable/cover crop rotation in a Mediterranean climate, during the five-year period at a recommended fertilizer rate.

Results are presented in this thesis from an ongoing field-plot experiment where four different winter cover crops were compared to a conventional-winter-fallow system, within a vegetable based rotation, at three different fertilizer rates (zero, intermediate and recommended). Two of the cover crops were relay-planted while the summer crop was growing, and the remaining three were fall-planted after harvest of the summer crops.

Leachate samples were collected from lysimeters installed beneath one cereal cover crop treatment and one fallow treatment at three fertilizer rates. The samplers are known as passive capillary wick samplers (PCAPS). These wick samplers were placed laterally from a ditch and rest beneath 1.2 m of undisturbed soil. In addition to NO_3-N leaching, temporal changes in inorganic soil N were examined at various depths from 0 to 20 cm under all five cropping treatments at three fertilizer rates between fall 1995 and summer 1997.

Chapter 1

LITERATURE REVIEW

The Nitrogen Cycle

Nitrogen (N) is an essential biological element, ranked fourth in abundance after O, C, and H in living tissues (Vitousek et al., 1997). Every living organism depends on N for its existence. Nitrogen has a unique global cycle because it has a large biologically unavailable (to most organisms) pool of N_2 gas in the atmosphere, and yet cycles widely among animals, plants, and microorganisms in aquatic and terrestrial ecosystems. Soil is a global source and sink of biologically-fixed N. The N cycle in soil is an important ecosystem component because soil is a medium for plant growth and turnover of decaying material, as well as the biological "filter" of the world's fresh water.

Nitrogen in soil exists in organic and inorganic forms. Organic forms of N include amino acids, which constitute proteins and enzymes in living organisms, and nucleic acids that make up DNA and RNA molecules. Inorganic forms of N include nitrate-N (NO_3-N) and ammonia-N (NH_4-N), which are the forms readily taken up by plants, and N_2 and N_2O, which are found in the gas phase of soil.

Prior to the advent of industrially-fixed N, all of the biologically active pool of N was fixed by a relatively small group of microorganisms or deposited from the atmosphere after being reduced by lightening. Biological N gains in the soil occur when microorganisms fix N by reducing N_2 to produce NH_4 and organic N. Nitrogen losses from the soil can be from erosion, runoff, leaching, volatilization, denitrification, and removal of plant residue. Erosion carries away sediment containing organic and inorganic N during runoff events. Leaching is a downward movement of soil nutrients, such as NO_3-N, below the rootzone and into ground and surface water. Nitrogen can undergo various transformations in soils. It can be lost in the gaseous forms via NH_3 volatilization and through microbial denitrification of NO_3 to N_2 and N_2O. Other N transformations include immobilization, the uptake of NO_3 or NH_4 into plant or microbial tissue; ammonification, the oxidation of organic N compounds to NH_4; and nitrification, the oxidation of NH_4 to NO_3. Nitrogen mineralization is another term used for the conversion of organic N compounds to mineral N.

Primary production is often N limited in many terrestrial and aquatic ecosystems (Galloway et al., 1994). Humans have upset the natural N cycle of the globe by increasing the quantity and use of industrially-fixed N steadily since World War II (Stevenson, 1982). Industrial N fixation prior to 1940 was near zero, but since then it has increased exponentially. Before the 1970's, most N fertilizer was applied in developed countries, but an increasing amount is being applied in developing countries (Vitousek et al., 1997). Kates et al. (1990) reported that more than half of all industrially-fixed N ever produced was applied between 1980 to 1990. Some of this N has contaminated lakes, rivers, and groundwater supplies and has decreased biodiversity in terrestrial, aquatic and marine ecosystems (Vitousek et al., 1997). About one-half of U.S. citizens rely on groundwater supplies (Keeney and Follet, 1991). Reliance on groundwater and surface waters undoubtedly will increase with increasing population demands. High concentrations of NO_3-N in drinking water pose health risks to livestock and humans and can cause "blue baby" syndrome, methemoglobinemia, in infants under three months of age (Sharkoff and Lober, 1995).

Nitrate Leaching Under Cover Crops

The use of cover crops is an ancient technique, with written accounts of the practice dating back 3,000 years to the Chou dynasty (Harlan, 1899). Cover crops are used to protect soil from erosion, reduce weeds, and improve the nutrient cycling of cropping systems (Kuo et al., 1997; Ranells and Wagger, 1997; Stivers-Young, 1998). Prior to 1950, investigations of nutrient leaching in combination with cover crops were mostly focused on N fixation and soil fertility (Joffe, 1933; Volk and Bell, 1945). More recently, the motivation for studying these systems has shifted to include environmental and economical issues with increasing public concern about nonpoint source pollution from agricultural sources and increased cost of fertilizer N (Macdonald et al., 1989; Martinez and Guiraud, 1990; Meisinger et al., 1991; McCracken et al., 1994; Owens et al., 1995; Brandi-Dohrn et al., 1997).

Excess N in fresh and marine waters can negatively affect human health and biodiversity. With increased concern for protecting water resources, biological diversity, and human health, considerable efforts are being made to quantify N losses from soil leaching (mainly NO_3-N) and denitrification (Rosenani et al., 1994).

Management practices greatly affect the amount of residual soil N available for leaching. In Minnesota, Yadav (1997) estimated that 15% of applied N is deposited in groundwater every year and found that reduced tillage practices also were significant in reducing the amount of NO_3-N leached. The amount of NO_3-N found in leachate is also a function of soil type, rainfall or irrigation, plant uptake, and the interrelationships between solubilities of different forms of nutrients (Volk and Bell, 1945). High NO_3-N concentrations in groundwater leachate have been reported with increased rates of fertilizer N applications (Owens, 1990; Errebhi et al., 1998). Research has shown that soils receiving excess organic amendments are prone to leaching NO_3-N (Trindade et al., 1997) as a result of increasing mineralizable N pools. Many farmers may inadvertently over-apply fertilizer N to crops in the form of organic amendments as well as chemical fertilizers which can contribute to N loading of surface and groundwater. Errebhi et al. (1998) used N budgets and reported that potato growers in Minnesota can reduce NO_3-N leaching and improve yields by reducing quantities of N applied at planting.

Researchers also are investigating alternative cropping practices such as winter cover cropping to reduce NO_3-N leaching (Martinez and Guiraud, 1990; Meisinger et al., 1991; McCracken et al., 1994; Brandi-Dohrn et al., 1997). Ditsch et al. (1993) reported the ability of winter cover crops to capture excess N that might otherwise leach below the root zone is between 12 and 91 kg N ha^{-1}. In a double-cropping forage system in Portugal, mixtures of winter cover crops containing oats, barley, and Italian ryegrass grown from October to May in 1994 and 1995 took up between 80 and 100 kg N ha^{-1} y^{-1} (Trindade et al., 1997). In France, Italian ryegrass grown as a winter cover crop decreased NO_3-N leaching in a winter-wheat-corn rotation by about 60% compared to winter fallow, with indirect evidence that the leached NO_3-N came from mineralization and not from residual fertilizer N (Martinez and Guiraud, 1990). In some cases, volunteer cereals and weeds often perform as well as sown cover crops, which suggests they may be more cost effective (Allison et al., 1998a). Allison et al. (1998a) showed that cover crops generally produce more biomass and take up more N if they are sown by early August rather than September.

The amount of inorganic N present in fall may be a strong indicator of the amount of NO_3-N that may be leached during the winter. Winter cover crops have been shown to reduce the amount of inorganic soil N during fall (Allison et al., 1998a) while having little effect on inorganic soil N during the summer growing season (Allison et al., 1998b). In northeastern U.S., *Brassica* and *Phacelia* planted in late August have been shown to take up more than 100 kg ha^{-1} soil N before winter kill in December (Stivers-Young, 1998). Ditsch et al. (1993) showed winter rye recovered on average 65.5 kg ha^{-1} of fertilizer-derived N over a two year period on a well drained silt loam, in the Ridge Valley of Virginia.

In addition to capturing excess N, cover crops are planted to recycle N in the soil-crop system. Synchronization of cover crop N mineralization with the growth of the following summer crops is ideal for maximizing use of soil derived N. Macdonald et al. (1989) found in winter wheat systems that most of the leaching N loss was a result of N mineralization rather than from residual fertilizer applied in spring. Leguminous cover crops fix N and may increase inorganic soil N compared to cereal cover crops but may not be as effective at capturing soil N as cereal cover crops (Ranells and Wagger, 1997). Little information is available on the subsequent release of N from cover crop residues after their destruction (Knott, 1996). Knowledge of the growth potential and rates of degradation of incorporated cover crops is required for the selection of an appropriate cover crop for a particular climate (Kuo et al., 1997).

Soil Solution Samplers

Soil solution monitoring methods can be used in the field to study the extent and nature of chemical leaching in production agriculture. Several methods are available for sampling the vadose zone. Litaor (1988) concluded in his study that "there is no single device that will perfectly sample soil solution in all conditions encountered in the fields". These sampling methods include soil cores, soil suction cup samplers, pan lysimeters, and wick samplers. However, the reliability of soil solution samplers is often questionable due to the spatial variability in field soils (Moutonnet and Fardeau, 1997). Other limitations of soil solution samplers may include cost and installation.

Soil cores sampling and analysis is reliable, but lacks the ability to continuously monitor NO_3 concentrations, and core samples cannot be taken from the same location (Boll et al., 1992). Porous suction cup sampling is a common and inexpensive method. Limitations of this method are that the volume of soil sampled is unknown and they cannot sample continuous flow (Barbee and Brown, 1986). Zero-tension pan lysimeters are capable of sampling a large cross sectional area, unlike suction cup samplers and soil cores. However, they lack the ability to sample under unsaturated conditions (Boll et al., 1992) and have a long stabilization period (Brandi-Dohrn et al., 1996). The objectives of a study also may influence the researcher in choosing a particular sampling method. If the objective is to gain an understanding of a specific soil layer and its internal processes, then tension samplers may be the best choice; however, if the objective is to investigate the loss of solutes from a soil layer, then zero-tension soil solution samplers may be more appropriate (Magid and Christensen, 1993). A soil solution sampler designed to study internal mechanisms of soil layers as well as nutrient losses through a known cross sectional area in a soil would be ideal.

Passive capillary samplers are a promising alternative to zero-tension pan lysimeters and suction cup samplers due to their ability to collect both saturated and unsaturated flow (Brandi-Dohrn et al., 1996). The samplers are constructed with a hanging fiberglass wick that is in direct contact with the soil and has a negative matric potential. The suction at the top of the wick sampler is designed to match the matric potential of the soil, which can be predicted using the equation developed by Knutson and Selker (1994):

$$\mathrm{h} = (1/\alpha)\ln\Big[\exp(\alpha z)\Big(q(A_s/A_wK_s + 1)\Big) - \Big(q(A_s/A_wK_s)\Big)\Big]$$

where h is the negative matric potential at the top of the wick, α is the exponential constant for the wick after Gardner's unsaturated hydraulic conductivity model, z the length of the wick (negative), A_s the sampling area, A_w the cross-sectional area of the wick, and K_s the saturated hydraulic conductivity of the wick (Brandi-Dohrn et al., 1996). Knutson and Selker (1996) also showed that wick samplers have negligible effects on travel time and dispersion of solutes. Well-designed soil solution samplers are important for collecting data that can be used to develop and validate models used to describe processes in the vadose zone.

Computer Models for Estimating N Processes

Useful computer models have been developed and tested for predicting potential groundwater contamination from agricultural sources and for simulating C and N dynamics. Simulation modeling and advances in mathematical modeling of nonpoint source pollution have increased opportunities for developing farming systems that provide greater environmental protection. Experimental data can be used to understand N mass flow, rates of N microbial transformations, and plant N uptake when applied to a mechanistic simulation model (Clay et al., 1985). Vegetable cropping systems are particularly challenging to model because they absorb large amounts of fertilizer N (150 to 300 kg N ha^{-1}) and have short growing seasons (Cavero et al., 1998) which may explain the lack of information on whole soil-crop modeling in vegetable cropping systems. No model has been shown to adequately describe all soil-crop processes (Clay et al., 1985; Jemison et al., 1994).

A class of models exists called CERES models that can be used to model entire soil-crop systems (Quemada and Cabrera, 1995). These models share a common submodel called CERES-N, where fixed percentages of crop residue biomass are assigned to three pools: carbohydrates, cellulose, and lignin. Some models allow the user to vary the size of these residue pools.

Addiscott (1977) developed a computer model for leaching based on layer calculations for an indefinite number of layers and found agreement between predicted and observed soil NO_3-N concentrations. The NCSWAP (N and C cycles in the soil-water-plant system) model was used to develop further understanding of characteristics of the soil-plant system (Clay et al., 1985). The CENTURY model developed by Parton et al. (1988) can simulate impacts of climate and farm practices on C, N, P, and S dynamics in soil-crop systems, but has not been used to simulate multicrop rotation systems (Yiridoe et al., 1997).

Hutson and Wagnet (1995) developed the Leaching Estimation And Chemistry Model (LEACHM) that simulates the vertical movement of water and chemicals in the unsaturated zone. LEACHM contains submodels that simulate the movement of nitrates (LEACHN), pesticides (LEACHP) and salinity (LEACHC) based on numerical solutions. In leaching simulations, LEACHM applies the Richard's equation to water regimes:

$$\partial\theta/\partial t = C_w\, \partial h/\partial t = \partial\theta/\partial z \left[K(\theta)\, \partial H/\partial z \right] - U(z,t)$$

where θ is the volumetric water content, h is the pressure potential of the soil, H is the sum of h and soil water potential (hydraulic head), C_w is the differential water capacity ($\partial\theta/\partial h$, mm^{-1}), z is depth (mm), t is time (dc), and **U** is water taken up by plants (d^{-1}).

The submodel LEACHN uses N transformation equations for mineralization, nitrification, and denitrification that require C/N ratios and biomass estimations for organic pools. The model LEACHN does not predict N uptake or crop growth, but uses annual input data for N uptake. Smith et al. (1998) successfully used the model LEACHN to predict NO_3-N leaching in clay soils. Evaluation of LEACHN showed that the predictive capability might be improved if it provided a more complex routine for uptake of N by corn (Jemison et al., 1994).

The Nitrate Leaching and Economic Analysis Package (NLEAP) computer model was developed to help farmers, extension agents, and government agencies predict site-specific NO_3-N leaching (Shaffer et al., 1991). Both NLEAP and LEACHN have been used for field and regional scale applications. Khakural and Robert (1993) used LEACHN and NLEAP as a screening tool to develop regional maps for NO_3-N leaching potentials (NLP) and found both models to be good predictors of total seasonal NO_3-N leaching. Wylie et al. (1995) and Shaffer et al. (1996) used NLEAP in combination with geographical information systems to identify NO_3-N "hot-spots" in alluvial aquifers in eastern Colorado.

The model NLEAP takes soil (two-layers), climate, and crop management data and projects N budgets. The model has the ability to perform a simplified screening analysis for determining an annual leaching risk potential and NO_3-N available for leaching (NAL). More detailed analyses can be done using a monthly or an event-by-event analysis, that require more detailed data input. The NAL is calculated by the following formula:

$$\mathrm{NAL} = N_f + N_p + N_{rsd} + N_n - N_{plt} - N_{det} - N_{oth}$$

where N_f is the amount of fertilizer added to the soil (kg/[ha time step]), N_p is the quantity of N added by precipitation, N_{rsd} is the amount residual soil NO_3-N in the two soil layers (0-0.3 m and 0.3-1.5 m), N_n is the amount of NO_3-N (kg/[ha time step]) added to the system through nitrification of NH_4-N (kg/[ha time step]), N_{plt} is the amount of NO_3-N taken up by the crop (kg/[ha time step]), N_{det} is the amount of NO_3-N lost via denitrification (kg/[ha time step]. Shaffer et al. (1991) provide details of N transformation equations and water balance equations used in NLEAP monthly analysis.

Denitrification in NLEAP is calculated by the equation

$$N_{det} = k_{det}\,(\mathrm{N1T1})(\mathrm{TFAC})[\mathrm{NWET} + \mathrm{WFAC}(\mathrm{ITIME} - \mathrm{NWET})]$$

where k_{det} is a rate constant for denitrification, N1T1 is the NO_3 content for the top 30 cm of soil, TFAC is the soil temperature stress factor, and NWET is the number of wet days in a time step, ITIME is the length of the time step, and WFAC is the soil water stress factor (range 0.0-1.0), based on equations for aerobic and anaerobic processes (Linn and

Doran, 1984) that take into account water-filled pore space (WFP). For aerobic processes the equation is

$$\mathrm{WFAC} = 0.0075(\mathrm{WFP})$$

when $\mathrm{WFP} \leq 20$. The equation takes the form,

$$\mathrm{WFAC} = -\ 0.253 + 0.0203(\mathrm{WFP})$$

if $20 \leq \mathrm{WFP} < 59$, and

$$\mathrm{WFAC} = 41.1\{\mathrm{EXP}[(-0.0625)(\mathrm{WFP})]\}$$

when $\mathrm{WFP} \geq 59$, and for denitrification under anaerobic conditions,

$$\mathrm{WFAC} = 0.000304\{\mathrm{EXP}[(0.0815)(\mathrm{WFP})]\}.$$

The TFAC is used in other N transformations and is computed using an Arrenhius equation:

$$\mathrm{TFAC} = 1.68\mathrm{E}9\ (\mathrm{EXP}\{-13.0/[1.99\text{-}3)(\mathrm{TMOD} + 273]\})$$

where TMOD is equal to (T-32)/1.8 when $T \leq 86$ °F, and TMOD is equal to 60 – (T-32)1.8 when $T > 86$ °F. T is the soil temperature (°F).

Contributions of N, from mineralization of organic matter and crop residues, are calculated in NLEAP using several equations. The first equation calculates NH_4-N nitrification with,

$$\mathrm{N_n} = k_n(\mathrm{TFAC})(\mathrm{WFAC})(\mathrm{ITIME})$$

where k_n is a zero-order rate coefficient for nitrification (kg ha $^{-1}$ d^{-1}). Calculated mineralization from soil organic matter is done using,

$$\mathrm{NHM} = k_{omr}(\mathrm{SOM})(\mathrm{TFAC})(\mathrm{WFAC})(\mathrm{ITIME})$$

where NHM is amount of NH_4-N mineralized (kg ha $^{-1}$), k_{omr} is the rate constant, and SOM is the soil organic matter content (kg ha $^{-1}$). Other crop residues and organic matter are calculated with the equation

$$\mathrm{CRES} = P_c(\mathrm{RES})$$

where RES is the residues (kg ha $^{-1}$), P_c is the fraction of residue that is carbon, while CRES is the C content (kg ha $^{-1}$). The amount of residue C metabolized (CRESM) is calculated with

$$\mathrm{CRESM} = k_{resr}(\mathrm{CRES})(\mathrm{TFAC})(\mathrm{WFAC})(\mathrm{ITIME})$$

where k_{resr} is the first order rate coefficient (1 /d). After each time step, NLEAP updates the residue C content using

$$\mathrm{CRES} = \mathrm{CRES} - \mathrm{CRESM}$$

where CRESM must be lower than CRES. Net mineralization and immobilization are determined by

$$\mathrm{NRESM} = (\mathrm{CRESR})(1/\mathrm{CN} - 0.042)$$

where NRESM is the net residue N mineralized (kg ha $^{-1}$ time step^{-1}). The current C:N ratio of the residues is CN. After each time step, the N content of decaying residues is updated using,

$$\mathrm{NRES} = \mathrm{NRES} - \mathrm{NRESM},$$

With the constraint of NRESM $\leq$ NRES. Also, the new value for CN is calculated for the next time step with

$$\mathrm{CN} = \mathrm{CRES}/\mathrm{NRES}.$$

The mineralization equations have the assumptions that: 1) crop residues contain an average percent of C; 2) net mineralization and immobilization is zero at C:N ratio of 24:1; and 3) soil microbes have a C:N ratio of 6:1.

Statistical Models for Predicting Soil Parameters

Multiple linear regression (MLR) can be used to predict an array of soil parameters and to show the relative importance of different soil properties on the parameter of interest. Bauder et al. (1993) used MLR to explain the variability in county well sample NO_3-N concentrations using 67 independent variables, and Lucey and Goolsby (1993) used MLR to predict NO_3-N concentrations in a river from climatic and stream-flow data. Laird et al. (1992) used MLR to predict adsorption constants in soil. Dick and Tabatabai (1987) used MLR to study soil factors affecting hydrolysis of polyphasphates, and Afif et al. (1993) used MLR to predict P availability in calcareous soils. Multiple linear regression also was used to study temporal structural stability of soil within crop treatments (Perfect et al., 1990) and to predict soil quality based on electrical conductivity measurements (McBride et al., 1990).

In MLR analysis, the researcher usually is interested in the significance of relationships between independent and the dependent variables. MLR analysis may help to understand the relative importance of the effects of different independent variables and the extent that a given independent variable will affect the dependent variable. When using MLR, the researcher must be aware of not only that basic assumptions are met, such as normality and equal variance, but also of the effects of multicolinearity of independent variables. As a result of the correlation, the regression coefficient of any independent variable depends on which other independent variables are in the model (Neter et al., 1983).

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Chapter 2

NITRATE LEACHING AND INORGANIC SOIL N UNDER WINTER COVER CROPS IN WESTERN OREGON

Abstract

Winter cover crops hold potential to reduce nitrate-nitrogen (NO_3-N) leaching to groundwater by taking up excess soil NO_3-N in fall before high leaching periods in winter. Four winter cover crop systems were investigated in the Willamette Valley of western Oregon from 1995 to 1997. The experiment was designed to examine the potential of fall-planted cereal cover crops to reduce NO_3-N leaching in vegetable systems. In addition, the experiment included a comparison of fall-planted and relay-planted winter cover crops with winter fallow in affecting winter inorganic soil N. The experiment was a randomized complete block split-plot design. Whole plot treatments were cereal cover crops, grown in rotation with summer crops, broccoli and sweet corn. Broccoli and sweet corn were grown in alternate years. Split-plot treatments were three rates of fertilizer N: recommended (N2), medium (N1), and zero (N0) N. Cover crops generally did not change inorganic soil N concentrations from year to year. Cover crop biomass production and N uptake generally declined from 1994 to 1997. Fall-planted triticale significantly reduced NO_3-N leaching compared to fallow ($P < 0.05$) in 1995 and 1996 at all three fertilizer rates. Total mean NO_3-N collected under fallow treatments was 58% higher in 1995-1996 and 56% higher in 1996-1997 than under cover crop treatments at the N2 rate. Higher N fertilizer rates resulted in significantly higher NO_3-N leaching in 1995 and 1996.

Introduction

Contamination of groundwater by nitrate-nitrogen (NO_3-N) is a public health and environmental concern, as well as an economic concern for production agriculture (Keeney and Follet, 1991; Khakural and Robert, 1993; Jemison and Fox, 1994). The contamination of drinking water by NO_3-N may cause adverse human effects such as methemoglobinemia or "blue baby" syndrome (Keeney and Nelson, 1982). A maximum of 10 mg L^{-1} NO_3-N or 45 mg L^{-1} NO_3^- for drinking water has been set by the U.S. Environmental Protection Agency (USEPA).

The National Water-Quality Assessment (NAWQA) program of USGS surveyed 70 shallow domestic wells in the Willamette Valley, Oregon, in 1993 and found 9% were above the USEPA drinking water standard for NO_3-N (U.S.G.S., 1998). In this region more than 500,000 people rely on groundwater for domestic use (U.S.G.S., 1997). Leaching potential of agricultural chemicals in western Oregon soils is high during winter because of high precipitation and mild temperatures. About 70-80% of the annual precipitation (1036 mm) falls between November and March, and less than 5% falls in July and August (U.S.G.S., 1998).

Fall-planted cover crops are able to recycle soil N after summer crops are harvested (Kauffman, 1994; McCracken et al., 1994; Burket et al., 1997). Brandi-Dohrn et al. (1997) found that cereal rye reduced the NO_3-N concentration in leachate when fertilizer was applied at a recommended rate for the three winters between 1992 and 1995. Cover crops also provide nutrients as green manure and decrease soil erosion from bare soil (Quemada and Cabrera, 1995).

In 1992, the research site was equipped with passive capillary wick samplers to quantify leachate and agricultural chemicals under winter fallow treatments compared to cereal rye at three fertilizer rates. Leachate volume, cover crop N uptake, cover crop biomass yield, soil inorganic N, and nitrate concentrations in water samples were determined.

The objectives of this study were to: 1) determine if fall planted cereal cover crops could reduce nitrate leaching by capturing excess soil NO_3-N in fall at different fertilizer rates and 2) determine the relative effects of fall-planted and relay-planted winter cover crops on inorganic soil N.

Materials and Methods

Experimental Site

The 0.9-ha site is at the Oregon State University, North Willamette Research and Extension Center in Aurora, OR. The site was managed as a continuous wheat-fallow rotation from 1982 until 1989, prior to the initiation of a cover crop and vegetable rotation study. The soil is of glaciolacustrine genesis and has been classified as a Woodburn Variant loam (fine-loamy, mixed, mesic Aquultic Argixeroll) with an inclusion of Willamette Variant loam (fine-loamy, mixed, mesic Pachic Ultic Argixeroll) that bisects the site from NE to SW. The terrain has slopes from 0 to 3%. Average annual rainfall is 1036 mm, 75% of which falls from October through March, and the mean annual temperature is about 11°C (U.S.G.S., 1998). Table 2.1 shows mean precipitation for the time period of this study. The experimental design is a randomized complete block split-plot, with vegetable and cover crop, or vegetable crops and fallow (control) as the whole-plot treatments (162 m^2). Split-plot treatments (54 m^2) are three rates of N fertilizer: zero (N0), medium (N1), and recommended (N2).

Table 2.1. Crop-year rainfall during study.

Year	Rainfall September-September	 November-April
	mm	
1994	1320	960
1995	1590	1240
1996	1760	1350

Vegetable and Cover Crops

Irrigated summer crops were sweet corn (*Zea mays* L. cv. Jubilee), grown during even-numbered years, and broccoli (*Brassica oleracea* L. var italica cv. Gem), grown during odd-numbered years. Summer crops were managed as described by Burket et al. (1997). Split-plots of sweet corn were fertilized with urea-N at 0 (N0), 56 (N1), or 224 (N2) kg ha^{-1}. Broccoli split-plots were fertilized at 0 (N0), 140 (N1), or 280 (N2) kg ha^{-1}. Weeds were managed manually and with herbicides. Herbicides and rates of application were as follows: Atrazine at 2.24 kg ha^{-1} or alachlor at 3.36 kg ha^{-1} for sweet corn, and trifluran at 0.84 kg ha^{-1} and lorsban at 1.5 kg ha^{-1} for broccoli, but only on fallow and fall-planted cover crop plots. Harvest samples of corn and broccoli were taken from 4.5 m sections of two rows within each split-plot. Total plant biomass and total plant N were determined for each crop from a subsample (0.5 kg). Post-harvest residue was incorporated by plowing and disking before planting the cover crop.

Winter cover crop treatments were winter fallow as a control, 'Kenland' red clover (*Trifolium pratense L.*), 'Celia' triticale (*Triticosecale X*), triticale /winter pea

(*Pisum sativum L.*) mix. In 1995 and 1996, 'Celia' triticale replaced 'Wheeler' cereal rye as a cover crop in all three treatments containing rye. Cover crops were either relay-planted while the summer crop was growing or fall-planted after harvest of the summer crop. Cropping sequences are given in Table 2.2.

Table 2.2. Cropping rotation sequence at North Willamette Research and Extension Center. This rotation was repeated at all three fertilizer rates.

		Fallow	Fall-Planted Cover Crop		Relay-Planted Cover Crop	
Year	Season		Cereal	Mix	Legume	Cereal
1992	Spring	Wheat	Corn	Corn	Corn	Corn
	Fall	Fallow	Rye	Pea/Rye	Red Clover	Rye
1993	Spring	Broccoli	Broccoli	Broccoli	Broccoli	Broccoli
	Fall	Fallow	Rye	Pea/Rye	Red Clover	Rye
1994	Spring	Corn	Corn	Corn	Corn	Corn
	Fall	Fallow	Rye	Pea/Rye	Red Clover	Rye
1995	Spring	Broccoli	Broccoli	Broccoli	Broccoli	Broccoli
	Fall	Fallow	Triticale	Pea/Triticale	Red Clover	Triticale
1996	Spring	Corn	Corn	Corn	Corn	Corn
	Fall	Fallow	Triticale	Pea/Triticale	Red Clover	Triticale
1997	Spring	Broccoli	Broccoli	Broccoli	Broccoli	Broccoli
	Fall	Fallow	Triticale	Pea/Triticale	Red Clover	Triticale

Seeding rates were 25 kg ha $^{-1}$ for red clover, 90 kg ha^{-1} for triticale, and 110 kg ha^{-1} for pea plus 40 kg ha^{-1} for triticale as a mix. In spring, above-ground biomass samples were taken from 1.0 m^2 quadrants from each subplot. A subsample was saved from each sample (0.5 kg) to determine total N and dry weight biomass. In early April, cover crops were incorporated with a moldboard plow and disked to a depth of 15 cm.

Cover crop and vegetable subsamples were dried in a forced air oven at 60°C. Samples were ground with a Cyclotec mill (1.0 mm screen). All samples were analyzed for total N by using Kjeldahl digestion followed by steam distillation (Bremner and Mulvaney, 1982).

Soil Solution Samplers

During the fall of 1992, 32 lysimeters, known as passive capillary wick samplers, were installed 1.2 m below an undisturbed soil profile for the fallow and fall-planted cereal rye crop treatments. The wick samplers were installed from a trench by digging laterally into the soil 1.2 m below the soil surface. The samplers were built and installed according to (Brandi-Dohrn et al., 1996). In brief, the samplers were inserted into the lateral hole, and the opening was sealed with bentonite clay. Split-plots N1 and N2 each had one lysimeter and N0 split-plots had two lysimeters. Leachate samples were taken with a vacuum pump from high-density polyethylene tubing that led from the lysimeters to the soil surface.

Leachate

Water flux and NO_3-N concentrations were measured from 1992 to the present. Water samples were collected according to Brandi-Dohrn, et al. (1996) after 30 to 50 mm of cumulative rainfall and stored overnight at 4°C. Water samples were diluted with deonized water (1:1) and frozen until analysis. Concentrations of NO_3-N were determined on a Dionex 2000i ion chromatograph with a Dionex AS4A-SC separator column and an AG4A-SC guard column (Dionex Corp. Sunnyvale, CA). The experiment became unbalanced when six of the 32 wick samplers in the same block became inaccessible during most of the sampling periods from 1994 through 1997 because of runoff from a nearby nursery. Accurate flux values could not be estimated for the inacessible wick samplers because of the long duration that the samplers remained under water. Two of the samplers were from an N1 split-plot fallow treatment, and the other four samplers were from a cover crop plot, eliminating all three split plots. Leachate data collected at the site from 1992 to 1994 was presented by Brandi-Dohrn et al. (1997).

Soil

Soil was sampled for each split plot by taking 10 to 15 cores (2.5 cm dia.) which were homogenized and stored at 4°C. Soil was sampled from 0 to 20 cm monthly in the fall and quarterly the rest of the year. Deep sampling was done in September at 0-20, 20-40, 40-80, and 80-120 cm, and in February from 0-20, 20-40, and 40-80 cm. In February, soils were too wet to sample below 80 cm.

The soil samples were air-dried for 24 h, sieved through a 2-mm screen, and stored at room temperature. Ten grams of each sample were shaken for 1 h in 75 mL of 2 *M* KCl and filtered through a No. 42 Whatman filter paper. The soil extracts were transferred to 20 mL plastic scintillation vials and stored at 0°C. Soil extracts were analyzed for extractable NO_3-N and ammonium (NH_4-N) using a continuous flow analyzer (Lachat, Milwakee, WI). General soil characteristics are given as means across all treatments from data presented by Bandick (1997) and are presented in Table 2.3.

Table 2.3. General soil characteristics at North Willamette Research and Extension Center vegetable rotation site (0-20 cm depth) taken in Fall 1994.

pH	Bulk Density	Organic Matter	Total exchange capacity	Total C	Total N
				g kg^{-1} soil	
5.8	1.24 (g cm^{-3})	3.8 (%)	15.3 ($cmol_c$ kg^{-1})	16.8	1.05

Percent organic matter was determined by combustion. Cation exchange capacity was determined using ammonium acetate extraction and spectrophotometric determination of NH_4^+, and total organic C was determined by dry combustion with a Dohrman DC-80 total C analyzer (Santa Clara, CA). Total N was deremined using the Kjeldahl method (Bremner and Mulavaney, 1982). and pH with elcectrode in a 1:1 soil:water solution.

Statistical Analysis

Analysis of variance was performed using PROC GLM of SAS ver. 6.12 (SAS, 1996). All data were log transformed to account for unequal variance. The least significant difference procedure was used for pairwise comparisons of treatment means. All significant differences, unless otherwise noted, are at $P \leq 0.05$.

Results

Nitrate Leaching under Fallow and Fall-planted Triticale Treatments: 1995-1997

We defined the winter season as the period when daily flux of NO_3-N and daily percolation was >10% of the 3-yr average from 1994 to 1997. In winter of 1995-1996 (W95-96), the leaching period was from 4 November 1995 to 27 May 1996; in winter 1996-1997 (W96-97), the period was from 24 October 1996 to 2 April 1997. These periods accounted for 77% of total rainfall (1595 mm) in W95-96 and 77% of the total (1755 mm) in W96-97.

Mean NO_3-N concentrations in leachate were significantly lower under triticale ($P < 0.01$) than NO_3-N concentrations found under winter-fallow at all three fertilizer rates. In 1995, mean NO_3-N concentrations (mg L^{-1}) collected under triticale and fallow treatments, respectively, were 3.6 and 5.9 at N0 rate, 7.8 and 11.4 at N1 rate, and 11.0 and 18.5 at N2 rate. At the N1 rate in W95-96, NO_3-N concentrations were kept below the EPA standard under triticale during the peak of the winter season, but concentrations remained higher than 10 mg N L^{-1} at the N2 rate (Fig. 2.1). Mean-annual treatment differences between triticale and fallow in W96-97 were not as great as in W95-96, and were 1.3 and 2.0 at N0 rate, 1.3 and 2.4 at N1 rate, and 4.4 and 6.1 at N2 rate. Leachate NO_3-N concentrations during W96-97 remained below the EPA standard at all three fertilizer rates, and triticale significantly reduced NO_3-N concentrations compared to fallow at the N2 fertilizer rate. Cover crop treatment differences for NO_3-N leaching were greatest in fall and spring. In W95-96, the amount of NO_3-N leachate measured under fallow was on average 53 kg ha^{-1} greater than under triticale at the N2 rate, and in W96-97 the amount was 18 kg ha^{-1} NO_3-N greater under fallow than triticale (Table 2.4).

Increased fertilizer N resulted in significantly higher NO_3-N concentrations in leachate for both triticale and fallow in W95-96. In W96-97, mean NO_3-N concentrations between N1 and N0 rates were not significantly different, but both showed lower NO_3-N leaching than N2 (Table 2.4).

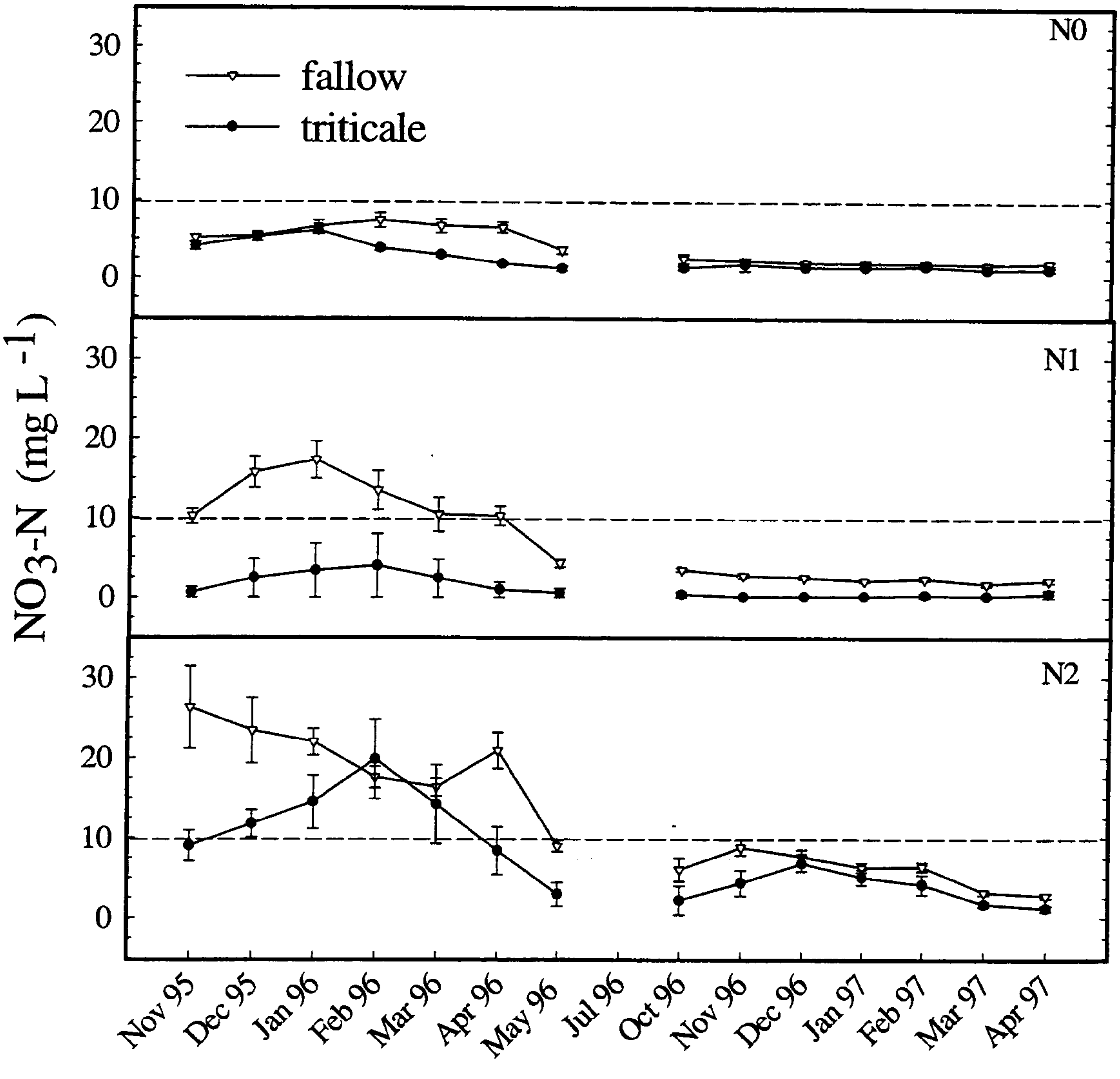

Fig. 2.1. Concentrations of NO_3-N in leachate collected by wick samplers under fallow and triticale treatments at zero (top), intermediate (middle), and recommended (bottom) fertilizer N rates. Error bars = standard error (SE) of the mean. Where error bars are not visible, SE is smaller than the size of the symbol.

Table 2.4. Mass of NO_3-N and leachate volume collected by passive capillary wick samplers under triticale and fallow treatments.

Crop Year	N rate	Cover crop	NO_3-N	Leachate
			— $kg^{-1} ha^{-1} y^{-1}$ —	— cm —
95-96	N0	None	23.0 (4.1)†	38.9 (3.5)†
		Triticale	14.9 (2.6)	40.3 (5.5)
	N1	None	49.9 (16.1)	40.6 (1.3)
		Triticale	36.7 (20.0)	39.4 (10.9)
	N2	None	90.9 (6.6)*	45.2 (0.9)
		Triticale	37.9 (15.0)	38.7 (37.9)
96-97	N0	None	7.2 (1.7)	36.8 (5.2)
		Triticale	4.5 (1.1)	34.1 (7.6)
	N1	None	9.7 (1.9)	42.0 (4.3)
		Triticale	4.9 (2.1)	38.2 (13.6)
	N2	None	33.3 (8.1)*	52.6 (6.8)
		Triticale	14.7 (6.5)	34.2 (11.9)

† Number in parenthesis is the SE of the mean.
* Significant at $P < 0.05$.

Winter cover crops and inorganic soil N

In September 1995, the average mass of extractable soil NO_3-N under fallow (0-80 cm depth: data not shown) was 229.8 kg ha^{-1} compared to 113.1 kg ha^{-1} under triticale (Table 2.5). At the N2 rate in February 1996, only 13% of the total inorganic soil N from September 1995 remained under the fallow treatment, and about 30% remained under the triticale treatment at the same rate. In February 1997, 30% of the total inorganic soil N from September 1996 was found under fallow treatment compared to 23% under cover crop treatment.

Table 2.5. Cumulative inorganic soil nitrogen under cover crop (triticale) and fallow treatments at zero (N0), medium (N1) and recommended (N2) fertilizer rates. Mean separations between treatments were done using Fischer's Least Significant Difference procedure.

	Total NO_3-N			Total NH_4-N			Total Inorganic N		
Cover crop	N0	N1	N2	N0	N1	N2	N0	N1	N2
				kg ha^{-1}					
				7 September 1995 (0-120 cm)					
Fallow	23.3aA†	128.0aB	285.3aC	30.7aA	58.3aAB	104.2aB	53.0aA	186.3aB	389.5aC
Triticale	27.4aB	111.5aA	115.8bA	39.8aA	51.7aA	49.2aA	67.2aB	163.2aA	165.0bA
				15 February 1996 (0 – 80 cm)					
Fallow	35.6aA	30.1aA	33.0aA	25.1aA	13.1aA	18.4aA	60.7aA	43.2aA	51.4aA
Triticale	30.8aA	41.3aA	33.8aA	28.4aA	15.6aA	15.5aA	59.2aA	56.9aA	49.3aA
				20 September 1996 (0 – 120 cm)					
Fallow	11.7aA	16.5aA	51.2aB	24.5aA	25.0aA	30.1aA	36.2aA	41.5aA	81.3aB
Triticale	10.7aA	17.9aA	82.4aB	23.5aA	23.3aA	28.7aA	34.2aA	41.2aA	111.1aB
				15 February 1997 (0 – 80 cm)					
Fallow	11.5aA	12.8aA	11.3aA	11.1aA	11.3aA	13.3aA	22.6aA	24.1aA	24.6aA
Triticale	16.5aA	14.5aA	13.2aA	12.6aA	10.5aA	12.9aA	29.1aA	25.0aA	26.1aA

† Within each year, lower case letters show comparisons between fallow and triticale at each N rate (columns) and upper case letters show comparisons among N rates for each cover crop (rows). Mean comparisons are separate for each year and those with the same letter in a column or row do not differ significantly with respect to N rate or cover crop treatment at $P < 0.05$.

Analysis of variance showed that year, month of sampling, and N fertilizer rates had significant effects on soil NO_3-N and NH_4-N concentrations at 0-20 cm depth from 1995-1997. Soil NO_3-N and NH_4-N concentrations in September 1995 from 0 to 40 cm were significantly higher than in September 1996 at the same depth for N1 and N2 treatments (Figs. 2.2-2.5). Nitrogen rates significantly affected inorganic N in September both years (0 to 80 cm). From September to February, inorganic N decreased significantly which resulted in no N rate treatment effect in February of W95-96 or W96-97.

The treatment differences that were observed in leachate NO_3-N concentrations between fallow and triticale, were not seen in inorganic soil N concentrations for the same period, except on 7 September 1995 at the N2 rate (Figs. 2.2-2.5). No significant cover crop treatment effects on inorganic soil N from 40 to 120 cm were found (Figs. 2.2-2.5).

Compared to N rate, cover cropping had less of an effect on inorganic soil N. With the exception of September 1995 under triticale, at the N2 rate, cover crops had no effect on soil NO_3-N but did have some effects on NH_4-N concentrations (Figs. 2.6-2.11). From September to November 1995, soil inorganic N showed a higher degree of variability at the N1 after the failed broccoli crop. By December of 1995, the variability in inorganic soil N had decreased across all cover crop treatments. The decrease in variability was associated with an increase in leaching rates that occurred from November through February.

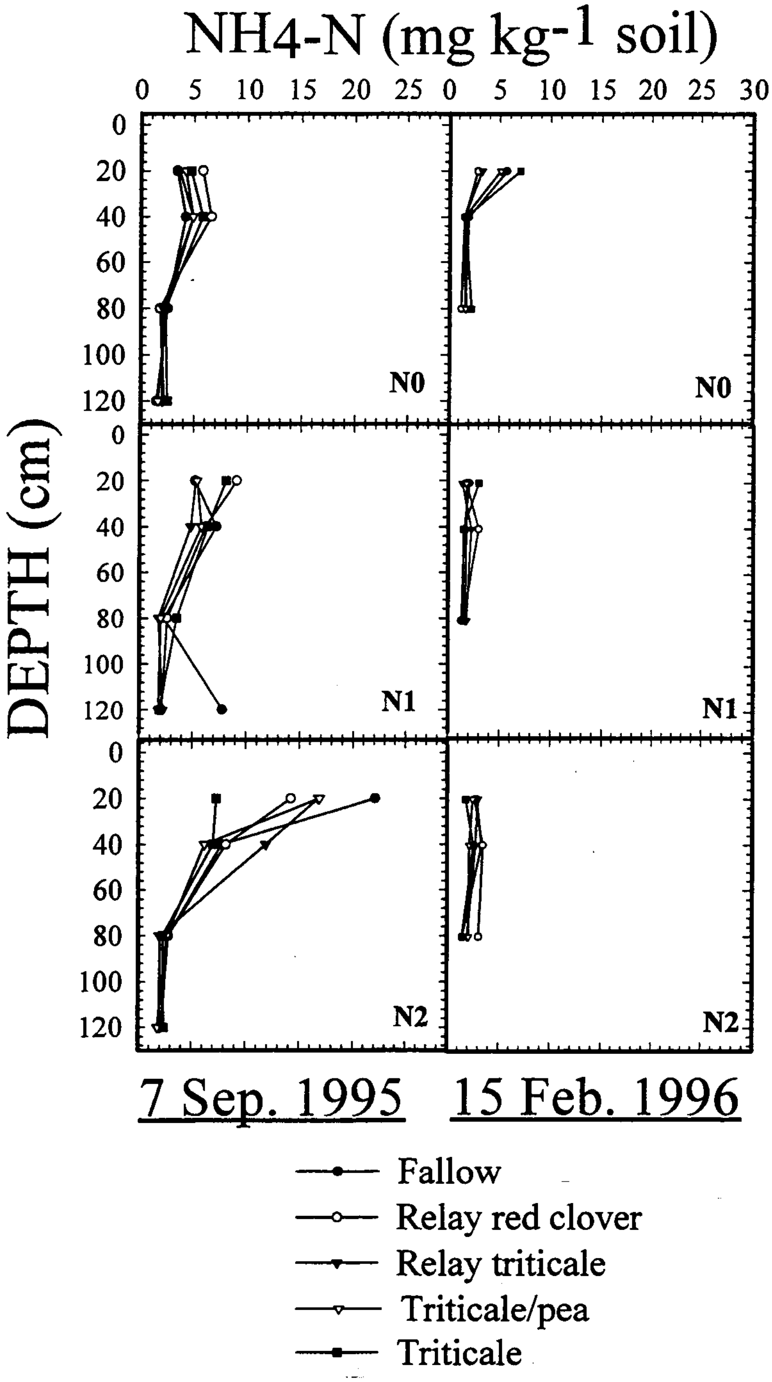

Fig. 2.2. Ammonia-N under cover crop treatments with depth following a broccoli harvest.

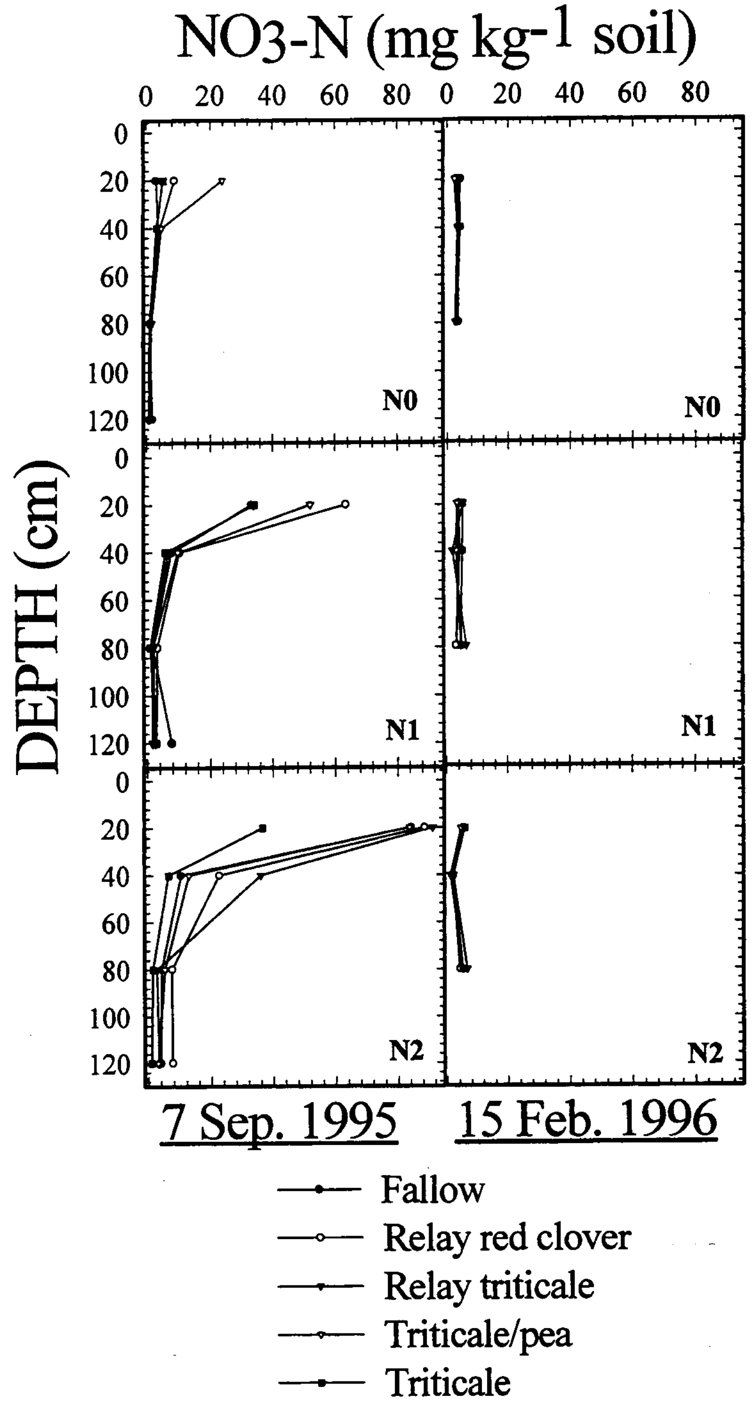

Fig. 2.3. Nitrate-N under cover crop treatments with depth following a broccoli harvest.

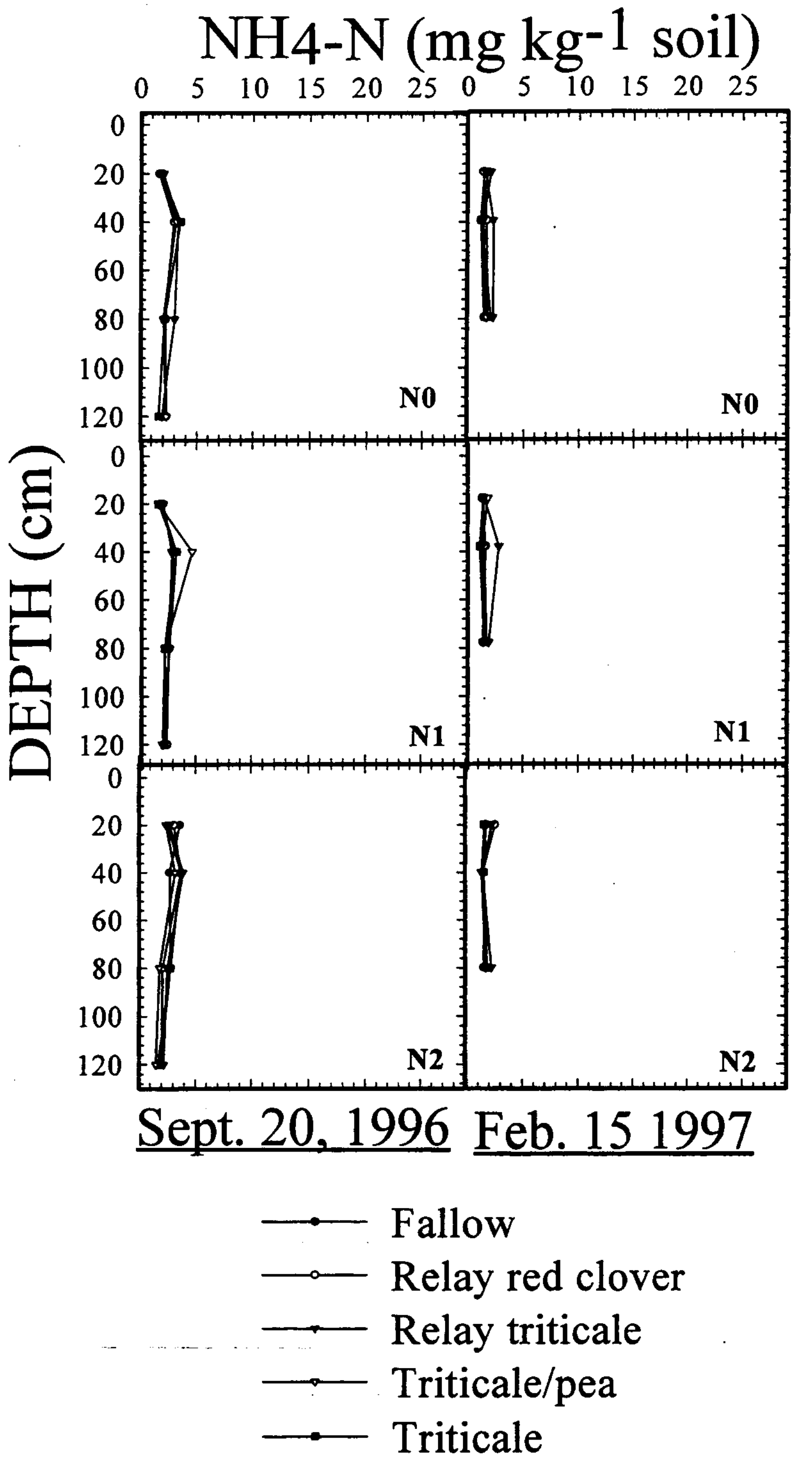

Fig. 2.4. Ammonium-N under cover crop treatments with depth following a corn harvest.

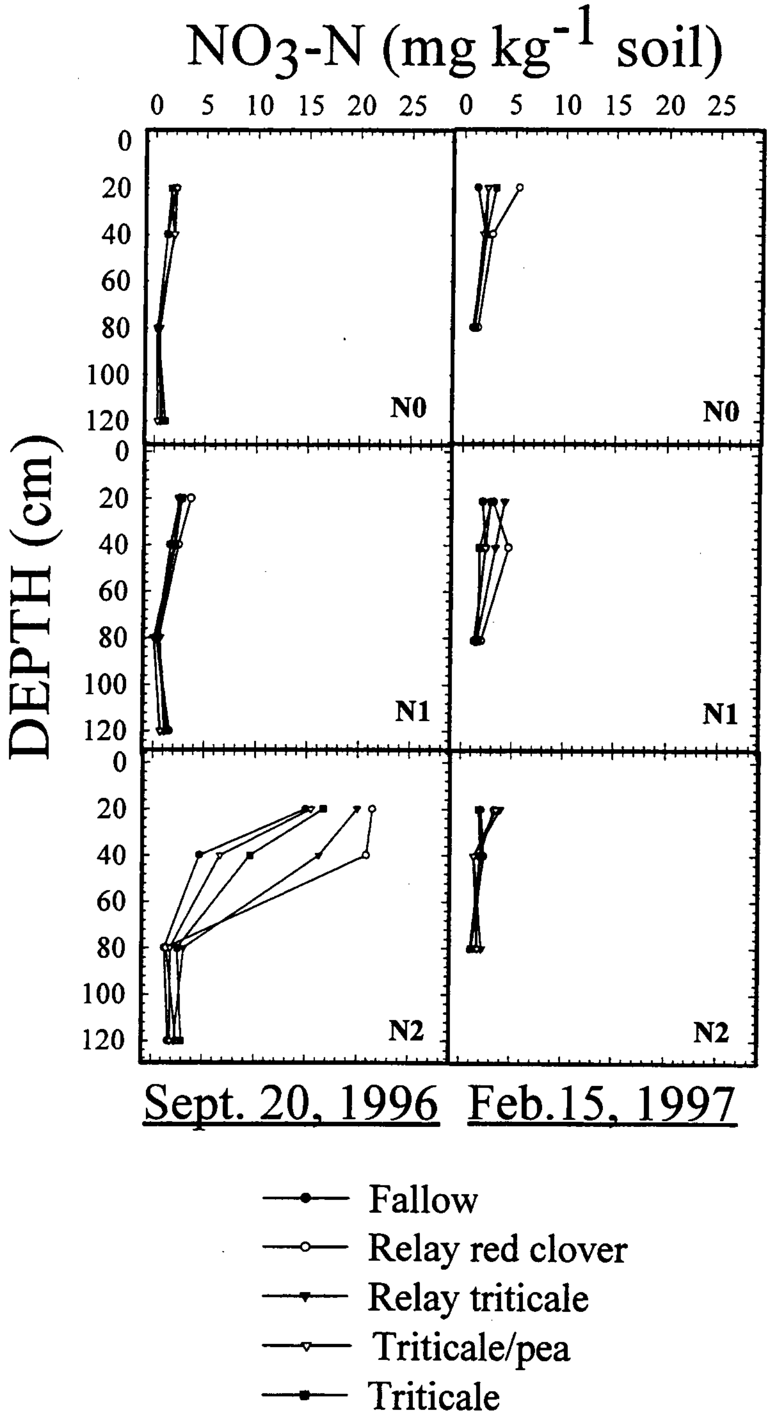

Fig. 2.5. Nitrate-N under cover crop treatments with depth following a corn harvest.

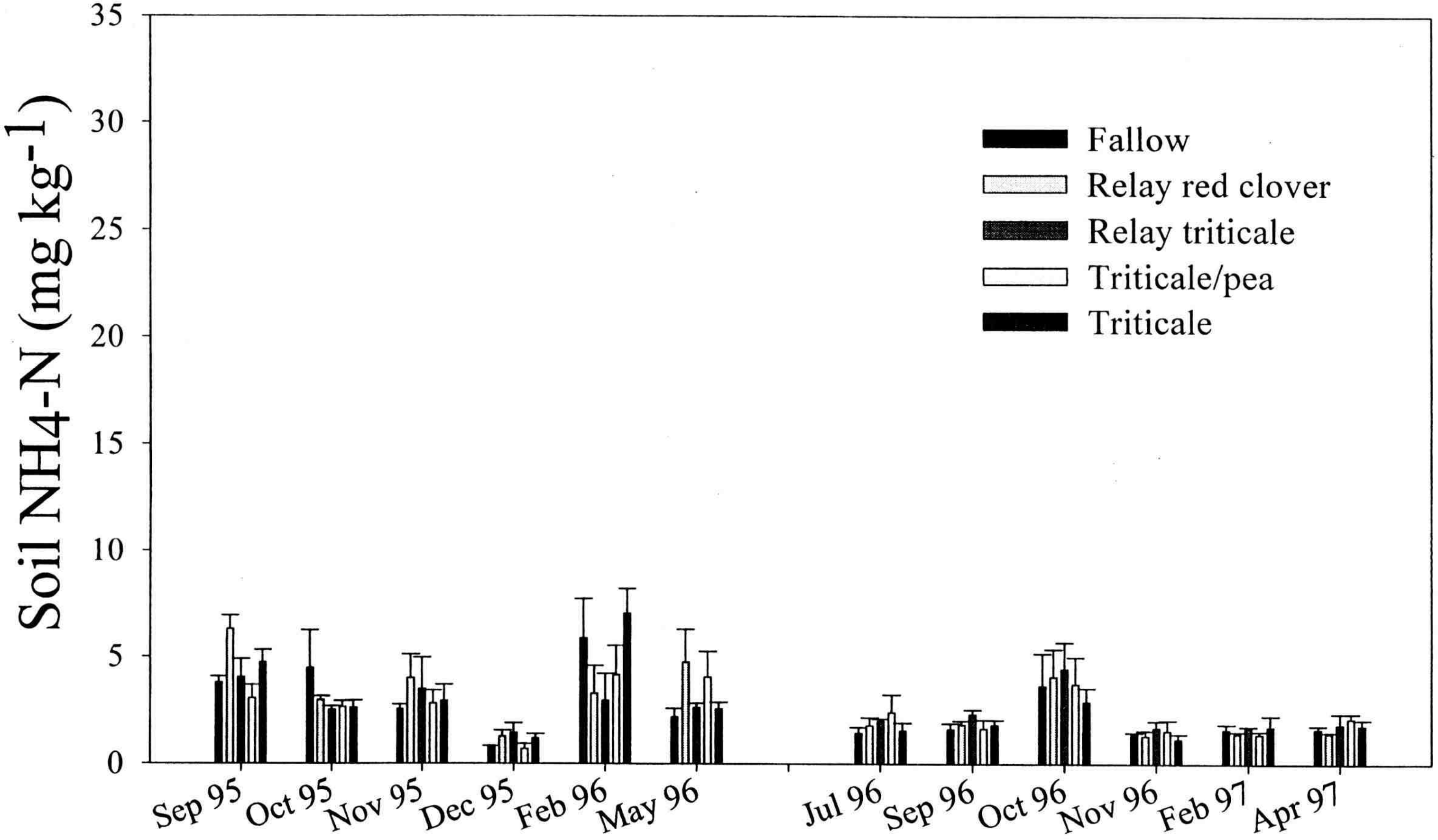

Fig. 2.6. Soil NH_4-N at N0 fertilizer rate (0-20 cm) under five cover cropping treatments (Error bars = standard error of mean).

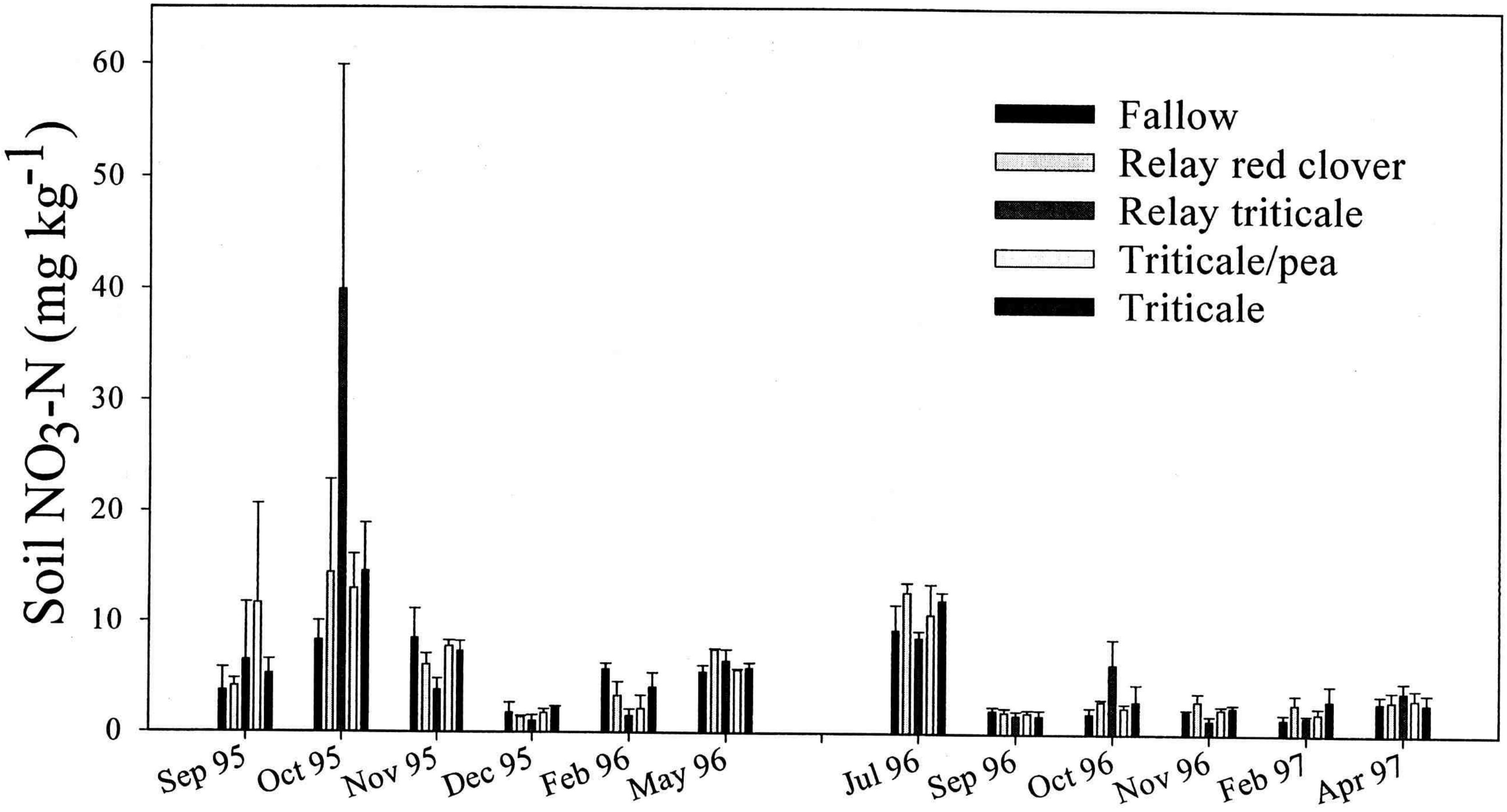

Fig. 2.7. Soil NO_3-N at N0 fertilizer rate(0-20 cm) under five cover cropping treatments (error bars = standard errof mean).

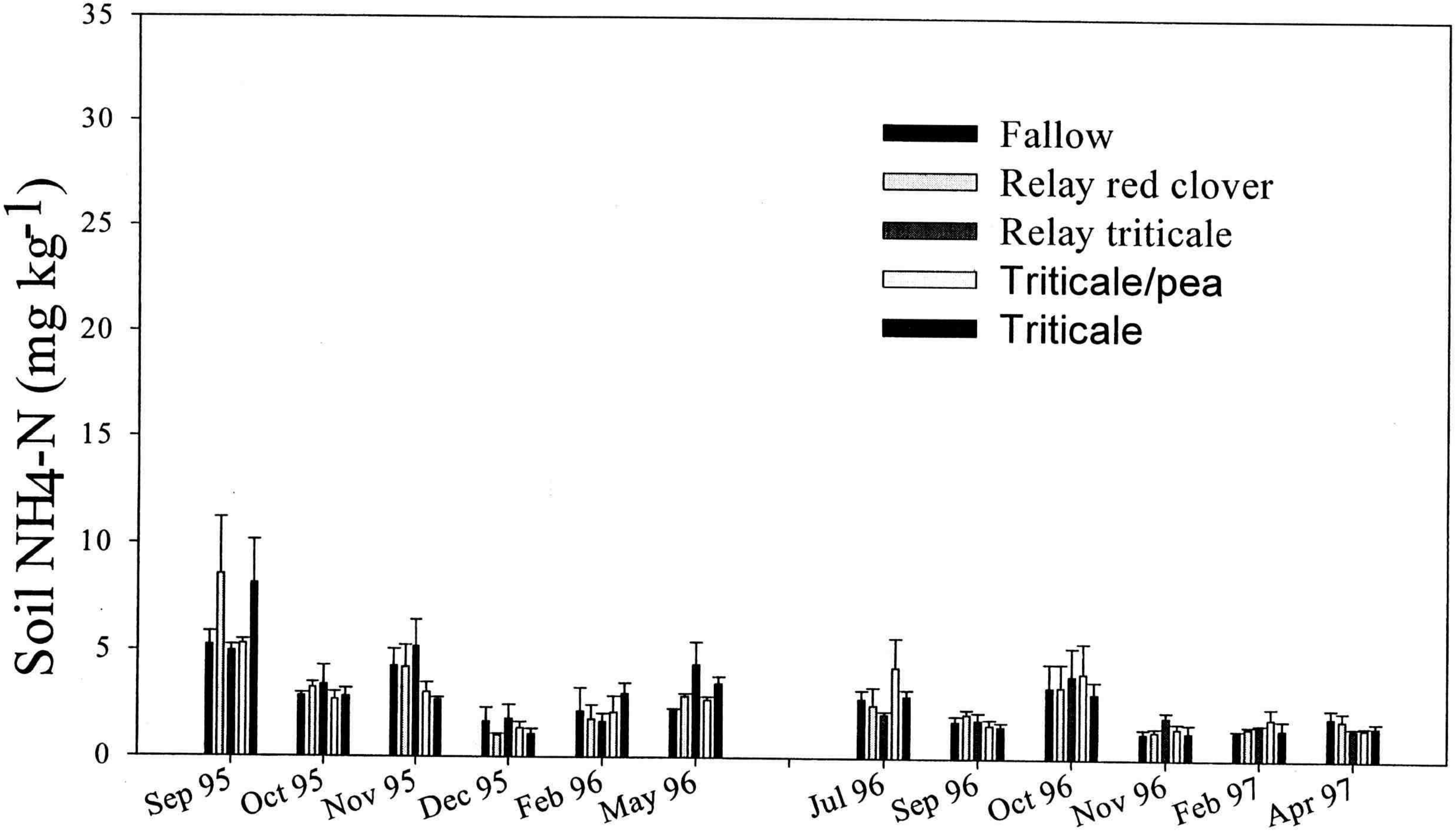

Fig. 2.8. Soil NH_4-N at N1 fertilizer rate (0-20 cm) under five cover cropping treatments (Error bars = standard error of mean).

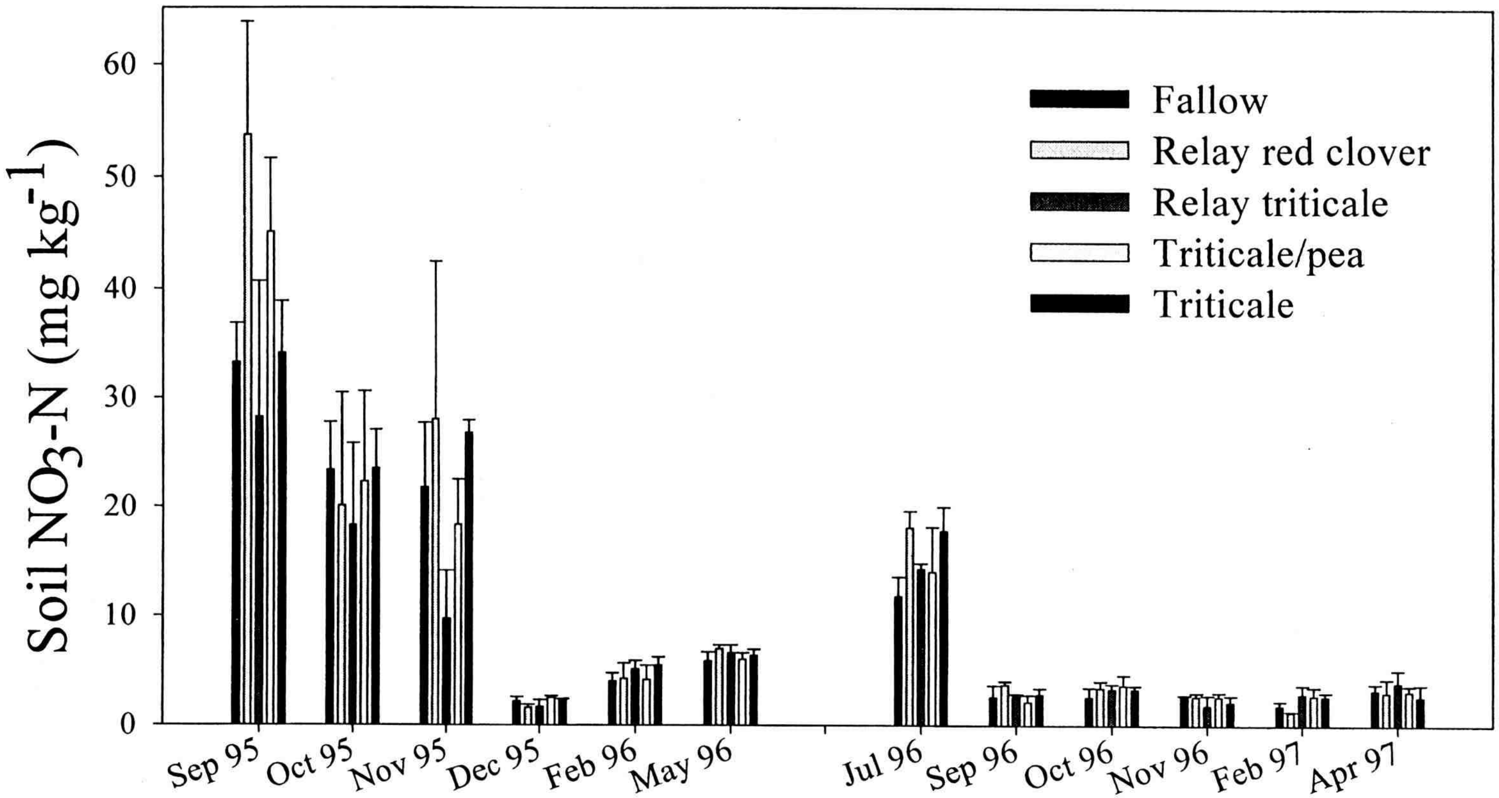

Fig. 2.9. Soil NO_3-N at N1 fertilizer rate(0-20 cm) under five cover cropping treatments (error bars = standard errof mean).

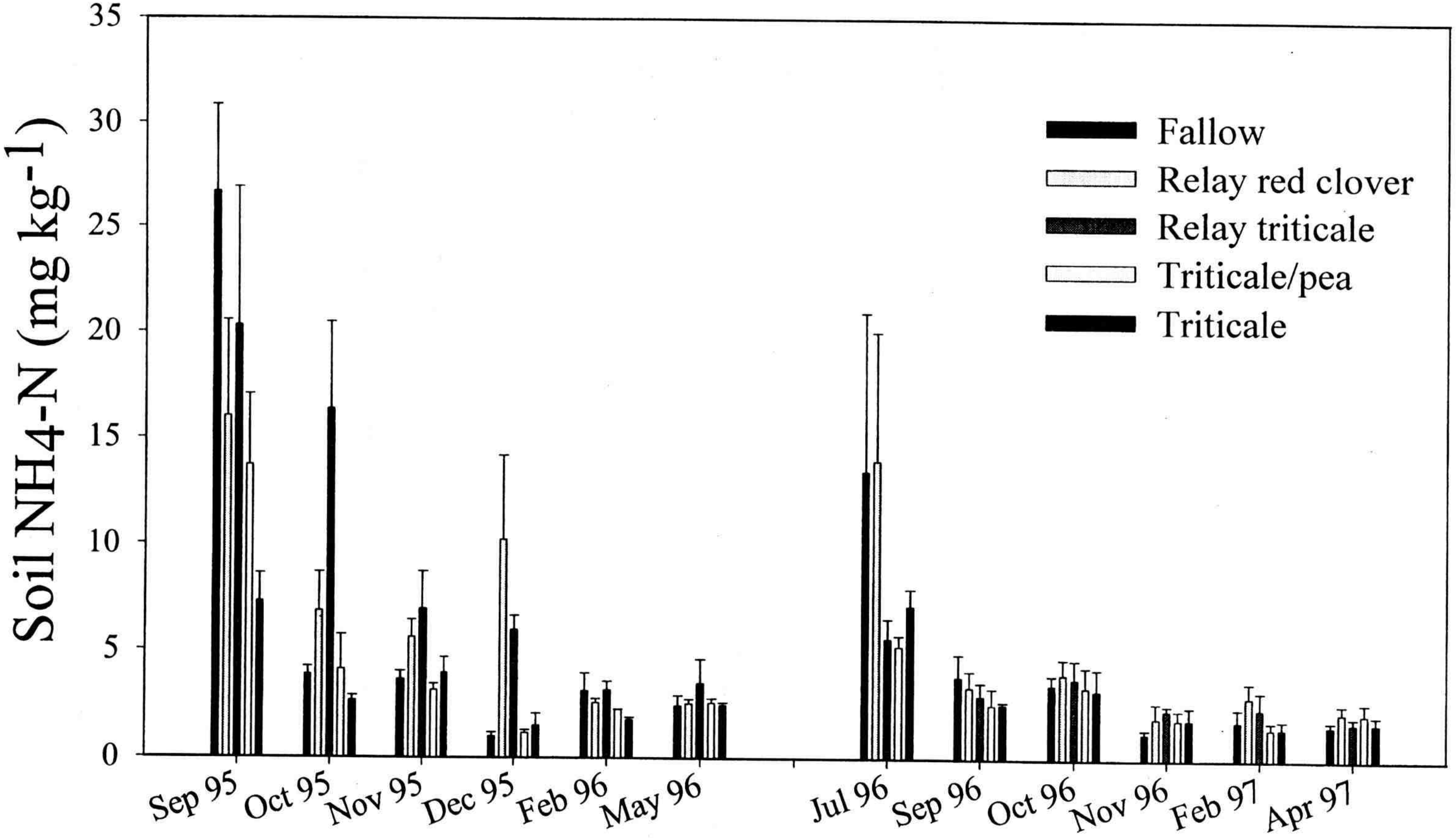

Fig. 2.10. Soil NH_4-N at N2 fertilizer rate (0-20 cm) under five cover cropping treatments (Error bars = standard error of mean).

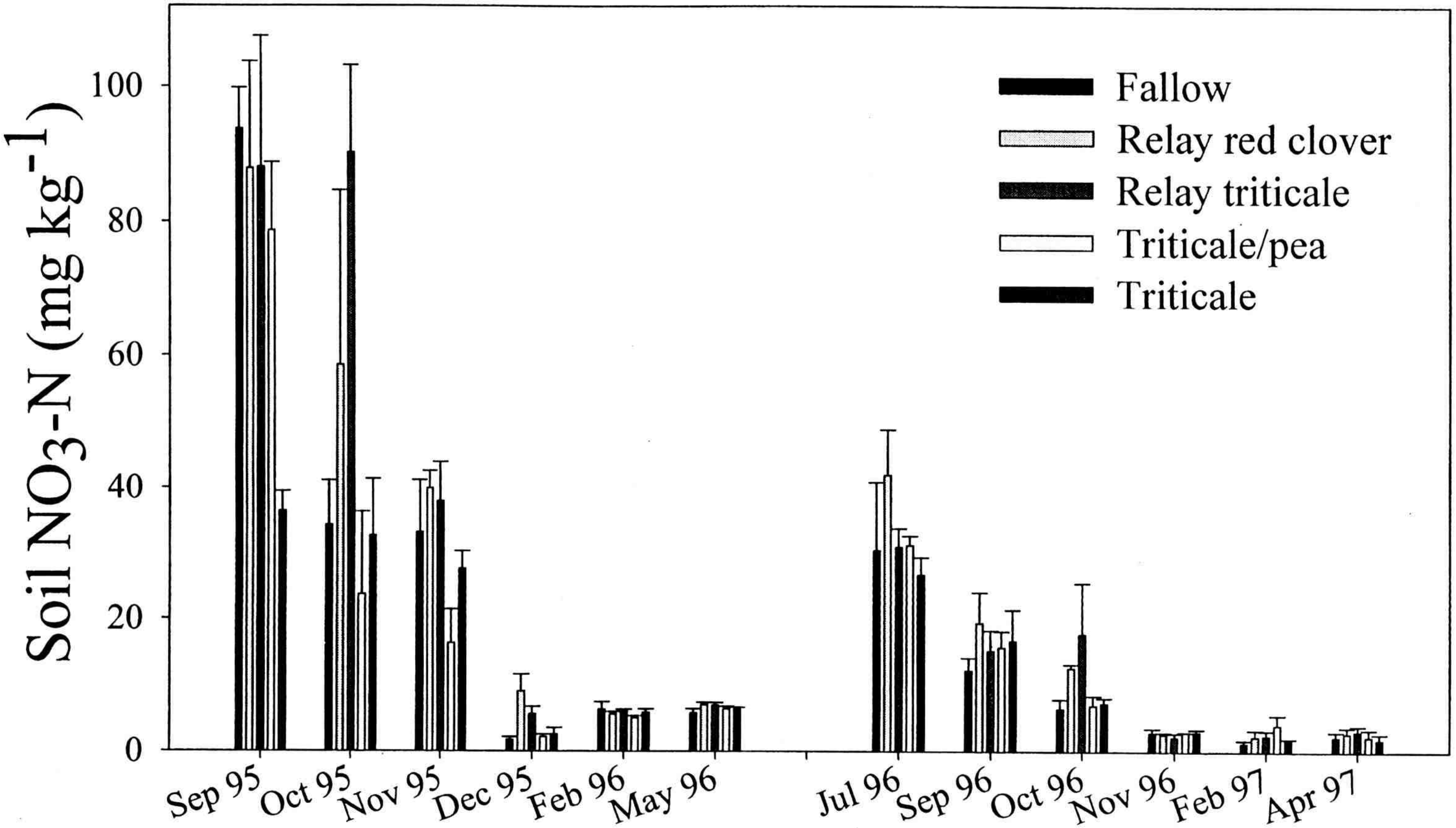

Fig. 2.11. Soil NO_3-N at N2 fertilizer rate(0-20 cm) under five cover cropping treatments (error bars = standard errof mean).

High concentrations of soil NH_4-N in the fall might be indicative of N mineralization from organic N that may be a source for NO_3-N leaching. Generally fall soil NH_4-N values were low (< 10 mg N kg^{-1} soil), except in fall when NH_4-N concentrations were as high as 21 mg kg^{-1} (Fig. 2.10). At the N0 rate, NH_4-N (0 to 20 cm) decreased from September 1995 to December 1995 and then increased in February indicating an increase in mineralization of organic residues, but this trend was not observed at the N0 rate in 1996-1997 (Fig. 2.6). In 1996-1997, NH_4-N increased from September to October then decreased again with the onset of winter rains.

Cover Crop biomass and N uptake

Subtracting the total amount of NO_3-N captured beneath the fallow from that captured beneath the cover crop is an indication of the amount of N the cover crop prevented from leaching. Using this information, the cover crop N uptake represented 19% and 55% of the amount of N captured below triticale at the N2 rate for W95-96 and W96-97, respectively (Tables 2.4 and 2.6). Triticale biomass production at the N2 rate in

Analysis of variance showed that crop year and N rate had significant effects on cover crop dry biomass production and total N uptake in 1995-1996 and 1996-1997 (Tables 2.6 and 2.7). Cover crops also differed significantly in biomass production and N uptake. Cover crop biomass yields generally declined from 1994 to 1997. Red clover generally had greater N uptake at N0 and N1 rates than at N2 rates, but the difference was only significant in 1994. W95-96 was on average 30% lower than in W96-97.

In W95-96 and W96-97 N uptake by triticale at N0, N1, and N2 rates were not significantly different (Table 2.6). Also, mean triticale N uptake in W96-97 was not statistically different from W95-96 (Table 2.6). Among cover crops within years, triticale generally took up less N than did red clover, with the exception of 1995-1996 at the N2 rate. Enhanced N uptake by the relay planted triticale compared to the fall-planted triticale was observed at the N1 and N2 rates in 1995-1996 but not in 1994-1995 or 1996-1997.

We observed that the relay-planted triticale did not grow uniformly on the plots, although it appeared more vigorous in growth compared to fall-planted triticale. Total N uptake for N2 triticale/pea cover crop was significantly higher than for other cover crops in 1994-1995 and 1996-1997, but was lower in 1995-1996 (Table 2.6).

Total N uptake and biomass production among cover crops at N1 rate from 1994-1995 were not significantly different and do not explain the differences observed in soil inorganic N in May 1996 (Tables 2.6 and 2.7).

Table 2.6. Mean winter cover crop N uptake for 1994 through 1997.

	Total N uptake		
Winter cover crop	N0	N1	N2
	kg ha^{-1}		
April 1995			
Relay clover	27 aA†	26 aAB	21 aB
Relay cereal rye‡	26 aA	14 aA	17 aA
Cereal rye/pea	30 aA	31 aA	46 bB
Cereal rye	7 bA	14 aA	10 aA
April 1996			
Relay clover	25 bA	25 aA	17 bA
Relay triticale	9 aA	19 abAB	41 aB
Triticale/pea	14 aAB	10 bB	17 bA
Triticale	9 aA	9 bA	9 bA
April 1997			
Relay clover	14 aA	14 aA	9 aA
Relay triticale	4 bA	6 aA	10 aA
Triticale/pea	17 aAB	12 aB	31 bA
Triticale	6 bA	6 aA	7 aA

† Within each year, lower case letters show comparisons among cover crops at each N rate (columns) and upper case letters show comparisons among N rates for each cover crop (rows). Mean comparisons are separate for each year and those with the same letter in a column or row do not differ signifciantly with respect to N rate or cover crop at $P < 0.05$.

‡ Triticale replaced cereal rye in 1995.

Table 2.7. Mean winter cover crop dry biomass for 1994 through 1997

	Total dry biomass		
Winter cover crop	N0	N1	N2
	kg ha^{-1}		
April 1995			
Relay clover	1376 aA†	1366 aA	1062 bB
Relay cereal rye‡	1640 aA	1129 aA	1498 abA
Cereal rye/pea	1560 aA	1713 aA	2147 aA
Cereal rye	491 bA	727 aA	741 bA
April 1996			
Relay clover	897 aA	947 bcA	648 aA
Relay triticale	592 aA	1067 cA	2258 bA
Triticale/pea	777 aA	494 aB	846 aA
Triticale	454 aA	539 abA	517 aA
April 1997			
Relay clover	504 aA	596 aA	534 bA
Relay triticale	248 aA	445 aA	605 bA
Triticale/pea	469 aA	458 aA	1178 aB
Triticale	345 aA	347 aA	478 abA

† Within each year, lower case letters show comparisons among cover crops at each N rate (columns) and upper case letters show comparisons among N rates for each cover crop (rows). Mean comparisons are separate for each year and those with the same letter in a column or row do not differ significantly with respect to N rate or cover crop at $P < 0.05$.

‡ Triticale replaced cereal rye in 1995.

Discussion

Cover crop biomass production for W95-96 and W96-97 was similar to W94-95 (Brandi-Dohrn et al., 1997). No significant difference in biomass was found between N rates in fall 1995 (Table 2.7), and biomass production generally was low. Apparently, this result was not due to lack of soil N because soil N increased with increased rates of N in September 1995. The poor growth in fall was likely caused by excess rainfall during October and November, 1995 when 143 and 259 mm of rainfall were recorded at the site, respectively. Rainfall for these two months was 182 and 169% of the 30-year average at this site. In addition, between 6 February and 9 Febuary 1996, 210 mm of rainfall was recorded at the site which was 191% of the 30-yr monthly average (110 mm) rainfall for February. In fall 1996, soil N may have been limiting to the cover crop at the N1 rate, but probably not at the N2 rate (Table 2.5). Again, climate probably played the greatest role in cover crop biomass reduction. From 19 November to 21 November 1996, three consecutive days of frost combined with a high-intensity-rainfall event on 19 November (94 mm) may have adversely affected cover crop growth. In addition, in December 1996, about 400 mm of rainfall was recorded, or about 222% of the 30-year average (180 mm) for December. Excess precipitation in fall has been shown to severely decrease growth of cover crops adapted for western Oregon (Thomas Buford, August, 1998, personal communication).; therefore, three consecutive years of high precipitation may have caused poor growth of cover crops from 1994 through 1997.

The absence of an N rate effect on cover crop biomass and N uptake may explain why NO_3-N concentrations were not reduced below 10 mg L^{-1} in W95-96 under triticale at the N2 rate. Low triticale biomass production was less critical to groundwater quality in 1996 since the summer corn crop took up nearly 148 kg ha^{-1} of soil N at the N2 rate, and NO_3-N leachate concentrations were kept below 10 mg L^{-1} for both fallow and triticale treatments.

When NO_3-N leaching results from 1995 through 1996 are compared to results at the same site from 1992 to 1994 (Brandi-Dohrn et al., 1997), the trends suggest that cereal cover crops may have a greater impact on mitigating NO_3-N leaching during years of average precipitation, since 1995 and 1996 had rainfall greater than 150% of the 30-year average at this research site (Table 2.1).

A study-wide comparison of pooled treatment means, combining these data with previous data published by Brandi-Dohrn et. al (1997), showed cereal-cover cropping significantly reduced NO_3-N leaching below 10 mg L^{-1} at all three fertilizer rates during five consecutive years. At the N2 rate, average NO_3-N was 8.9 ($\pm$ 0.4) mg L^{-1} under cereal cover crops and 13.6 ($\pm$ 0.5) mg L^{-1} under fallow. Treatment effects from 1995 through 1997 support results from 1992 through 1994, where cereal rye reduced NO_3-N leaching at the N2 rate.

In summer 1995, high inorganic soil N was found in fallow compared to triticale plots at the N2 fertilizer rate from 0 to 20 cm (Figs. 2.2 to 2.4). A similar trend was observed by (Kauffman, 1994) in the same plots during September 1993, where cereal rye had lower NO_3-N concentrations from 0-20 cm compared to a fallow and rye/pea mix at the N1 and N2 rates, but the differences were not found to be significant.

This effect may be due to incorporation of a cover crop in spring, which can cause N immobilization if the C:N ratios of the cover crop are sufficiently high. However, the cereal cover crops had C:N ratios < 30:1 (data not shown) which is generally thought to be below the range when net immobilization of N occurs.

An N balance was done at the N2 rate to determine the amount of NO_3-N not recovered in our analyses. We estimated the average mass of NO_3-N present in February from 0 to 120 cm depth. Soil NO_3-N from 80 to 120 cm was assumed equal to the average concentrations of NO_3-N from 40 to 80 cm (11.0 kg N ha $^{-1}$ in 95/96 and 3.0 kg N ha $^{-1}$ in 96/97), because we were unable to sample at 80-120 cm in February under wet soil conditions. We assumed a small change in the quantity of soil NO_3-N from February to May and no additional losses and transformations of N. This assumption is justified since there was no significant difference in NO_3-N concentrations (0-20 cm) between February and spring soil samples. Atmospheric N input was assumed negligible, since it has been estimated to contribute about 1 kg N ha^{-1} in the western third of the U.S. (Schepers and Mosier, 1991).

With these assumptions, the quantity of NO_3-N (kg ha $^{-1}$) in the soil during September (SOIL-N_{SEP}) is roughly equal to the sum of NO_3-N in leachate (LEA-N), NO_3-N in the soil during February (SOIL-N_{FEB}), and total N in the cover crop (CC-N). Cover crop N uptake may be overestimated because cover crops were not sampled for N content until April of each year.

$$\text{UNRECOVERED } NO_3\text{-N} = \text{SOIL-}N_{SEP} - (\text{LEA-N} + \text{SOIL-}N_{FEB} + \text{CC-N})$$

Using this equation we estimate that 150 and 25 kg NO_3-N ha^{-1} was unrecovered under fallow and triticale N2 treatments in winter 95/96, which accounts for 53 and 22% of fall soil NO_3-N, respectively. In W96-97, unrecoverable NO_3-N was 4 kg ha^{-1} in the fallow N2 plots, or 7 % fall soil NO_3-N, versus 45 kg ha^{-1} in triticale N2 plots, 51% fall soil NO_3-N. The majority of unrecoverable NO_3-N (i.e. N not found in cover crop, wick samplers, and February soil samples) may have been lost in leachate because of a decrease in collection efficiency of the wick samplers during high intensity rainfall events and through heterogeneous denitrification.

Increased denitrification under triticale plots may explain some of the difference in leachate N concentrations between fallow and triticale treatments during winter. Cereal cover crops have the potential to contribute short-term organic C to the soil (Hu et al., 1997), which can supply an additional C source for denitrification that is not found under fallow treatments. Increased organic C may occur only at the N1 and N2 fertilizer rates where cover crop biomass production is greatest. Mendes (1998) found no significant differences in total organic carbon between fallow and cereal cover crops in September 1995 and September 1996 at the N0 fertilizer rate. Denitrification is known to increase with increased fertilizer and increased C and N inputs (Myrold, 1988; Horwath et al., 1998). Horwath et al. (1998) estimate that as much as 30 kg ha^{-1} of applied fertilizer N can be lost by denitrification in poorly drained soils, while other estimates range from 4 to 14 kg N ha^{-1} (Meisinger and Randall, 1991).

Since cover crop residues are incorporated every year before planting the summer crop, we might expect a higher quantity of organic N in triticale plots compared to fallow plots (Kuo et al., 1997). However, if weed or volunteer growth is substantial in the fallow treatments, the scavenging of soil N and contribution of organic C and N by weeds is equivalent to a planted cover crop (Allison et al., 1998a).

Soil samples taken from 0-20 cm on 15 July 1996 show a general increase in NO_3-N compared to soil samples taken on 11 May 1996 (Figs. 2.7, 2.9, and 2.11). Corn was planted on 30 May 1996, and the first application of urea took place on 18 June 1996. The increase in NO_3-N in the N1 and N2 can be attributed to the application of fertilizer along with mineralization of cover crop residue. A similar increase of NO_3-N in the N0 plots also may be a result of residue mineralization and the oxidation of soil NH_4-N (Figs. 2.6 and 2.7). The same increase of NO_3-N in fallow plots suggests that weed residue also was being mineralized during corn emergence. Ammonium-N at the N0 and N1 rate declined or remained constant from May to July (Figs 2.6 and 2.8), while mean NO_3-N concentrations increased (Figs. 2.7 and 2.9), indicating increased mineralization in all treatments. A three-fold increase of NO_3-N from May 1996 to July 1996 was observed in the fallow and relay red clover plots at the N2 rate (Fig. 2.11) but with a high degree of variability associated with the July samples. The variability may have been caused by uneven distribution of fertilizer N in the surface soil. Kauffman (1994) reported net mineralization at the N0 rate at the same research site during summer and at the same site in 1992 and 1993. The increase was observed at treatments containing cereal rye/pea mix and cereal rye. In contrast to our study, no increase of NO_3-N was observed in the fallow treatment.

In a cover crop experiment in northeastern U.S., Stivers-Young (1998) also reported minimal treatment differences in inorganic soil N when oats (*Avena sativa* L.), phacelea (*Phacelia tanacetifolia* Benth.), radish (*Raphanus sativus* L.), white senf mustard (*Brassica hirta* Moench.), kale (*Brassica oleracea* L.), canola (*Brassica napus* L.), turnip (*Brassica rapa* L.), and yellow mustard (*Brassica hirta* Moench.) were compared for their ability to assimilate fall soil N. They observed that inorganic soil N under cover crop was generally lower compared to fallow, but not significantly different at $P \leq 0.05$. Similarly, Allison et al. (1998b) found cover crops had no effect on inorganic soil N at the time of sowing or at harvest of a summer beet crop. In contrast to our study, cereal rye did reduce mineral soil N on a silt loam in a corn rotation in VA, USA (Ditsch et al., 1993), but the cover crop averaged 82 and 49 kg N ha $^{-1}$ from 1990 to 1991 which was much higher than the mean N uptake in our study from 1994 through 1997 (Table 2.4).

Nonlegume cover crops, such as cereal rye, may be more effective in reducing NO_3-N leaching than are legume cover crops, such as red clover, because they are able to scavenge more residual soil N (Meisinger et al., 1991; McCracken et al., 1994). Based on cover crop N uptake alone, our data supports this observation only in April 1996 at the N2 rate when the relay triticale had a higher uptake of N than other treatments (Table 2.6). At the N2 rate, the cereal/pea mix had the highest N uptake in 1994 and 1996, but not in 1995. Relatively few differences in inorganic soil N are found at higher rates after the peak of the rainy season (Figs. 2.5-2.10). Ranells and Wagger (1997) found that a rye/red clover mix recovered more labeled fertilizer ^{15}N than did a red clover monoculture but less than a rye monoculture.

Perspectives

The five-year cover cropping study showed marked temporal changes in soil N dynamics at higher N rates, and a reduction of nitrate leaching under cover crop treatments. Higher rates of N fertilizer resulted in greater NO_3-N leaching, except in 1996-1997 when NO_3-N leaching at theN1 and N2 rates were not significantly different. Reduction in NO_3-N concentrations in leachate did not relate to soil N data or aboveground N uptake by cover crops. Soil NO_3-N decreased from September through

February from 0-120 cm during each year. Nitrate-N leaching below 80 cm from November to February and possible microbial N transformations during the same period, diminished the N1 and N2 fertilizer N treatment effects on inorganic soil N.

We saw very little temporal variability in soil inorganic N content at zero and intermediate N rates compared to higher N rates. The sweet corn during summer 1996 may have been more effective in reducing nitrate leaching than were cover crops, which indicates increased N uptake efficiency by the summer crop may be as important as a winter cover crop for preventing the NO_3-N leaching. Perhaps a good crop of triticale would have further reduced NO_3-N losses from 1995 to 1997.

Effects of different cover crop treatments on inorganic soil N were limited. These results suggest that NO_3-N leaching characteristics under fall-planted triticale were similar to relay-planted triticale, relay-planted red clover and fall-planted triticale/pea mix.

This study stresses the importance of planting a cover crop to scavenge residual nitrogen should the summer crop have poor yields, and the importance of planting a cover crop early to maximize the number of growing degree days before the first frost. A decrease in NO_3-N leaching under cover crops with no apparent changes in inorganic soil N indicates an alternative sink for N. Possibilities for N sinks include microbial immobilization and denitrification. Residue C:N ratios in this study were generally not above 30, which decreases the likelihood of immobilization as an N sink. Further studies are needed to determine temporal and spatial changes in soil nutrients along with microbial biomass N and activity as influenced by cover cropping and increased C and N inputs. Understanding long-term nutrient cycling and microbial dynamics in relation to seasonal changes and cropping systems could increase fertilizer use efficiency and protect groundwater resources. Long-term agricultural studies tend to be resource intensive and require extraordinary management and supervision; however, the gains in knowledge and understanding of complex ecological systems to be acquired from long-term agricultural studies cannot be underestimated.

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Chapter 3

MODEL PREDICTION OF NITRATE LEACHING: MULTIPLE LINEAR REGRESSION AND NITRATE LEACHING AND ECONOMICAL ANALYSIS PACKAGE (NLEAP)

Abstract

Predicting leaching of agricultural chemicals in wet climates is important for reducing risks of aquifer contamination. The availability of a long-term soil and nitrate-nitrogen (NO_3-N) leaching data set provided an opportunity to develop and test NO_3-N leaching models in western Oregon. The objectives of this investigation were: 1) to develop and test a statistical model for predicting NO_3-N leaching using crop, soil, leachate and climate data from a 5-yr vegetable rotation study in western Oregon, and 2) to evaluate the ability of the Nitrate Leaching And Economical Analysis Package version 1.3 (NLEAP) to predict monthly NO_3-N leaching in western Oregon under a cereal cover crop. Multiple linear regression was used with annual leachate NO_3-N (kg ha^{-1}) as the dependent variable and fall soil NO_3-N, cover crop N uptake, summer crop N uptake, summer crop fertilizer N rate, summer crop biomass (kg ha^{-1}), cover crop biomass, and leachate collected (cm^3) as independent variables. Stepwise multiple linear regression showed that a four independent variable model (log transformed fall soil NO_3-N, leachate volume, summer crop N uptake, and N fertilizer rate) best predicted NO_3-N leaching ($P < 0.001$ and $R^2 = 0.57$). Comparisons were made between NLEAP and field data for mass of NO_3-N (kg ha^{-1}) leached kg ha^{-1} between the months of September and May from 1992 to 1997. Predictions with NLEAP were better correlated to observed data during high-rainfall years compared to dry or average-rainfall years.

Introduction

Models that can predict N losses can be useful for guiding management of agricultural systems to save money and reduce the incidence of pollution from runoff and leaching of agricultural chemicals. In Oregon's Willamette Valley, roughly 500,000 people rely on groundwater from shallow alluvial aquifers for domestic use (U.S.G.S., 1998). As population is expected to increase with time, so will the importance of optimizing agricultural systems that protect the quantity and quality of groundwater resources. Several computer models have been developed that can be used to predict the leaching of chemicals into groundwater and model soil N dynamics in cropping systems.

The CERES models are a class of computer models used for simulating the whole crop and soil system in the field and are relatively widespread (Quemada and Cabrera, 1995). A well known model, the Leaching Estimation and Chemistry Model (LEACHM), has a submodel, LEACHN, that applies Richard's equation to modeling N dynamics and leaching in the unsaturated zone (Wagenet and Hutson, 1989; Jabro et al., 1995). Other models include the Nitrogen-Tillage-Residue-Management (NTRM) model (Radke et al., 1991), the Agricultural Production Systems Simulator (APSIM) (Asseng et al., 1998), the CENTURY model (Parton et al., 1988), and the Nitrogen Leaching and Economical Analysis Program (NLEAP) (Shaffer et al., 1991). NLEAP has been successfully evaluated for its potential to predict site specific nitrate leaching (Follett et al., 1994; Follett, 1995) as well as for identifying and predicting regional NO_3 leaching (Wylie et al., 1995; Shaffer et al., 1996).

Alternatively, multiple linear regression (MLR) can be a powerful tool to aid researchers for making statistical predictions based on data sets with a large number of variables. Few studies in agriculture have used field-plot N data and regression analysis as a model for predicting potential NO_3-N leaching. Multiple linear regression analysis has proven useful for predicting a variety of soil parameters, such as adsorption constants in soil (Laird et al., 1992), P availability (Afif et al., 1993), and temporal structural stability of soil within crop treatments (Perfect et al., 1990). Multiple linear regression was used by McBride et al. (1990) to predict soil quality based on electrical conductivity measurements. Bauder et al. (1993) used MLR to explain the variability in county average well sample NO_3-N concentrations using 67 independent variables; Lucey and Goolsby (1993) used MLR to predict NO_3-N concentrations in a river from climatic and stream-flow data. Dick and Tabatabai (1987) used MLR to identify factors most responsible for hydrolysis of polyphosphates in soils.

No studies have been done to evaluate NLEAP for its ability to predict NO_3-N leaching in a Mediterranean climate such as that found in western Oregon and Washington. Most soil-crop system models have been used on non-vegetable systems without cover crops (Cavero et al., 1998). Consequently, this led us to develop and investigate models to apply to a whole soil-crop vegetable system in a Mediterranean climate.

The NLEAP model was chosen because it is easily obtained and has applicability to site specific and regional situations. The objectives for this study were to: 1) develop a statistical model using MLR, and to test this model for prediction of annual NO_3-N leaching and 2) evaluate NLEAP's ability to predict NO_3-N leaching in western Oregon during winter in a non-equilibrium cropping system, that included cover crops, and to determine the model's response sensitivity to parameter adjustments.

Materials and Methods

Soil, crop and leachate data were collected during five years from the 0.9-ha site at the Oregon State University, North Willamette Research and Extension Center in Aurora, OR. The site was managed as a uniform wheat-fallow rotation from 1982 until 1989 when it became a cover crop and vegetable rotation study. The soil is of glacio-lacustrine genesis and has been classified as a Woodburn Variant loam (fine-loamy, mixed, mesic Aquultic Argixerol) with an inclusion of Willamette Variant loam (fine-loamy, mixed, mesic Pachic Ultic Argixerol) that bisects the site from NE to SW. General soil characteristics of the site were measured according to Bandick (1997) and are given in Table 3.1. The terrain has slopes from 0 to 3%. Average annual rainfall is 1036 mm (Fig. 3.1), 75 to 80% of which falls from October through March (U.S.G.S., 1998). Average rainfall data from 1992 through 1996 are given in Table 3.2. The mean annual temperature is about 11°C.

Table 3.1. General soil characteristics at North Willamette Research and Extension Center vegetable rotation site (0-20 cm depth).

pH	Bulk Density	Organic Matter	Total exchange capacity	Total C	Total N
	— g cm^{-3} —	%	— cmol$_c$ kg^{-1} —	— g kg^{-1} soil —	
5.8	1.24	3.8	15.3	16.8	1.045

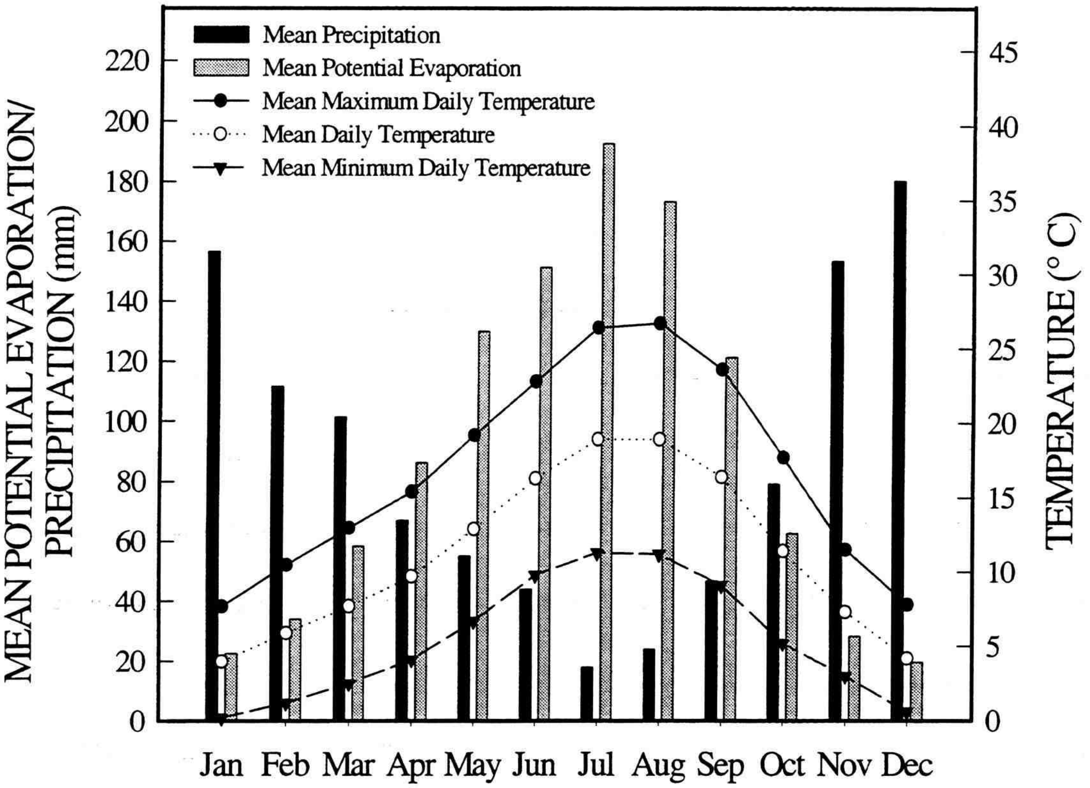

Fig. 3.1. Climatic data taken at North Willamette Research and Extension Center from 1961-1990 (Oregon Climate Service, Oregon State University).

The experimental design is a randomized complete block split-plot, with summer vegetable crops plus winter cover crops, or vegetable crops plus winter fallow (control) as the whole-plot treatment (162 m^2). Summer vegetable crops were broccoli (*Brassica oleracea*. L. var italica cv. Gem), grown during odd-numbered years, and sweet corn (*Zea mays* L. cv. Jubilee), grown during even-numbered years. Whole plots were 9 x 18 m, and each whole plot was divided into three split-plot treatments (54 m^2) with three different rates of N fertilizer: zero (N0), medium (N1), and recommended (N2). Split-plots of sweet corn were fertilized with urea-N at 0 (N0), 56 (N1), and 224 (N2) kg ha^{-1}. Broccoli split-plots were fertilized at 0 (N0), 140 (N1), and 280 (N2) kg·ha^{-1}.

During the 5-yr study, soil samples from 0-120 cm depth were taken in September and in February from 0 to 80 cm depth according to Kauffman (1994). Summer crops and winter cover crops were grown according to Burket et al. (1997), and leachate samples were taken from passive capillary wick samplers as described by Brandi-Dohrn et al. (1997).

Table 3.2. Crop-year rainfall during study.

Year	Rainfall September-September	 November-April
	mm	
1992	1090	690
1993	760	650
1994	1320	960
1995	1590	1240
1996	1760	1350

Regression Model

To develop a regression model for predicting NO_3-N leaching, cumulative annual NO_3-N leachate data across all treatments were used. Approximately 15% of the data were randomly selected for model validation and not used during model development. These data were log transformed to account for unequal variance. Independent variables were analyzed for colinearity before running the analysis. Multiple linear regression was performed using PROC REG with the STEPWISE option in SAS version 6.13 for Windows (SAS, 1996). Residuals were analyzed to confirm the assumption of linearity after log transformation. Missing data for the regression model included summer crop data from the fallow plots in 1992, which were still under a wheat-fallow rotation, and summer crop data from 1995, when the broccoli did not yield reportable data.

NLEAP

Evaluation of the NLEAP version 1.13 model was done using the monthly analysis option. Input data came from soil, winter cover crop, and climate data from our research site for the winters of 1992-1996. NLEAP contains five input files in the monthly analysis format: 1) soil data, 2) crop and management data, 3) irrigation and N management, 4) aquifer information, and 5) climate input data. We evaluated NLEAP to predict monthly NO_3-N leaching at the N2 fertilizer rate under the winter cover crops cereal rye (1992-1994) and triticale (1995-1997). The winter crop selected in NLEAP was winter wheat.

Simulations were conducted by calibrating cover crop yield estimates to adjust NO_3-N leaching to annual observed NO_3-N leaching. Predicted monthly NO_3-N leaching was then compared to observed NO_3-N leaching. Second, a sensitivity analysis also was done on several input parameters to determine their relative effects on NO_3-N leaching.

Climate input data came from data measured at the research station. The number of wet days in a month was defined as the sum of days that received greater than 0.1 cm of rainfall. Input yield estimates based on climate types are required in the crop management file. In NLEAP's crop management file, yield estimates are based on annual rainfall and placed into one of three categories, average, wet, and dry. Average and dry years had the same estimated yield goal based on observed data taken at the research site in 1992-1993 (average rainfall-year) and 1993-1994 (dry rainfall-year). The years 1994, 1995, and 1996 were considered wet years by western Oregon standards. Rainfall during these three years was about 127, 150 and 200% of the 30-year average in western Oregon.

Simulation periods ran from August to July of the following year, but the leaching period was generally from November to May. The summer vegetable crop cycle was not included in the simulation because of limitations in crop selections, but addition of residue from the summer crop was added for sensitivity analysis. Average input values from soil data taken at the site between 1992 and 1995 were used in simulations. The soil parameter values used in the simulations are given in Table 3.3.

Table 3.3. Selected soil input data used for NLEAP modeling.

Parameter	Input
Soil Textural class	Silt Loam
Hydrologic Group	B
Percent slope	1
Drainage Class	Moderately Well Drained
Landscape Position	Flood Plain
% Organic Matter	2.0
Bulk Density (g cm $^{-3}$)	1.3

The hydrologic group is chosen based on drainage capability class of the soil. Soils in hydrologic group A are highly permeable soils, while soils in group D are the least permeable. Percent organic matter was selected as an average from data given by Brandi-Dohrn (1993) and Bandick (1997) at a depth of 20 cm.

Detailed analysis in NLEAP is done to calculate water and N balances on two soil layers, the top 30 cm and to the bottom of the root zone at a maximum of 1.5 m. All soil C and N transformations are confined to the upper profile. The transformations include denitrification, volatilization of ammonia (NH_3), and mineralization of soil organic matter, nitrification, and mineralization-immobilization in association with crop residues, organic wastes and manure.

Results and Discussion

Multiple Linear Regression

The MLR model was significant ($P < 0.001$) and explained 57% of the variability in leachate data when log transformed soil NO_3-N (kg ha^{-1} y^{-1}) (LSNO3), fertilizer N rate (NRATE), summer crop N uptake (SCN), and amount of leachate collected by wick samplers (CM) were used as predictor variables for total NO_3-N leached annually (Table

3.4). Fall soil NO_3-N (kg ha $^{-1}$) explained 30% of the variability in the model. Summer crop N uptake (SCN) was inversely related to NO_3-N leached ($P < 0.05$), and explained only 4% of the variability. Total crop and cover crop biomass, and cover crop N uptake (CCN), total inorganic soil N (NO_3-N + NH_4-N) and fall soil NH_4-N (kg ha^{-1}) were not significant as independent variables.

Table 3.4. Regression equations describing log NO_3-N kg ha^{-1} y^{-1} leaching.

Model equation	R^2
Y = 0.81 + 0.30(LSNO3) ***	0.31
Y = -0.53 + 0.30(LSNO3) + 0.025(CM)*	0.50
Y = -0.15 + 0.30(LSNO3) + 0.025(CM) + 0.0032(NRATE)*	0.53
Y = -0.48+ 0.30(LSNO3) + 0.025(CM) + 0.0032(NRATE) -0.0027(SCN)*	0.57

*, ***, Significant at 0.05 and 0.001 probability levels, respectively.

Summer crops generally took up more N with increased fertilizer (Table 3.5). Nitrogen rate had little or no effect on N uptake by the cereal cover crops from 1994-1997, which may explain the lack of significance that CCN and biomass had for the model. When the level of significance for variable entry into the model was raised from 0.15 to 0.30, CCN was permitted into the model as an independent variable but was not significant ($P \leq 0.30$), and CCN did not dramatically improve model linearity ($R^2 = 0.58$). A steady decline in N uptake by cover crops as well as decreased treatment effects between fertilizer rates may also be contributing factors for CCN being a poor predictor variable for NO_3-N leaching. The absence of summer crop (corn) data from 1992 on the fallow plots, and of broccoli in 1995, might have decreased the significant inverse relationship found between summer crop N uptake and NO_3 leaching. In 1992, the winter-fallow plots were still in a wheat rotation and could not be planted to sweet corn; in 1995, the summer crop of broccoli failed and no reliable crop data were obtained. Removal of crop year data collected in 1995-1996 from the model did not improve the amount of variation explained by the independent variables and did not change the order, number or type of variables that were accepted into the model. For example, the amount of variation in NO_3-N leaching, explained by the variable soil NO_3-N (kg ha $^{-1}$) after the 1995 data were omitted, was 28% compared to 30% including the data.

Table 3.5. Mean N uptake by summer crops under fallow and cover crop and three N fertilizer treatments.

Year-Summer Crop	Cover Crop	**N0**	**N1**	**N2**
			kg ha^{-1}	
1992-Corn	Cereal rye	101.0 (10.7)†	150.5 (19.7)	255.0 (39.9)
	Fallow	ND	ND	ND
1993-Broccoli	Cereal rye	95.3 (38.1)	169.5 (38.7)	165.3 (40.7)
	Fallow	87.0 (11.5)	182.5 (9.0)	176.5 (13.8)
1994-Corn	Cereal rye	19.3 (12.0)	49.0 (33.0)	59.8 (27.0)
	Fallow	30.8 (16.2)	46.8 (26.0)	76.0 (17.3)
1995-Broccoli	Triticale	ND	ND	ND
	Fallow	ND	ND	ND
1996-Corn	Triticale	46.0 (26.5)	92.3 (48.5)	165.3 (25.4)
	Fallow	49.3 (11.8)	93.3 (4.9)	163.0 (14.5)

†Number in parenthesis is percent coefficient of variability.

Soil NH_4-N also was not significant in the model. Ammonia-N is less readily leached from soil than NO_3-N because of its positive charge, which may partially explain the lack of significance NH_4-N had in the model. Generally, one would assume that a large pool of NH_4-N in the soil prior to the onset of winter would lead to increased NO_3-N leaching if mineralization was taking place. These soil data showed an increase in both NH_4-N and NO_3-N in fall for several years, so it is surprising that no significant linear relationship existed between NH_4-N and NO_3-N leaching in this study. These results, however, do not preclude that a nonlinear relationship existed between NH_4-N and NO_3-N leaching.

The amount of NO_3-N varies with depth in response to rainfall and crop uptake of N from year to year. This variability can cause difficulty in accurately predicting N leaching using multiple years of field data. Other researchers have experienced similar difficulties in predicting N leaching. Jemison and Fox (1994) attempted to predict leachate concentrations under N fertilized and manured corn treatments using nonlinear regression and found both significant and insignificant relationships between fall soil NO_3-N (mg kg $^{-1}$) and over-winter leachate concentrations of NO_3-N (mg L^{-1}). The significant relationships occurred within years, but the insignificant relationships took place across several years. Jemison and Fox (1994) explained that variations in soil NO_3-N with depth from year to year might have caused a decrease in the significance. Significant, but weak ($r = 0.45$-0.56) relationships also were present when the researchers compared leachate concentrations to total NO_3-N from 0-120 cm. These results indicate that year-to-year variations in soil N levels with depth make predictability difficult.

Cover crop N uptake is affected by the date of establishment and weather patterns in the fall. Improved cover crop N uptake in this study may have improved the significance of CCN. Vos and van der Putten (1997) using regression, showed the importance of sowing date for N accumulation by cover crops, based on data from sowing dates between late August and early October. They also showed that earlier sowing dates were positively correlated with greater cover crop dry matter yield, and Delgado (1998) showed improved soil NO_3-N scavenging by early-planted winter cover crops using NLEAP simulations. Research in western Oregon showed that cover crop growth positively correlated with the sum of growing degree days the crop experiences before the first frost and was negatively correlated with the quantity of rainfall during this growing period (Thomas Buford, August 1998, personal communication).

The amount of rainfall measured at the site (Table 3.2) was not well correlated ($r = 0.31$) with total quantity of leachate collected in the wick samplers. This result decreases the practicality of using leachate collected as an explanatory variable in the regression analysis. The low correlation of rainfall and leachate volume is probably due to changes in soil moisture storage during wetting-up periods in the fall and drying periods in the spring, and runoff during high intensity rainfall events. Nitrate leaching also is dependent on antecedent soil moisture (Martin et al., 1991) and will have a higher potential of leaching at higher soil moisture contents. Lucey and Goolsby (1993) found significant correlation between rainfall, change in soil moisture, and maximum daily loads of NO_3-N in streams using a MLR model. Their model explained up to 70% of variability in NO_3-N concentrations in Iowa streams from 1979 to 1990.

The four-variable MLR model was verified by correlating cumulative NO_3-N (kg ha^{-1}) from the data originally omitted during development of the model with predicted values using the four-variable regression equation. These data were moderately correlated (r = 0.65), but a paired-t test showed a significant difference between predicted and observed data.

A second correlation was made against observed data for the period of 1992 through 1996, under cereal cover crop treatments at the N2 fertilizer rate. These comparisons were made to detect the model's ability to predict NO_3-N leaching (Fig. 3.2). A significant (P = 0.05) and positive relationship (r = 0.96) was found between annual predicted and observed NO_3-N leaching.

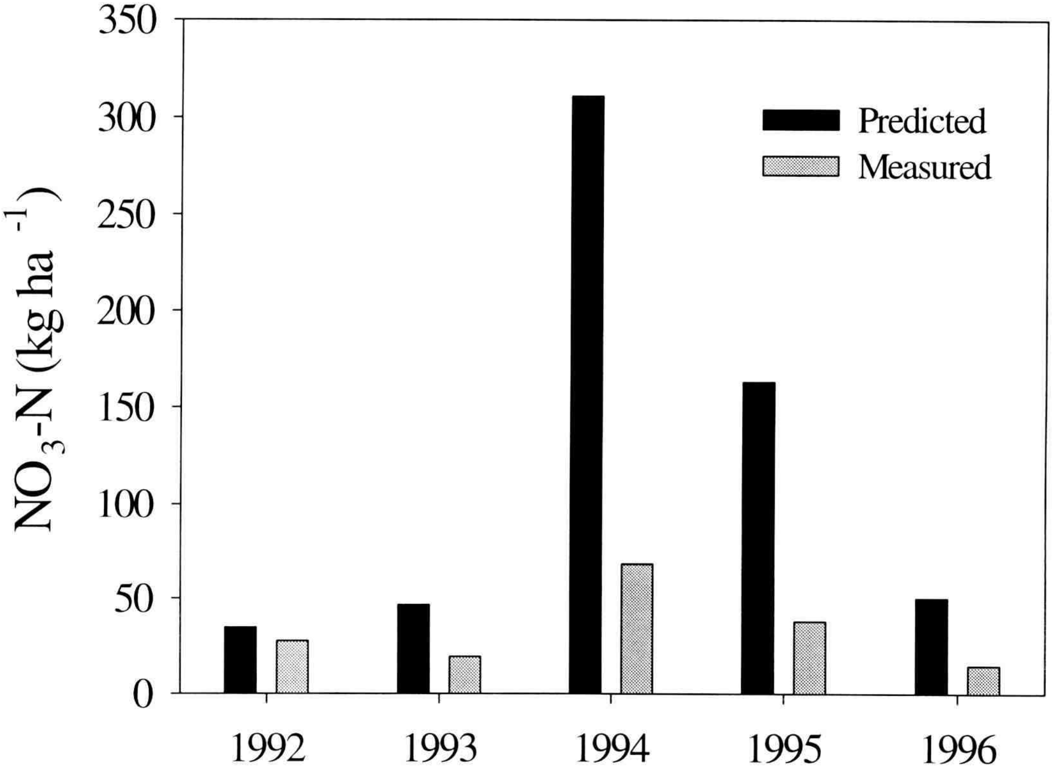

Figure 3.2. Comparison of measured and predicted NO_3-N leached under cereal cover crops at the N2 fertilizer rate, 1992-1995.

On average, the regression model predicted 77% more leaching than the observed values for the five-year period. Predicted average quantity leached was 149 kg N ha^{-1}y^{-1} compared to the observed average of 33 kg N ha^{-1}y^{-1}. Model prediction was closest to observed values in 1992 (34.6 compared to 27.7 kg N ha^{-1}y^{-1}), followed by 1993 (46.3 compared to 19.3 kg N ha^{-1}y^{-1}) and 1996 (50.1 compared to 14.7 kg N ha^{-1}y^{-1}). Model prediction in 1994 was highest (310.8 kg N ha^{-1} y^{-1}) compared to a observed quantity of 68.1 kg N ha^{-1}y^{-1}. Most of the discrepancy in the model predicted values in 1994 was probably a result of low mean N uptake by corn (59.8 kg N ha^{-1}) compared to 255 kg N ha^{-1} in 1992 and 165 kg N ha^{-1} in 1996 (Table 3.5).

Model accuracy for predicting NO_3-N leaching was not strong and is speculated to be attributed to the spatial and temporal variability in soil N dynamics, moisture content, temperature, percolation and climatic factors, as well as the inability of the wick samplers to intercept leachate at an efficiency greater than 80% (Brandi-Dohrn et al., 1996). The MLR model did not include data to explain significant temporal variations in soil dynamics, such as moisture fluctuations and changes in microbial biomass C and N, nor variations in cover crop N uptake. Other researchers have used stepwise multiple regression to explain temporal fluctuations in soil parameters. Perfect et al. (1990) explained up to 85% of temporal variation in soil structural stability between two cropping treatments by taking monthly samples and using stepwise multiple regression to explain variability for each sampling event.

Addition of physical soil properties such as variations in bulk density and field saturated hydraulic conductivity were not considered in this model. Little evidence exists that suggests spatial variations in field saturated hydraulic conductivity would further explain the variability in NO_3-N leaching. Contrary to the assumption that hydraulic conductivity is practical for assessing groundwater contamination risks, Hess (1995) showed that field-saturated hydraulic conductivity was not a good indicator of percolation at this site.

NLEAP Model Evaluation

Correlation of predicted monthly NO_3-N leaching and observed data varied from year to year, and correlation coefficients (r) ranged from -0.59 to 0.94. Realistic yield estimates for cereal rye and triticale were not possible because cover crops at the site were not allowed to mature, and yield estimates in NLEAP are not based on total dry biomass accumulation, but rather on total grain yield (kg ha^{-1}) when yield goals were calibrated for total N uptake. Results of the simulations are shown in Figure 3.3.

In 1992-1993, predicted leaching was negatively correlated ($r = -0.60$) to observed data, but a paired t-test showed the means between observed and predicted values were not significantly different ($P = 0.96$). In 1992-1993, NLEAP underestimated leaching in November, December, and January by an average of 5.79 kg ha^{-1} mo^{-1}, and over-estimated leaching in March, April and May, by an average of 5.83 kg ha^{-1} mo^{-1}.

Correlation was poor ($r = 0.21$) between monthly predicted and observed values for 1993-1994. In November and December1993, NLEAP under predicted NO_3-N leaching by 4.3 and 5.3 kg ha^{-1}. Predicted values were well matched to observed values in February and April, 1994, but NLEAP predicted greater leaching in March 1994 by 5.4 kg ha^{-1}.

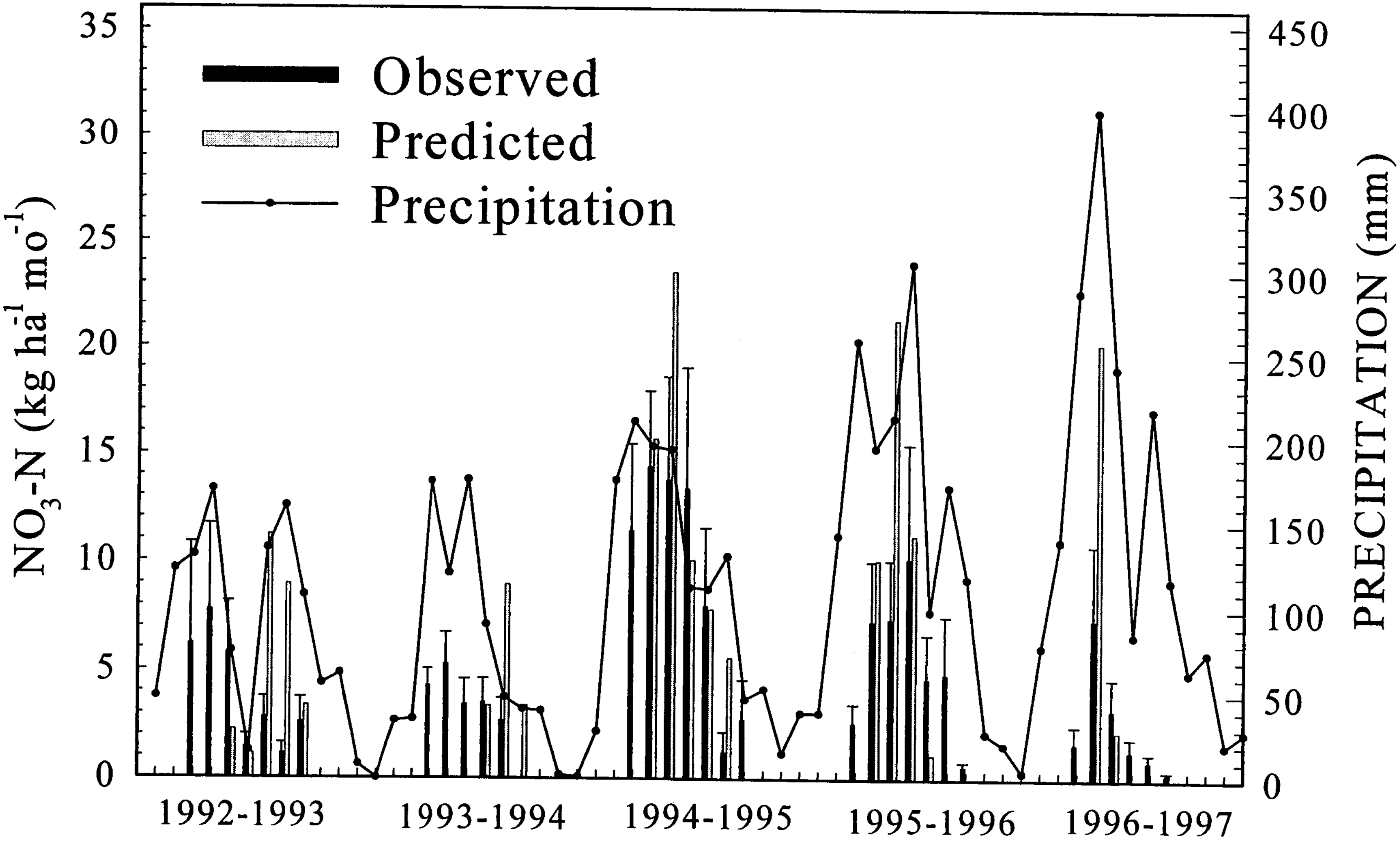

Fig. 3.3. Observed vs. NLEAP predicted NO_3-N leaching under cover crop at N2 rate. Error bars = standard error of mean of observed data.

For 1994-1995, predicted and observed NO_3-N leaching data were moderately well correlated ($r = 0.62$) and means were not significantly different ($P = 0.9$). Predicted values were higher than observed values in January and March 1995 by 9.7 and 4.4 kg N $ha^{-1.}$

In 1995-1996, correlation between observed and predicted values also was moderately good ($r = 0.70$) and showed no significant mean differences. Predicted NO_3-N leaching was 13.9 kg ha^{-1} greater than observed data in January 1996. From March to May 1996, NLEAP predicted greater quantities of NO_3-N leachate by an average of 3.3 kg ha^{-1}.

The best correlation between predicted and observed NO_3-N leaching was in 1996-1997 ($r = 0.94$). Again, a paired t-test showed no mean differences existed between predicted and observed monthly values ($P = 0.59$). The greatest discrepancy between observed and predicted data was in December 1996, when NLEAP predicted 20.2 kg N ha^{-1} compared to 7.4 ($\pm$ 3.4) kg N ha^{-1}.

With the exception of 1993, NLEAP predicted less NO_3-N leaching each November than observed values. Leaching in November at the North Willamette site is often variable and dominated by macropore flow before the soil reaches field capacity.

Sensitivity Analysis

Sensitivity analysis was done for NLEAP simulations from 1992 and 1994 to compare NLEAP response in an average rainfall year to a wet year (Table 3.6). Selected soil parameters, crop management and yield estimates were adjusted to detect relative changes in mineralization, NO_3 leaching (NL) and leaching potential (LP). The leaching

Table 3.6. Results of sensitivity analysis showing sensitivity as a percentage of change in leaching potential and NO_3 leaching.

Parameter	Input value		Change in Leaching Potential		Change in NO_3-N Leaching	
	Initial	Adjusted	1992†	1994‡	1992	1994
			%			
Percent organic matter (20 cm)	2.0	4.0	0	0	+8	+ 4
Bulk Density (g cm^{-3})	1.3 - 1.3¶	1.4 - 1.4	0	0	0	+ 2
Plant available water capacity (cm^3 cm^{-3})	0.34 - 0.34	0.19 - 0.19	+45	+32	+108	+ 22
Water content at start of run (cm^3 cm^{-3})	0.19 - 0.2	0.25 - 0.25	+15	+ 11	+33	+8
	0.19 - 0.2	0.34 - 0.34	+40	+29	+75	+10
Water Content at 1500 kPa (cm^3 cm^{-3})	0.12 - 0.15	0.09 - 0.12	+10	+7	+58	+8
Yield Estimate (kg ha^{-1})	1250	625	0	0	+108	+14
Yield Estimate (kg ha^{-1})	1250	2500	0	0	-41	-24

† Original LP and NL values in 1992 were 50.8 cm and 13.2 kg NO_3-N ha^{-1}.

‡ Original LP and NL values in 1994 were 71.1 cm and 53.9 kg NO_3-N ha^{-1}.

¶ The first number is the parameter for 0 to 30 cm depth, and the second number is for 30 to 150 cm.

potential is the predicted total quantity of leachate leached below the root zone (1.5 m). Yearly average of NLEAP inputs for crop residue may have been underestimated and averaged 250 kg ha^{-1} y^{-1}. When the cover crop residue quantity was increased to 1000 kg ha^{-1} the amount of N mineralized was only increased on average 0.1 kg ha^{-1} y^{-1}. Alternatively, the crop residue was entered as an incorporated organic waste with a C:N ratio of 50, at a rate of 250 kg ha^{-1} y^{-1} that was incorporated into the soil, and the model showed that predicted N mineralization was not sensitive to this change in management. These results suggest that the quality and C:N ratios of plant residue selected in the irrigation and N management file most likely limit rates of mineralization. Increasing organic matter from two to four percent in the top 20 cm increased NO_3-N leaching (NL) by 1.1 kg ha^{-1} in 1992 and 2.2 kg ha^{-1} in 1994 and had no effect on leaching potential for either year.

The model was not sensitive to an increase in bulk density from 1.3 to 1.4 g cm^{-3} in 1994, but increased NL by 1.1 kg in 1994. This result might have been caused by decrease in porosity and increased flow combined with increased rainfall compared to 1992.

Under field conditions, plant available water capacity (PAWC) can be variable with depth. To determine the effects of changing input parameters on model output data, PAWC was changed from 0.34 cm^3 cm^{-3}, to 0.19 cm^3 cm^{-3}. The results of these changes were that NL was increased by 14.3 kg in 1992 and by 12.1 kg in 1994, and LP was increased by 22.9 cm in 1992 and 1994.

The quantity of water-filled pore space (WFP) in the soil is important in predicting the amount of N leaching. When the water content at the start of the run was increased from 0.19 cm^3 cm^{-3} to 0.25 cm^3 cm^{-3}, LP and NL increased by the same amounts for both years. The increases were 7.6 cm for LP and 4.4 kg for NL. The initial water content again was raised to 0.34 cm/cm, and the increase in LP was the same for both years (20.3 cm), but NL was different. The NL increased 9.9 kg in 1992 and 5.5 kg in 1994.

The original input value for water content at –1500 kPa was decreased by four percent in the top 30 cm and by three percent from 30 to 120 cm (Table 3.6). After this change, LP was increased by 5.1 cm for both years, and NL increased by 7.7 kg in 1992 and 4.4 kg in 1994. The increase in LP and NL is probably a result of increased average pore size when water content is lowered since larger pores do not hold water as strongly at lower potentials as do smaller pores. This shift in pore size would cause more water to be leached at a lower water content at wilting point, or reduce the water holding capacity of the soil.

In 1992, when cover crop yield estimates were lowered from 2500 to 1250 kg ha^{-1}, LP did not change, but NL increased by 14.3 kg. If yield estimates were increased to 3760 kg ha^{-1}, again no change in LP occurred, but a decrease of 5.5 kg in NL was observed. In 1994, the cover crop yield estimate was lowered from 1250 to 625 kg ha^{-1}, LP showed no change and NL increased by 7.7 kg. When yield estimates were increased to 2500 kg ha^{-1}, LP again showed no change and NL decreased 13.2 kg. These results indicate that yield estimates have a greater affect on N uptake potential than evapotranspiration or water uptake, and that the change in NL is not linearly related to yield estimates. The ability to enter annual N uptake by crops could aid in the prediction of N leaching in the soil profile. Smith et al. (1998) successfully used the model LEACHN to predict NO_3-N leaching in clay soils. The model LEACHN does not predict N uptake or crop growth, but uses annual input data for N uptake.

Nitrate leaching output by NLEAP was sensitive to yield goal estimates entered in the crop and management file. Yield goal ranges were calibrated for total NO_3-N leaching values obtained from field data. Selecting yield estimates in this manner may distort actual N uptake by the cover crop. Therefore, yield goal estimates were not necessarily in agreement with actual crop data.

The results of this NLEAP simulation support other research that shows relative quantities of annual NO_3-N leaching is determined by amount of total soil NO_3-N in fall (Macdonald et al., 1989). A qualitative estimate of NO_3-N leaching risk is done by NLEAP based on the quantity of residual NO_3-N available in the soil that may be leached below the root zone (1.5 m). Accordingly, a low rating for NO_3-N leaching risk is 0 to 40 kg N ha^{-1}, a medium rating is 40 to 80 kg N ha^{-1}, and a high rating is > 80 kg N ha^{-1} (Pierce et al., 1991; Shaffer et al., 1991). The high variability in annual precipitation during the study and possible under-sampling during winter 1995-1996 may have contributed to poor predictions by the model. In addition, initial field soil moisture was estimated from precipitation data during each simulation. On average NLEAP predicted greater total NO_3-N leaching by 27% for all five years (Fig. 3.3).

Observed and predicted leachate volume data were well correlated the first three years ($r = 0.99$), but greater quantities were predicted for 1995-1996 and 1996-1997 (Table 3.7). Annual runoff potential estimation by NLEAP ranged from a low of 0.8 cm in 1992-1993 to a high of 11.7 cm in 1995-1996 with the highest monthly runoff predicted in February 1996 (7 cm), followed by 5.6 cm in November 1996, 5.1 cm in April

1995 and 5.0 cm in March 1996. Nitrate leaching risk potential was rated low for the dry and average rainfall-years of 1992 and 1993, and NLPR was high for the high rainfall-years 1994 through 1996.

Table 3.7. NLEAP predicted and observed leachate volumes under winter cover crop, and NO_3-N leaching risk potential (NLRP).

Year	Predicted leachate volume	Observed leachate volume (SE)	NLRP
	cm	cm	
1992	40.4	35.2 (5.8)	Low
1993	18.8	20.7 (3.3)	Low
1994	65	53.6 (5.8)	High
1995	77	37.5 (9.0)	High
1996	89.9	34.2 (12.1)	High

A key component of the model N transformations that our field data did not contain was denitrification potential. Denitrification was estimated by NLEAP in the upper profile using the following formula taken from Shaffer et al. (1991).

In this study, denitrification estimates by NLEAP were highest from September through November when mean daily temperatures were above 40°F (4.4°C) and soil NO_3-N concentrations were highest in the top 30 cm. Predicted denitrification was nearly zero from January to June. Annual denitrification estimates ranged from a low of 4.7 kg N ha^{-1} y^{-1} in 1993-1994 to a high of 19.5 kg N ha^{-1} y^{-1} in 1995-1996. Wide variations in measured denitrification have been reported and are common. For example, reported amounts of denitrification in poorly drained soils of the Willamette Valley, OR range from 3 kg N yr^{-1} (Myrold, 1988) to 30 kg N yr^{-1} (Horwath et al., 1998). In Horwath et al.'s (1998) study, the denitrification rates were observed in spring when mean soil temperatures ranged from 13 to 16°C and soil NO_3-N concentrations were as high as 12 kg ha^{-1}. In our study, soil NO_3-N averaged 15.8 ± 0.8 kg ha^{-1} in the top 20 cm of soil on 11 May 1996 and 6.9 ± 2.3 kg ha^{-1} on 18 April 1997, indicating soil N was not limiting for denitrification activity in spring months. These conditions suggest that NLEAP might underestimate denitrification during spring in western Oregon.

Critical data that were missing and had to be estimated for the model were soil moisture content at the start of the run. Adapting NLEAP to be used with a winter cover crop was problematic for two reasons: 1) the initial soil input parameters does not allow the user to define amount of soil NH_4-N in the soil at the start of the run, and 2) the selection of cover crops is limited. The crop management file allows users to define management systems for multiple crops, but the model was sensitive to the time of planting when only the period of the cover crop growth (September to May) was evaluated, excluding the summer crop cycle. When the summer crop cycle was excluded, inputs of fertilizer also were excluded. The user can still define the amount of residual soil NO_3-N from 0 to 1.5 m but not the amount of NH_4-N. Consequently, without a term for the oxidation of NH_4-N to NO_3-N, the amount of nitrification occurring during winter may be underestimated. The loss of this term limits nitrification to the soil organic matter (OM) fraction, where mineralization of the OM fraction is assumed to be 2% yr^{-1} by the program.

The NH_4-N content in the top 30 cm of soil is the sum of inputs that come from fertilizers, manures, organic wastes, precipitation and irrigation, organic matter, crop residues, and residual soil NH_4-N from the previous time step minus plant uptake of residual soil NH_4-N from the previous time step, NH_3-N volatilization, and NH_4-N lost to runoff. Mineralized N estimates by NLEAP averaged only 3.7 kg N yr^{-1} for all five years.

Perspectives

These modeling experiments show the importance of climate variability on modeling whole soil-crop systems. Modeling vegetable rotation systems with winter cover crops is challenging because of the short growing seasons and high inputs of fertilizer N (Cavero et al., 1998). Microbial processes are difficult to quantify and pose a problem in modeling soil-crop systems for improving agronomic efficiency and decreasing pollution (Molina and Smith, 1998). The model NLEAP was not designed to answer every question of nitrate leaching (Shaffer et al., 1991); therefore, applications for research purposes pose certain limitations:

1. Keyboard data entry: All data inputs are done at the keyboard. Although keyboard input is practical for small data sets and single-year simulations, it makes the task of simulating large data sets time consuming;
2. No SI units: NLEAP does not use SI units. NLEAP's practicality as an international tool for predicting leaching is also limited by its reliance on the English system.
3. Limits to kind of crops grown: NLEAP allows user to choose 10 crops (winter wheat, sunflower, alfalfa, soybean, sugar beats, potatoes, grain silage, sorghum silage, corn silage, and fallow).
4. Nitrogen transformations are limited to the upper profile, which may cause an underestimation of the denitrification potential in the lower horizons.
5. Does not allow input of annual N uptake by crops.

Despite these limitations as a research tool, NLEAP may still serve a practical need for people who wish to assess the potential risks of NO_3-N leaching on a site-specific and regional scale. The difficulty of relying on yield goals to adjust for N uptake precluded the ability to conduct an accurate N balance.

Both NLEAP and the MLR model predicted greater NO3-N leaching during wet years. Factors responsible for these differences can be attributed to 1) low spatial correlation of percolation rates at the research site; 2) uneven root uptake patterns; 3) spatial variability of soil 4) variations in climate; 5) less than 100% efficiency in sampling percolation. During years of low to average rainfall, the MLR prediction was more closely matched to the observed values. During average rainfall years, collection efficiency of the samplers tends to be higher. Both NLEAP and the MLR model can be good qualitative predictors for relative amounts of NO_3-N leaching if the residual fertilizer N concentrations in the top meter of soil is known.

The MLR results lend support to the concept that nitrate leaching is dependent upon many factors that occur prior to the onset of winter, including summer crop performance, N fertilizer application rates, and residual inorganic soil N. Two dominant factors that contribute to the accuracy of model predictions are amount of rainfall and changes in soil moisture storage.

Better prediction with NLEAP can be achieved when actual climate data is used in the monthly analysis then if mean climatic values are used. The model is sensitive to yield goal estimates and soil moisture input. The use of NLEAP in western Oregon is limited by the kind of crops that can be selected by the model, especially vegetable crops and cover crops. Reducing or increasing yield estimates can adjust for some of these limitations, but these adjustments may distort the outcome of the simulation.

These results also show that NO_3-N leaching is not determined by the rate of fertilizer application alone. More models need to be developed for soil-crop systems to decrease the incidence of pollution from farming and to increase the efficiency of agriculture. The choice of model to be used is largely driven by the question to be answered in an agronomic system. Applied models for agricultural producers must be simple enough to do timely analyses.

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SUMMARY

Nitrogen cycling in vegetable rotation systems is a dynamic process and often associated with high N inputs and a high variability in N uptake patterns. This study showed that NO_3-N leaching was significantly lower under triticale ($P < 0.01$), a cereal cover crop, compared to winter-fallow at all fertilizer rates: zero (N0), medium (N1), and recommended (N2). In 1995, mean NO_3-N concentrations (mg L^{-1}) collected under triticale and fallow treatments, respectively, were 3.6 and 5.9 at N0 rate, 7.8 and 11.4 at N1 rate, and 11.0 and 18.5 at N2 rate. Mean NO_3-N concentrations (mg L^{-1}), collected under triticale and fallow treatments in 1996, were 1.3 and 2.0 at N0 rate, 1.3 and 2.4 at N1 rate, and 4.4 and 6.1 at N2 rate. Higher fertilizer rates generally resulted in significantly higher NO_3-N leaching except in 1996, when differences between N0 and N1 rates were not found to be significant.

Inorganic soil N concentrations were more affected by N rate, climate and summer crop N uptake than by cover crop N uptake. Cover crop type and sowing method (i.e. relay-planted or fall-planted) generally had no effect on soil NO_3-N or NH_4-N, except in fall of 1995 when fallow treatments had significantly higher soil NO_3-N and NH_4-N concentrations than the triticale treatments from 0 to 20 cm. Fertilizer N rate had significant effects in 1995 on inorganic soil N, with higher N rates resulting in higher soil N concentrations. This result was probably due to low N uptake by the summer broccoli crop. No fertilizer treatment or cover crop differences in inorganic soil N were observed the following February 1996 from 0 to 80 cm. Fertilizer N treatment effects on inorganic soil N observed in September of each year were eradicated by February, most likely a result of high rainfall that leached NO_3-N below 80 cm and possible denitrification. In fall 1996, fertilizer N rate had no significant effects on inorganic soil N, as the summer corn crop captured a large quantity of fertilizer N.

The unrelated results between NO_3-N collected in leachate and that collected in soil samples could suggest differential microbial populations and activities with respect to pore-size distribution. In this regard, one would assume the NO_3-N collected in leachate could predominantly come from a different pore-size distribution than NO_3-N sampled by the soil probe. These results also might indicate that more sensitive tests and analyses need to be developed to understand the temporal changes in NO_3-N fluxes with respect to soil sampling methods.

A statistical model was developed from five years of field plot data using multiple linear regression. Fall soil NO_3-N (kg ha^{-1}) was found to be the most significant variable ($P < 0.001$) for predicting NO_3-N leaching ($r^2 = 0.31$), followed by leachate volume collected ($r^2 = 0.19$), vegetable N uptake ($r^2 = 0.04$), and fertilizer N rate ($r^2 = 0.02$). Together, these four variables explained 57% of the variability in NO_3-N leaching from 1992 to 1997. Soil NH_4-N and cover crop N uptake were not significantly correlated to NO_3-N leaching. These results suggest that post-harvest/fall-soil NO_3-N content and rainfall quantity are critical factors in western Oregon, affecting NO_3-N contamination of groundwater from agriculture. A steady decline in cover crop N uptake from 1994 to 1997, during three very wet winters, may have contributed to the lack of significance of cover crop N uptake in the regression model.

NLEAP was used to simulate winter leaching data in a Mediterranean climate between November and May, from 1992 to 1997 at the recommended fertilizer rate, under cereal cover crops. NLEAP performed total-annual NO_3-N leaching simulations well. Monthly NO_3-N leaching simulation was less accurate. Better monthly correlation between simulated and measured NO_3-N leaching (kg ha^{-1}) was achieved during wet years of 1994, 1995 and 1997 (r = 0.62, 0.70, and 0.94) than in normal to dry years of 1992 and 1993 (r = -0.6 and 0.21). These correlation differences may be attributed to less uniform soil moisture profiles during drier periods compared to wetter periods. NLEAP was found to be sensitive to yield input data of the cover crop as well as antecedent soil moisture content. Crop selection parameters of NLEAP were limited for vegetable rotation/winter cover crop systems.

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