NLEAP Computer Model and Multiple Linear Regression Prediction of Nitrate Leaching in Vegetable Systems

Hudson Minshew,[1]
John Selker,[2]
Delbert Hemphill,[3] and
Richard P. Dick[4]

SUMMARY. **Predicting leaching of residual soil nitrate-nitrogen (NO_3-N) in wet climates is important for reducing risks of groundwater contamination and conserving soil N. The goal of this research was to determine the potential to use easily measurable or readily available soil–climatic–plant data that could be put into simple computer models and used to predict NO_3 leaching under various management systems. Two computer programs were compared for their potential to predict monthly NO_3-N leaching losses in western Oregon vegetable systems with or without cover crops. The models were a statistical multiple linear regression (MLR) model and the commercially available Nitrate Leaching and Economical Analysis Package model (NLEAP 1.13). The best MLR model found using stepwise regression to predict annual leachate NO_3-N had four independent variables (log transformed fall soil NO_3-N, leachate volume, summer crop N uptake, and N fertilizer rate) ($P < 0.001$, $R^2 = 0.57$). Comparisons were made between NLEAP and field data for mass of NO_3-N leached between the months of September and May from 1992 to 1997. Predictions with NLEAP showed greater correlation 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 vegetation management choices were limiting for vegetable crops and for systems that included a cover crop.**

There is great interest in developing agricultural management systems to reduce N fertilizer losses to ground water or to identify situations where there are high risks for N pollution of ground water. In Oregon's Willamette Valley, roughly 500,000 people rely on ground water from shallow alluvial aquifers for domestic use [U.S. Geological Survey (USGS), 1998]. As population growth is expected to increase in the future, so will the importance of optimizing agricultural systems that protect the quality of ground water 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. These models could be useful if a few easily measurable soil properties could be used as input data to predict how various management systems will affect N ground water pollution.

There are a variety of such models available to predict N losses that include CERES (Quemada and Cabrera, 1995), LEACHM (Jabro et al., 1995; Wagenet and Hutson, 1989), NTRM (Radke et al., 1991), APSIM (Asseng et al., 1998), the CENTURY model (Parton et al., 1988), and NLEAP (version 1.13; Soil Science Society of America, Inc., Madison Wis.) (Shaffer et al., 1991). We chose NLEAP because agricultural professionals could more readily adopt it. This program has successfully predicted site specific (Follett, 1995; Follett et al., 1994) and regional NO_3 leaching (Shaffer et al., 1996; Wylie et al., 1995).

Until now, no studies have been done to evaluate NLEAP for its ability to predict NO_3 leaching in a Mediterranean climate (dry summers, wet winters) such as that found in western Oregon and Washington. Most soil-crop system models have been tested on nonvegetable systems without cover crops (Cavero et al., 1998).

Stepwise MLR can be a powerful tool to aid researchers in selecting the minimum number of independent variables from data sets with a large number of variables as predictors of a dependent variable (our dependent variable or what we wanted to predict was NO3 leaching). Few agricultural studies have used field-plot N data and regression analysis as a model for predicting potential NO_3 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), phosphorous availability (Afif et al., 1993), and temporal structural stability of soil within crop treatments (Perfect et al., 1990). Bauder et al. (1993) used MLR to explain the variability in county average-well-sample NO_3 concentrations using 67 independent variables; Lucey and Goolsby (1993) used MLR to predict NO_3 concentrations in a river from climatic and stream-flow data. A multiple regression model would be even simpler to use than the other computer models mentioned above, and so we wanted to determine the potential of this model to predict NO_3 leaching and compare it to NLEAP.

The objectives for this study were to 1) develop a simple statistical MLR model to predict annual NO_3-N leaching; 2) evaluate the MLR and NLEAP model's for their ability to predict NO_3-N leaching in vegetable crops of western Oregon; and 3) evaluate the practicality of these models to be used by agricultural professionals for assessing impacts of cropping systems on N losses to groundwater.

Materials and methods

Soil, crop and leachate data were collected during 5 years (1992–97) from a cover crop and vegetable rotation study at a 0.89 ha (2.2 acre) site at the Oregon State University, North Willamette Research and Extension Center in Aurora. The soil is of glaciolacustrine 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 northeast to southeast. General soil characteristics [0 to 20 cm (8 inches)] of the site were reported by Bandick (1997) and are given in Table 1. Slopes range from 0 to 3%. Average annual rainfall was 1036 mm (40.7 inches), 75% to 80% of which falls from October through March (USGS, 1998). Average rain-

---

[1] Department of Crop and Soil Science, Oregon State University, Corvallis.

[2] Department of Bioresource Engineering, Oregon State University, Corvallis.

[3] North Willamette Research and Extension Center, Oregon State University, Aurora.

[4] Department of Crop and Soil Science, Oregon State University, Corvallis; Corresponding author; e-mail Richard.Dick@orst.edu.

fall data from 1992–96 are given in Table 2. The mean annual temperature was 11 °C (19.8 °F).

The experimental design was a randomized complete block split plot, with a summer vegetable rotation in combination with winter cover crops or winter fallow (control) as the whole-plot treatment that was started in the fall of 1989. Summer vegetable crops were broccoli (*Brassica oleracea* cv. Gem), grown in 1991, 1993, 1995, and 1997, and sweet corn (*Zea mays* cv. Jubilee), grown in 1990, 1994, and 1996. In 1992 the winter fallow–conventional treatment winter wheat (*Triticum aestivum*) was grown to mimic the conventional crop rotations that farmers generally did at that time; but the winter cover plot plots did have corn. Summer crops were managed as described by Burket et al. (1997). Whole plots were 9 × 18 m (29.25 × 58.5 ft), and each whole plot was divided into three split-plot treatments [54 m^2 (581 ft^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} (0, 50 or 200 lb/acre) of N. Broccoli split-plots were fertilized at 0 (N0), 140 (N1), and 280 (N2) kg·ha^{-1} (0, 125 or 250 lb/acre) of N. Summer crops were irrigated as needed.

Weeds were managed with a cultivator, hand weeding and with herbicides. Herbicides and rates of application were as follows: Atrazine at 2.24 kg·ha^{-1} (2.0 lb/acre) or alachlor at 3.36 kg·ha^{-1} (3.0 lb/acre) for sweet corn and trifluran at 0.84 kg·ha^{-1} (0.75 lb/acre) for broccoli. Postharvest residue was incorporated by plowing and disking before planting the cover crop.

Winter cover crop treatments were fall-planted cereal rye (*Secale cereale*) in winters from 1992 until Fall 1995, when it was replaced by 'Celia' triticale (Tritcosecale X). The cover crops received no fertilization. Seeding rates were 73 kg·ha^{-1} (65 lb/acre) for both. Aboveground biomass samples were taken from 1.0 m^2 (10.8 ft^2) areas from each subplot in spring. A 0.5-kg (1.1-lb) subsample was saved from each sample 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 (6 inches).

During the 5-year study, soil samples from 0 to 120 cm (47 inches) depth were taken in September and in February from 0 to 80 cm (31 inches) depth according to Kauffman (1994). Leachate samples were taken from passive capillary wick samplers as described by Brandi-Dohrn et al. (1997).

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. About 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 linear model development [variables having correlation coefficient values (r) > 0.60 were not included in the same model] (Henao, 1976) to avoid models with artificially high R^2 values but low predictive value. Stepwise MLR was performed using PROC REG with the STEPWISE option in SAS version 6.13 for Windows (SAS, 1996) to develop the MLR model for predicting NO_3 leaching.

Residuals were analyzed to confirm the assumption of linearity after log transformation. Missing data for the regression model included summer crop data from the winter fallow treatment (this treatment was in wheat that summer) in 1992 and summer crop data from 1995, when the broccoli crop failed and no crop data were collected.

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 1992–93 to 1996–97. 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

Table 1. General soil characteristics at North Willamette Research and Extension Center, Aurora, Ore., vegetable rotation site [0–20 cm (8 inches) depth].

		Parameter	
pH	**Bulk density**	**Total C g·cm^{-3} (%)**	**Total N g·kg^{-1} soil (%)**
5.8	1.24	16.8 (1.7)	1.045 (0.104)

Table 2. Crop-year rainfall during study. Thirty-year mean rainfall for months from September to September was 103 cm (40.7 inches) and from November through April was 76.9 cm (30.3 inches).

	Rainfall cm (inches)	
Year	**September–September**	**November–April**
1992	107 (42)	69 (27)
1993	76 (30)	66 (26)
1994	132 (52)	97 (38)
1995	160 (63)	124 (49)
1996	175 (69)	135 (53)

Table 3. Selected soil input data used for NLEAP modeling.

Parameter	Input
Soil textural class	Silt loam
Hydrologic group	B
Slope	1%
Drainage class	Moderately well drained
Landscape position	Flood plain
Organic matter	2.0%
Bulk density	1.3 g·cm^{-3}

crops cereal rye (1992–93 to 1994–95) and triticale (1995–96 to 1996–97). 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 was done on several input parameters to determine their relative effects on NO_3-N leaching.

Climate 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 (0.04 inches) of rainfall. 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 1992–93 (average-rainfall year) and 1993–94 (dry rainfall-year). The years 1994, 1995, and 1996 were considered wet years because rainfall during these 3 years was about 127, 150 and 200% above the 30-year average for 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 as well as soil parameter values found in Table 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 (1 ft) and to the bottom of the root zone at a maximum of 1.5 m (5 ft). All soil carbon (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 fall soil NO_3-N ($kg \cdot ha^{-1}$ of N per year), fertilizer N rate (Nrate), summer crop N uptake (SCN), and amount of leachate collected by wick samplers (cm^3) were used as predictor variables for total NO_3-N leached annually (Table 4). Fall soil NO_3-N ($kg \cdot ha^{-1}$ of N) explained 31% 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, cover crop N uptake (CCN), total inorganic soil N (NO_3-N + NH_4-N) and fall soil NH_4-N ($kg \cdot ha^{-1}$ of N) were not significant as independent variables. Summer crops generally took up more N with increased fertilizer (Table 5), which did not happen for cereal cover crops from 1994–97 and may explain the lack of significance that CCN and cover crop biomass had for the model (data not shown).

From Fall 1991 to July 1992, the winter-fallow plots had winter wheat thus there was no corn yield for winter-fallow plots for 1992. In 1995 the summer broccoli crop failed (Table 5) and no broccoli yield data was taken. This might have affected the importance of crop yield as an independent variable in the model development shown in Table 4. Removal of crop year data collected in 1995–96 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.

Soil NH_4-N also was not significant in the model. Ammonium-N is less susceptible to leaching and is more stable over time than NO_3-N, which likely accounts for these results.

The amount of rainfall measured at the site (Table 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 rainfall or leachate volume as explanatory variables in a regression model. The low correlation between 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. 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 that a MLR model that included rainfall and the change in soil moisture for predicting maximum daily loads of NO_3-N explained up to 70% of variability in NO_3-N concentrations in Iowa streams from 1979 to 1990.

The four-variable MLR model was validated by using input data from the independent variables of data that was not used in the original model development. The predicted and observed NO_3-N leaching values based on the subset of validation data were moderately correlated ($r = 0.65$), but a paired *t* test showed a significant difference between predicted and observed data (data not shown).

A second correlation of annual, cumulative predicted NO_3-N leaching data was made against all observed NO_3-N leaching data for the period of 1992 through 1996, under cereal cover crop treatments at the N2 fertilizer rate (Fig. 1). A significant ($P = 0.05$) and positive relationship ($r = 0.96$) was found between annual predicted and observed NO_3-N leaching. On average, the MLR model predicted 77% more leaching than the observed values for the 5-year period. Predicted average quantity leached was 149 $kg \cdot ha^{-1}$ (133 lb/acre) of N per year compared to the observed average of 33 $kg \cdot ha^{-1}$ (29.5 lb/acre) of N per year. Model prediction was closest to observed values in 1992, 34.6 compared to 27.7 $kg \cdot ha^{-1}$ (30.9 to 24.7 lb/acre) of N per year, followed by 1993, 46.3 compared to 19.3 $kg \cdot ha^{-1}$ (41.3 to 17.2 lb/acre) of N per year and 1996, 50.1 compared to 14.7 $kg \cdot ha^{-1}$ (44.7 to 13.1 lb/acre) of N per year. Model prediction in 1994 was highest at 310.8 $kg \cdot ha^{-1}$ (277.5 lb/acre) of N per year compared to an observed quantity of 68.1 $kg \cdot ha^{-1}$ (60.8 lb/acre) of N per year. Most of the discrepancy in the model predicted values in 1994 was probably a result of low mean N uptake by corn [59.8 $kg \cdot ha^{-1}$ (53.4 lb/

Table 4. Regression equations predicting log nitrate-nitrogen (NO_3-N) leaching as kg·ha^{-1} of N per year (Y); 1.0 kg·ha^{-1} = 0.89 lb/acre.

Model equation	R^2
Y = 0.81 + 0.30(log fall-soil NO_3-N)***	0.31
Y = –0.53 + 0.30(log fall-soil NO_3-N) + 0.025(leachate volume)*	0.50
Y = –0.15 + 0.30(log fall-soil NO_3-N) + 0.025(leachate volume) + 0.0032(N rate)*	0.53
Y = –0.48 + 0.30(log fall-soil NO_3-N) + 0.025(leachate volume) + 0.0032(N rate) – 0.0027(summer crop N uptake)*	0.57

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

Table 5. Mean nitrogen (N) uptake by summer crops under winter fallow or winter cover crops at three N fertilizer rates for summer vegetable crops. Data were used for both multiple linear regression development and NLEAP testing.

Year–summer crop	Cover crop	N uptake kg·ha^{-1} of N^{y} (CV)^{x}		
		N0^{z}	N1	N2
1992, Corn	Cereal rye	101.0 (10.7)	150.5 (19.7)	255.0 (39.9)
	Fallow	ND^{w}	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)

^{z}Zero (N0), intermediate (N1), and recommended (N2) N fertilizer rate.
^{y}1.0 kg·ha^{-1} = 0.89 lb/acre.
^{x}Number in parenthesis is percent coefficient of variation.
^{w}ND = not determined.

acre)] of N compared to 255 kg·ha^{-1} (227.7 lb/acre) of N in 1992 and 165 kg·ha^{-1} (147.3 lb/acre) of N in 1996 (Table 5).

Based on nonlinear regression of fall soil NO_3-N [mg·kg^{-1} (ppm) of N] versus winter NO_3-N leachate concentrations, Jemison and Fox (1994) suggested that the amount of NO_3 varies with depth in response to rainfall and crop uptake of N from year to year. These results indicate that year-to-year variations in soil N levels with depth make predictions difficult. Model accuracy for predicting NO_3 leaching was not strong and is speculated to be attributed to the spatial and temporal variability in soil N dynamics (e.g. N mineralization, microbial biomass N immobilization), 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).

Our goal was to develop a MLR model with easily measurable soil properties to predict NO_3 leaching that would only need to be measured in the fall before the leaching period. This precluded the use of temporally dynamic properties that require frequent sampling like microbial biomass C and N, N mineralization potential, and soil moisture. Perfect et al. (1990) measured various properties on a monthly basis. Using multiple regression they explained up to 85% of temporal variation in predicting soil structural stability between two cropping systems. Lack of incorporation of temporal dynamics in our MLR model development may have limited its potential to adequately predict NO_3 leaching.

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 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.

The results show that the complexity of NO_3 leaching is not well captured with a few independent variables in MLR model. This may not be surprising because of the complexity and temporal dynamics of biological and physical properties that control N cycling and hydrology. A further complication is that leachate volume was needed to significantly increase the predictability of the model (Table 4) but was not correlated with rainfall volume and thus this variable can not be measured easily by practitioners for use in this MLR model.

EVALUATION OF NLEAP. With the exception of 1993, NLEAP predicted less NO_3-N leaching each November than observed values (Fig. 2). Leaching in November at the North Willamette site is often variable and dominated by macropore flow before the soil reaches field capacity.

Correlation of predicted monthly NO_3-N leaching and observed data varied from year to year, and correlation coefficients 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. Yield estimates in NLEAP are not based on total dry biomass accumulation, but rather on total grain yield (lb/acre) when yield goals were calibrated for total N uptake.

Correlation coefficients within a year between predicted and observed NO_3-N leaching ranged from lows of –0.60 to 0.21 (1992 and 1994) and highs of 0.62 to 0.94 (other years). These years with high correlations also showed no significant differences (*t* test) between predicted and observed monthly values for NO_3-N leaching.

SENSITIVITY ANALYSIS OF NLEAP. Sensitivity analysis can be a useful tool to determine which input variables for the model are important in affecting the predictions of the model. This is simply done by making a series of runs where a range of values are put in the model for a given variable while other variables in the model are held constant. Sensitivity analysis was done for NLEAP simulations for

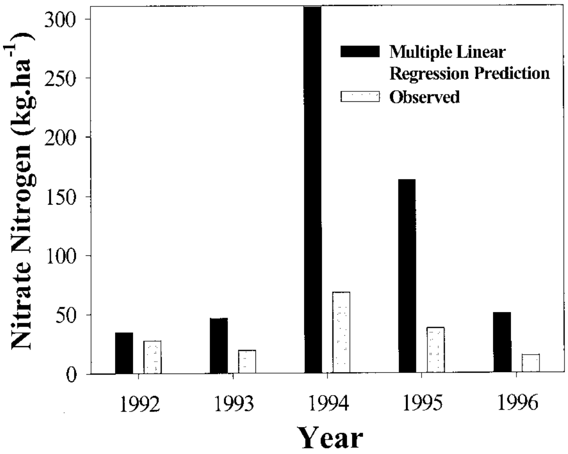

Fig. 1. Comparison of measured and predicted nitrate-nitrogen leached under cereal cover crops at the recommended nitrogen fertilizer rate (N2), using the equation developed by multiple linear regression 1992–95 data; 1 kg·ha^{-1} = 0.89 lb/acre.

1992, an average rainfall year, and 1994, a wet year, 1994. Selected soil parameters, crop management and yield estimates were adjusted to detect relative changes in N mineralization, NO_3 leaching and leachate volume. The leaching volume is the predicted total quantity of leachate volume leached below the root zone (1.5 m).

Residue quantity and quality (C to N ratios) controls N mineralization in NLEAP but running the model with a wide range of values for these input values had little effect on N mineralization prediction by NLEAP. Increasing organic matter from 2 to 4% in the top 20 cm increased NO_3-N leaching by 1.1 kg·ha^{-1} (1.0 lb/acre) of N in 1992 and 2.2 kg·ha^{-1} (1.9 lb/acre) of N in 1994 and had no effect on leaching potential for either year.

The model was not sensitive to bulk density or changes in soil organic matter and moderately sensitive to water-filled pore space in predicting either NO_3 leaching or leaching volume. But changing plant available water capacity (PAWC) from 0.34 to 0.19 cm^3·cm^{-3} (inches^3/inch^3) caused NO_3 leaching to increase 14.3 kg·ha^{-1} (12.9 lb/acre) of N in 1992 and by 12.1 kg·ha^{-1} (10.9 lb/acre) of N in 1994, and leaching volume by 22.9 cm (9.0 inches) in 1992 and 1994.

As expected increasing water content at the start of the run increased leaching volume. Similarly, NO_3-leaching losses increased 9.9 kg·ha^{-1} (8.9 lb/acre) of N in 1992 and 5.5 kg·ha^{-1} (4.9 lb/acre) of N in 1994 when initial water content was increased from 0.19 to 0.25 cm·cm^{-1} (inches/inch).

Cover crop yield changes did not affect leaching volume but it was inversely and linearly related to NO_3 leaching where lowering cover crop biomass from 2500 to 1250 kg·ha^{-1} (2232 to 1116 lb/acre) it increased losses by 14.3 kg·ha^{-1} (12.7 lb/acre) of N in 1992 and 7.7 kg·ha^{-1} (6.8 lb/acre) of N in 1994.

The ability to enter annual N uptake by crops could aid in the prediction of N leaching in the soil profile, which was shown for the LEACHN model by Smith et al. (1998). This may be a feature that could be added to NLEAP to improve prediction of NO_3 leaching.

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 available in the soil that may be leached below the root zone 1.5 m.

OTHER CONSIDERATIONS FOR NLEAP. The high variability in annual precipitation during the study and possible undersampling of the lysimeters during winter 1995–96 may have contributed to variable 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 5 years.

Observed and predicted leachate volume data were well correlated the first 3 years (r = 0.99), but this was overestimated for 1995–96 and 1996–97 (Table 6). Annual runoff potential estimation by NLEAP ranged from a low of 0.8 cm (0.3 inches) in 1992–93 to a high of 11.7 cm (4.6 inches) in 1995–96 with the highest monthly runoff predicted in February 1996 at 7 cm (2.8 inches), followed by 5.6 cm (2.2 inches) in November 1996, 5.1 cm (2.0 inches) in April 1995 and 5.0 cm (1.9 inches) in March 1996. Nitrate leaching risk potential was rated low for the dry and average-rainfall years of 1992 and 1993, and was high for the high rainfall-years 1994 through 1996 (Table 6).

A key component of the model is denitrification, which was not measured in our study. Denitrification was estimated by NLEAP in the upper profile using the 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 4.4 °C (40 °F) and soil NO_3-N con-

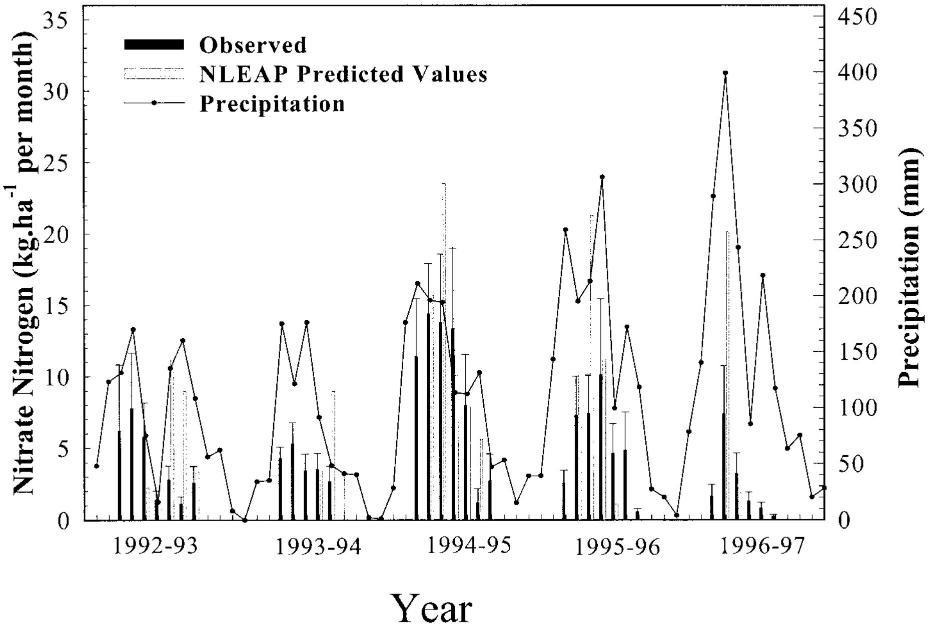

Fig. 2. Observed vs. NLEAP predicted nitrate-nitrogen leaching under cover crop at the recommended nitrogen fertilizer rate (N2). Error bars = standard error of mean observed data; 1 kg·ha^{-1} = 0.89 lb/acre, 1 mm = 0.04 inch.

Table 6. NLEAP and observed leachate volumes under winter cover crop and nitrate-nitrogen leaching risk potential (NLRP).

Year	Predicted leachate vol cm[z]	Actual leachate vol (SE) cm	NLRP
1992	40.4	35.2 (5.8)	Low
1993	18.8	20.7 (3.3)	Low
1994	65.0	53.6 (5.8)	High
1995	77.0	37.5 (9.0)	High
1996	89.9	34.2 (12.1)	High

[z] 1.0 cm = 0.39 inch.

centrations were highest in the top 30 cm. Predicted denitrification was nearly zero from January to June. These conditions suggest that NLEAP might underestimate denitrification during spring in western Oregon. Annual denitrification estimates ranged from a low of 4.7 kg·ha^{-1} (4.2 lb/acre) of N per year in 1993–94 to a high of 19.5 kg·ha^{-1} (17.4 lb/acre) of N per year in 1995–96. Wide variations in measured denitrification rates have been reported by other sources. For example, reported amounts of denitrification in poorly drained soils of the Willamette Valley, Ore., range from 3 kg·ha^{-1} (2.7 lb/acre) of N per year (Myrold, 1988) to 30 kg·ha^{-1} (26.8 lb/acre) of N per year (Horwath et al., 1998).

Soil moisture content was not collected and had to be estimated at the start of the run. Additionally, adapting NLEAP inclusion of a winter cover crop was problematic. 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 cover crop growth (September to June) 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 fraction, where mineralization of the organic matter fraction is assumed to be 2% per year by the program. Mineralized N estimates by NLEAP averaged only 3.7 kg·ha^{-1} (3.3 lb/acre) per year over 5 years. This is likely too low for this region (Kauffman, 1994).

Other practical limitations of NLEAP are as follows:

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 (Systéme International d'Unités): NLEAP does not use SI units. NLEAP's practicality as an international tool for predicting leaching is also limited by its reliance on the U.S. system of units.
3) Limited choice of crops: NLEAP allows user to choose 10 crops [winter wheat, wheat grain silage, sunflower (*Helianthus annuus*), alfalfa (*Medicago sativa*), soybean (*Glycine max*), sugar beets (*Beta vulgaris*), potatoes (*Solanum tuberosum*), sorghum silage (*Sorghum bicolor* x *S. vulgare sudanese*), 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.
6. Can take a considerable amount of time for a person to become familiar with the program and understand the file outputs.

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 difficulty of relying on yield goals to adjust for N uptake precluded the ability to conduct an accurate N balance.

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 leaching on a site-specific and regional scale, but a familiarity with computers and adequate data are required to successfully and accurately run the program. These requirements may limit its practicality for nonprofessionals or small-scale producers.

Both NLEAP and the MLR model predicted greater NO_3-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 properties; 4) variations in climate; and 5) less than 100% efficiency in sampling leachate. 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 qualitative predictors for relative amounts of NO_3-N leaching if the residual fertilizer N concentrations in the top 1 m (3.3 ft) of soil are known.

Using stepwise development of the MLR model supports the concept that NO_3 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. The MLR developed here is not tool for relatively accurate prediction of NO_3 leaching but use of stepwise regression can be useful for researchers or other professionals to identify factors of N management that are important for controlling NO_3 leaching.

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 correct for some of these limitations, but these adjustments may distort the outcome of the simulation.

These results also show that NO_3 leaching is not determined by the rate of fertilizer application alone but rather the interaction of rate and crop species. More practical, user-friendly models need to be developed for soil–crop systems to assist management decisions to reduce N pollution and increase the fertilizer N efficiency of agriculture. It is our conclusion that further improvements in prediction capabilities of N losses and simplicity of use are necessary before NLEAP can have widespread and practical applications.

Literature cited

Afif, E., A. Matar, and J. Torrent. 1993. Availability of phosphate applied to calcareous soils of west Asia and North Africa. Soil Sci. Soc. Amer. J. 57:756–760.

Asseng, S., I.R.P. Fillery, G.C. Anderson, P.J. Dolling, F.X. Dunin, and B.A. Keating. 1998. Use of the APSIM model to predict yield, drainage, and NO_3^- leaching for a deep sand. Austral. J. Agr. Res. 49(3):363–377.

Bandick, A.K. 1997. Field management effects on the thermal stability and activity of soil enzymes in whole soil and aggregates. MS thesis. Ore. State Univ., Corvallis.

Bauder, J.W., K.N. Sinclair, and R.E. Lund. 1993. Physiographic and land use characteristics associated with nitrate-nitrogen in Montana groundwater. J. Environ. Qual. 22:255–262.

Brandi-Dohrn, F.M. 1993. Field evaluation of passive capillary samplers in monitoring the leaching of agrochemicals. MS thesis. Ore. State Univ., Corvallis.

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

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

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

Cavero, J., R.E. Plant, C. Shennan, J.R. Williams, J.R. Kiniry, and V.W. Benson. 1998. Application of EPIC model to N cycling in irrigated processing tomatoes under different management systems. Agr. Systems 56(4):391–414.

Follett, R.F. 1995. NLEAP model simulation of climate and management effects on N leaching for corn grown on sandy soil. J. Contamination Hydrol. 20:241–252.

Follett, R.F., M.J. Shaffer, M.K. Brodahl, and G.A. Reichman. 1994. NLEAP simulation of residual soil nitrate for irrigated and nonirrigated corn. J. Soil Water Conservation 49(4):375–382.

Henao, J. 1976. Soil variables for regression of Iowa corn yields on soil, management, and climatic variables. PhD diss. Iowa State Univ., Ames.

Hess, M. 1995. Assessment of variability and monitoring methods for leaching under cover crop management. MS thesis. Ore. State Univ., Corvallis.

Horwath, W.R., L.F. Elliott, J.J. Steiner, J.H. Davis, and S.M. Griffith. 1998. Denitrification in cultivated and noncultivated riparian areas of grass cropping systems. J. Environ. Qual. 27:225–231.

Jabro, J.D., J.D. Toth, Z. Dou, R.H. Fox, and D.D. Fritton. 1995. Evaluation of N version of LEACHM for predicting nitrate leaching. Soil Sci. 60(3):209–217.

Jemison, J.M.J. and R.H. Fox. 1994. Nitrate leaching from nitrogen-fertilized and manured corn measured with zero-tension pan lysimeters. J. Environ. Qual. 23:337–343.

Kauffman, S.M. 1994. Inorganic N and soil biological dynamics in cover crop systems. MS thesis. Ore. State Univ., Corvallis.

Laird, D.A., E. Barriuso, R.H. Dowdy, and W.C. Koskinen. 1992. Adsorption of atrazine on smectites. Soil Sci. Soc. Amer. J. 56:62–67.

Lucey, K.J. and D.A. Goolsby. 1993. Effects of climatic variations over 11 years on nitrate-nitrogen concentrations in the Raccoon River, Iowa. J. Environ. Qual. 22:38–46.

Macdonald, A.J., D.S. Powlson, P.R. Poulton, and D.S. Jenkinson. 1989. Unused fertilizer N in arable soils—Its contribution to nitrate leaching. J. Sci. Food Agr. 46:407–419.

Martin, D.L., J.R. Gilley, and R.W. Skaggs. 1991. Soil water balance management, p. 199–235. In: R.F. Follet, D. Keeney and R.M. Cruse (eds.). Managing N for groundwater quality and farm profitability. Soil Sci. Amer., Inc., Madison, Wis.

Molina, J.-A.E. and P. Smith. 1998. Modeling carbon and N processes in soils, p. 253–290. In: D.L. Sparks (ed.). Advances in agronomy. vol. 62 Academic Press, San Diego, Calif.

Myrold, D.D. 1988. Denitrification in ryegrass and winter wheat cropping systems of western Oregon. Soil Sci. Soc. Amer. J. 52:412–416.

Parton, W.J., J.W.B. Stewart, and C.V. Cole. 1988. Dynamics of C, N, P, and S in grassland soils: A model. Biogeochemistry 5:109–131.

Perfect, E., B.D. Kay, W.K.P. van Loon, R.W. Sheard, and T. Pojasok. 1990. Factors influencing soil structural stability within a growing season. Soil Sci. Soc. Amer. J. 54:173–179.

Quemada, M. and M.L. Cabrera. 1995. CERES-N model predictions of N mineralized from cover crop residues. Soil Sci. Soc. Amer. J. 59:1059–1065.

Radke, J.K., M.J. Shaffer, K.S. Kroll, and J. Saponara. 1991. Application of the nitrogen-tillage-residue-management (NTRM) model for corn grown in low-input and conventional agricultural systems. Ecol. Modelling 55:241–255.

SAS. 1996. Statistical Analysis Software. Cary, NC, SAS Institute Inc.

Shaffer, M.J., M.D. Hall, B.K. Wylie, and D.G. Wagner. 1996. NLEAP/GIS approach for identifying and mitigating regional nitrate-nitrogen leaching, p. 283–295. In: D.L. Corwin and K. Loague (eds.). Applications of GIS to modeling of nonpoint source pollutants in the vadose zone . Amer. Soc. Agron. Soil Sci. Amer. Spec. Publ. 48.

Shaffer, M.J., A.D. Halvorson, and F.J. Pierce. 1991. Nitrate leaching and economic analysis package (NLEAP): Model description and application, p. 285–322. In: R.F. Follet, D. Keeney, and R.M. Cruse (eds.). Managing N for groundwater quality and farm profitability. Soil Soc. Amer., Inc., Madison, Wis.

Smith, C.J., F.X. Dunin, S.J. Zegelin, and R. Poss. 1998. Nitrate leaching from a riverine clay soil under cereal rotation. Austral. J. Agr. Res. 49(3):379–389.

U.S. Geological Survey. 1998. Water quality in the Willamette Basin Oregon, 1991–1995. U.S. Dept. Interior Circ. 1161.

Wagenet, R.J. and J.L. Hutson. 1989. LEACHM: Leaching estimation and chemistry model—A process based model of water and solute movement, transformations, plant uptake and chemical reactions in the unsaturated zone. Continuum. vol. 2. Water Resource Inst., Cornell Univ., Ithaca, N.Y.

Wylie, B.K., M.J. Shaffer, and M.D. Hall. 1995. Regional assessment of NLEAP NO_3-N leaching indices. Water Resources Bul. 31(3):399–408.