LONG-TERM MEASUREMENT OF NITRATE LEACHING BELOW CORN AGROECOSYSTEMS AND A RESTORED PRAIRIE

Kevin Masarik[1], John Norman[1], Kristofor Brye[2]
[1]University of Wisconsin-Madison, Madison, WI 53706
[2]University of Arkansas, Fayetteville, AR 72701

Abstract

Many studies have evaluated nitrogen leaching from tile drained agricultural soils, but less research has been performed on many well drained soils also common throughout the Midwest. This study measured nitrate leaching from chisel-plow (CP) and no-tillage (NT) agroecosystems in order to determine the effects of common agricultural practices on the quality of water that drains past the root zone of crops. In an effort to obtain background levels of nitrate leaching from a natural ecosystem, measurements were also performed on a 26-year-old restored tallgrass prairie (RP). Water drainage, nitrate leaching loss, and flow-weighted mean NO_3-N concentrations for 7-years of data are reported for all three ecosystems. Results indicate that 54, 37, and 16% of cumulative precipitation was lost to drainage, while 20, 19, and 0.4% of the total N input was leached as NO_3-N in the CP, NT, and RP ecosystems respectively. Almost three-quarters of the total nitrate lost from all ecosystems was leached during the spring months. Grain yield averaged 9.4 and 8.3 Mg ha^{-1} in the CP and NT systems. The flow-weighted mean NO_3-N concentration when determined for seven years was only 0.04 mg L^{-1} for the RP ecosystem and 9.6 and 13.3 mg L^{-1} for the CP and NT ecosystems respectively. While the agroecosystems are close to the 10 mg L^{-1} nitrate drinking water standard, the concentrations are less than many other studies which have reported larger concentrations for similar agricultural practices. Nitrate-N leaching is highly variable over time; long-term studies that measure flow-weighted mean concentrations may represent the best method for evaluating the effectiveness of best management practices in reducing pollution from non-point agricultural sources and improving water quality.

Introduction

Many concerns have been raised regarding the use of nutrient additions to increase crop production and the subsequent impact on the environment. The use of fertilizers and animal manure to supply nitrogen, an essential nutrient to crops, has resulted in elevated levels of nitrate in water resources throughout many agricultural regions. Because nitrate is an anion with little affinity for soil particles, it is easily leached past the root zone of crops and becomes a pollutant for other sectors of society.

Past studies have suggested that even with best possible management practices for optimal crop production, the concentration of NO_3-N in drainage water from fertilized agricultural land is often 2X or more greater than the nitrate drinking water standard (Andraski et al., 2000; Jemison and Fox, 1994). Other studies suggest that excessively high nitrate concentrations in groundwater may be the result of mismanagement rather than currently recommended practices. A study by Shepard (2000) surveyed Wisconsin farmers and showed that 60% of livestock farmers applied nitrogen at rates exceeding the economic optimum and 7% applied at rates three times the economic optimum.

The majority of past studies have only focused on the actual amount of annual NO_3-N loss from agricultural ecosystems. However, high variability in NO_3-N loss has been linked to variation in drainage as well as residual soil nitrogen (Randall and Iragavarapu, 1995). Large precipitation events, particularly after N fertilizer application, are capable of moving inorganic N pools from the soil surface past the reach of crop roots to groundwater in the form of NO_3-N. The loss of large amounts of N is common when wet years follow dry years, presumably from the carryover and accumulation of unused fertilizer and its susceptibility to leaching when drainage does occur (Randall et al., 1997). Long-term measurements that provide data from both wet and dry years are needed to truly understand how much N loss occurs over time and to determine differences in N loss and effects on water quality among different management practices and land-uses.

The objective of this study was to evaluate the effect of a continuous-corn rotation on the water quality on a well-drained soil by measuring leachate collected from optimally fertilized chisel plow and no-tillage agroecosystems over many years. As a means of comparing agricultural systems with other ecosystems, leachate from a restored prairie was also collected and measured. Water flux, NO_3-N leaching losses, and flow-weighted mean NO_3-N concentrations for seven years were examined in an effort to evaluate the ability of these ecosystems to meet current drinking water standards over the long term, determine how different land-uses affect water quality, and ultimately reduce the amount of nitrogen loss to water resources.

Methods and Materials

Two experimental sites were developed in 1995, an agricultural ecosystem at the University of Wisconsin-Madison Arlington Research Farm near Arlington, WI (43°17' N, 89° 22' E) and the other approximately 2.5 km northeast at a restored prairie in the Audubon Society's Goose Pond Sanctuary. Climate for this region is humid continental with a 40 year average rainfall of 792 mm. Temperatures in July average 21.9 °C while temperatures in January average -8.8 °C. Both sites are located on well-drained Plano silt loam with <3% slopes. The soil profile is similar for both sites and consists of approximately 2 m of loess over glacial till with silty-clay-loam subsoil texture.

In the fall of 1994 a randomized complete block design was established for continuous corn treatments of conventional chisel-plow and no-tillage. Four plots were created for each treatment with each plot measuring 6.1 m by 12.2 m. Every year during this study a 105-day relative maturity Round-Up Ready hybrid maize variety was planted in both tillage treatments at a rate of 80,308 seeds ha^{-1} and all plots received 10.1 kg N ha^{-1} starter fertilizer at planting and 180 kg N ha^{-1} of pelletized ammonium nitrate (NH_4NO_3) immediately following planting.

Six stainless steel ETLs (0.25 x 0.76 m) were installed in the field plots during the summer and fall of 1995. The ETLs were installed 1.4 m below the soil surface in replicated plots for the no-tillage, chiseled plow, and restored prairie systems. The ETLs were sampled approximately once every two weeks between March and December and approximately once every four weeks the rest of the year during periods when the soil surface was frozen. Samples were analyzed in the lab for NO_3-N and NH_4-N using colorimetric techniques.

Results and Discussion

The accurate measurement of water drainage is a critical component for the calculation of NO_3-N loss. The amount of precipitation, particularly during wet years, was a major factor controlling variation in the amount of annual water drainage. During 1998 and 2000 when the greatest amount of precipitation was received, the greatest amount of water drainage in all systems was also recorded. While the magnitude of water drainage among treatments varied, the annual drainage patterns were similar. Water drainages totaling 87, 83, and 85% of the annual drainage occurred in the winter and spring months in the chisel-plow (CP), no-tillage (NT), and restored prairie (RP) systems, respectively, even though the same period accounted for only 56% of the annual precipitation. It is important to note that drainage did occur even during periods when the upper regions of the soil profile were frozen; many studies neglect to measure water drainage during winter months. Low evapotranspiration rates resulting from low temperatures and limited plant activity are the primary cause for the increased drainage during this time period. By July plant uptake of water is at its greatest and most precipitation that fell evaporated or was taken up by plants and never drained past the root zone.

In all treatments very little water drainage occurred in the second half of the year (Figure 1). During summer months when transpiration rates generally exceed the amount of precipitation, plants were able to meet water demands by removing water stored within the soil matrix, significantly decreasing or eliminating water drainage below the root zone. Field capacity for a silt loam soil is approximately -30 kPa and very little drainage occurs when the soil profile is below field capacity. In five of the seven years, drainage amounts collected in the summer and fall months were very low. However, in 1998 and 2001 significant drainage did occur during this period. Soil-water matric potential measurements taken at 1.4 m below the soil surface suggest that water removal from the soil matrix during 1998 and particularly 2001 was minimal when compared with other years. Minimal water removal combined with above average summer and fall precipitation during these years resulted in significant water drainage during the second half of the year.

Annual NO_3-N leaching amounts for the seven years were highly variable in the two corn agroecosystems (Figure 1). Differences in annual NO_3-N leaching in the CP and NT systems were controlled by variability in both water drainage and NO_3-N concentration. The greatest NO_3-N leaching loss of 76 and 102 kg NO_3-N ha^{-1} occurred in 1998 and the least 9 and 6 kg NO_3-N ha^{-1} in 1999 for the CP and NT systems respectively. The decreased leaching loss in 1999 likely resulted from the combination of low drainage and low NO_3-N concentrations due to the purging of accumulated nitrogen from the soil during the previous year. While drainage volumes in the CP system were 263 and 239 mm for 1996 and 1999 respectively, drainage during the first half of the year in 1996 when NO_3-N concentrations were greater resulted in more than ten times the NO_3-N leaching loss than in 1999. In contrast to the corn agroecosystems NO_3-N leaching losses from the RP system were consistently low for all seven years and were insignificant when compared to the CP and NT systems.

The data for seven years was arranged into seasonal components and analyzed to determine annual trends in factors affecting water quality (Table 1). Although the amounts of water drainage and NO_3-N leaching losses were different, similar patterns emerged for all three systems. In the CP, NT, and RP systems most of the water drainage 58, 60, and 64% respectively occurred during the spring months. Nitrate-N leaching losses during the spring accounted for 73, 75, and 69% of the yearly totals for CP, NT, and RP systems respectively. These results suggest that water drainage and NO_3-N leaching during the spring has the greatest impact on water quality and is the most critical time for measuring the effects of leaching. It is difficult to distinguish from these results whether the majority of NO_3-N loss during spring is due to residual soil nitrogen or from spring applied fertilizer. While the flow-weighted mean NO_3-N concentrations were similar for spring and summer months, less summer water drainage resulted in substantial decreases in NO_3-N leaching. Winter resulted in the second greatest amount of water drainage and NO_3-N leaching followed by summer and fall for all three systems.

Data from long term studies are less likely to be misinterpreted because it includes natural variation common to studies subject to uncontrollable environmental variables. The 7-year period of this study was fairly representative of varying environmental conditions and included years with above average and below average precipitation, a major controlling factor for water drainage and NO_3-N leaching.

Cumulative data for all seven years is summarized in Table 2. While precipitation for all three systems was equal, the amount of precipitation that was lost to drainage was 54, 37, and 16% for the CP, NT, and RP systems respectively. The total nitrogen lost to leaching was 20 and 19% for the CP and NT systems respectively of the total amount of N input to the fields (fertilizer N and atmospheric N deposition). Only 0.4% of the total N input to the RP system (atmospheric N deposition) was leached as NO_3-N.

Throughout this study, significant amounts of N may have been sequestered in soil organic matter (SOM). Soil organic matter has the potential to accumulate in long-term continuous corn treatments that return crop residue back to the soil. A study by Vanotti and Bundy (1997), also performed on Plano silt loam soil, reported that soil organic carbon increases by 0.045 g kg^{-1} for every 1000 kg ha^{-1} yr^{-1} of corn stover above 5100 kg ha^{-1} yr^{-1} in moldboard plowed soils. In this study, the average amount of crop residue left on the field was 11.3 and 12.3 Mg ha^{-1} yr^{-1} for the CP and NT systems respectively. Assuming an average C:N ratio of 20:1 in SOM, it is possible that an estimated 262 and 303 kg ha^{-1} of N accumulated in the soil as SOM during the seven years of this study for the CP and NT systems respectively.

The combination of N leaching loss, grain N removal, and estimated accumulation of SOM N account for 95 and 90% of the nitrogen additions during the study in the CP and NT systems respectively. The small amount of remaining N that is unaccounted for in both treatments may be the result of denitrification, which was not measured in this study. A study by Brye et al. (2001) showed that the possible contribution of denitrification on this soil type was less than 25% of the total amount of leached nitrate, but is probably much less because conditions in well-drained soils are not conducive to denitrification.

Even though slightly more NO_3-N loss occurred in the CP system, it had less effect on the overall water quality because NO_3-N loads were diluted by increased drainage amounts. The flow-weighted mean NO_3-N concentration when determined for the 7-year period was 9.6 mg L^{-1} in the CP compared with 13.3 mg L^{-1} in the NT. Limited flow-weighted mean concentrations have been reported for agroecosystems that are not tile drained or for non-agricultural ecosystems. The RP system had a flow-weighted mean concentration of only 0.04 mg L^{-1} representing significantly better water quality in leachate compared to agroecosystems and shows no indication of reaching pollutant or degraded levels. However, CP and NT concentrations were close to 10 mg L^{-1} and suggest optimism that recommended agricultural practices used in this study are closer to meeting current drinking water standards than other studies have previously reported.

Conclusions

Results from the 7-year data set show NO_3-N leaching losses are highly variable from year to year and that annual precipitation patterns strongly influence leaching amounts. Years with above average precipitation resulted in greater amounts of water drainage, NO_3-N concentrations, and consequently greater NO_3-N leaching loss. The combined effect of yearly water drainage and NO_3-N concentration cycles resulted in approximately three-quarters of the annual NO_3-N leaching loss during the spring months. Large amounts can be lost even before fertilization and the start of the growing season. In contrast only 5% of the annual water drainage and 1% of the annual NO_3-N leaching occurred in the fall since much of the precipitation goes to replacing soil water storage and concentrations of NO_3-N in the soil are at the lowest.

This study shows it is possible to accurately measure flow-weighted mean concentrations in well-drained soils and natural ecosystems. The use of flow-weighted mean concentrations may be a more effective method of measuring water quality and the effects of best management practices with respect to NO_3-N pollution. The current TMDL program does not account for variability in drainage, a major factor affecting non-point pollutant loads. While the CP system resulted in a greater N loss by leaching, the flow-weighted mean NO_3-N concentration was only 9.6 mg L^{-1} compared with 13.3 mg L^{-1} for the NT. Greater drainage from the CP diluted N loads resulting in slightly better water quality in leachate than in NT.

This study emphasizes the importance of long-term data sets to properly assess factors affecting N loss from agricultural systems and improve the quality of water resources. Since results were obtained from a continuous corn rotation and other crop rotations have been shown to have less N loss and NO_3-N concentrations, optimism should be expressed that on certain soils responsible agricultural practices have the potential to meet or exceed current drinking water standards. Future research on crop rotations, the timing of fertilizer applications, and other nutrient management practices may help to reduce the impact of nitrate pollution even further; however, in order to improve water quality, strategies must also be developed that encourage the agricultural community to adopt recommended best management practices.

References

Andraski, T.W., L.G. Bundy, and K.R. Brye. 2000. Crop management and corn nitrogen rate effects on nitrate leaching. J Environ Qual 29:1095-1103.

Brye, K.R., J.M. Norman, L.G. Bundy, and S.T. Gower. 2001. Nitrogen and carbon leaching in agroecosystems and their role in denitrification potential. J Environ Qual 30:58-70.

Jemison, J.M., 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.

Randall, G.W., and T.K. Iragavarapu. 1995. Impact of long-term tillage systems for continuous corn on nitrate leaching to tile drainage. J Environ Qual 24:360-366.

Randall, G.W., D.R. Huggins, M.P. Russelle, D.J. Fuchs, W.W. Nelson, and J.L. Anderson. 1997. Nitrate losses through subsurface tile drainage in conservation reserve program, alfalfa, and row crop systems. J Environ Qual 26:1240-1247.

Shepard, R. 2000. Nitrogen and phosphorus management on Wisconsin farms: Lessons learned for agricultural water quality programs. Journal of Soil and Water Conservation 55:63-68.

Vanotti, M.B., L.G. Bundy, and A.E. Peterson. 1997. Nitrogen fertilizer and legume-cereal rotation effects on soil productivity and organic matter dynamics in Wisconsin, *In* E. A. Paul, et al., eds. Soil organic matter in temperate agroecosystems: long-term experiments in North America. CRC Press, Boca Raton.

Figure 1. Annual cumulative water drainage and nitrate leaching for the three treatments. Dashed line represents half of a year.

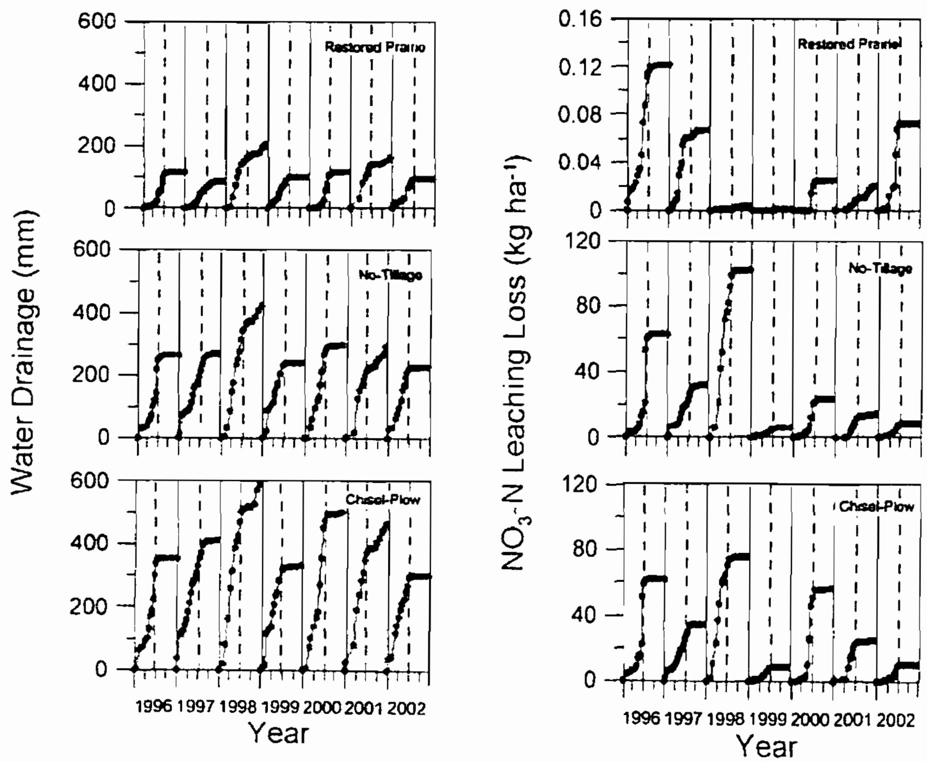

Table 1. Seasonal variation of drainage, leaching loss, and flow weighted mean concentration for chisel-plow (CP), no-tillage (NT), and restored prairie (RP) treatments. Standard error written in parentheses.

System	Season	Total water drainage		Total NO_3^--N leaching loss		Flow weighted mean NO_3-N concentration
		---mm---	---%---	---kg ha^{-1}---	---%---	---mg L^{-1}---
CP	Winter	845(207)	29	43(9)	15	5.2(0.2)
	Spring	1697(242)	58	206(7)	73	12.1(1.2)
	Summer	262(16)	9	32(8)	11	12.2(2.3)
	Fall	142(40)	5	2(1)	1	0.9(0.4)
NT	Winter	464(19)	23	38(16)	14	8.3(3.8)
	Spring	1204(71)	60	200(33)	75	16.6(3.7)
	Summer	238(77)	12	28(1)	10	13.4(4.8)
	Fall	104(37)	5	2(1)	1	2.0(1.2)
RP	Winter	186(6)	21	0.06(0.01)	19	0.03(<0.01)
	Spring	553(42)	64	0.2(0.01)	69	0.04(<0.01)
	Summer	81(1)	9	0.03(<0.01)	9	0.03(<0.01)
	Fall	48(13)	6	0.01(<0.01)	3	0.02(<0.01)

Table 2. Cumulative effects of water drainage and NO_3-N leaching for three systems over the 7-yr period.

	System		
	Chisel plow	No-tillage	Prairie
Total fertilizer N applied (kg ha^{-1})	1331	1331	-
Total atmospheric N deposition (kg ha^{-1})	71.8	71.8	71.8
Corn grain yield (Mg ha^{-1})	65.8	58.0	-
Total grain N removed (kg ha^{-1})	768	680	-
Amount N removed in grain (%)	55	48	-
Total precipitation (cm)	548	548	548
Total drainage (cm)	295	201	87
Precipitation lost to drainage (%)	54	37	16
Total NO_3^--N leaching loss (kg ha^{-1})	283	268	0.31
Amount N lost to leaching (%)	20	19	0.4
Flow weighted mean NO_3-N Conc. (mg L^{-1})	9.6	13.3	0.04

PROCEEDINGS OF THE

THIRTY-THIRD NORTH CENTRAL EXTENSION-INDUSTRY SOIL FERTILITY CONFERENCE

Volume 19

November 19-20, 2003
Holiday Inn University Park
Des Moines, IA

Program Chair:

John E. Sawyer
Iowa State University
Ames, IA 50011
(515) 294-1923

Published by:

Potash & Phosphate Institute
772 – 22nd Avenue South
Brookings, SD 57006
(605) 692-6280
Web page: www.ppi-ppic.org