Executive Summary: Gaseous Losses and Long-Term Fate of Nitrogen Applied to Kentucky Bluegrass Turf

Bruce Branham, Principal Investigator
Richard Mulvaney, Co-Principal Investigator
Brian Horgan, Graduate Student
University of Illinois
Department of Natural Resources and Environmental Sciences
Urbana, Il 61801
and
Kevin Frank, Co-Principal Investigator
Michigan State University
Department of Crop and Soil Sciences
E. Lansing, MI 48824

This research project seeks to build on previous research on the fate of nitrogen applied to turfgrass. Specifically, we wished to add to the relatively sparse literature on denitrification from turf. It is our hypothesis that the historically poor recovery of labeled fertilizer nitrogen (LFN) in studies designed to determine the fate of applied nitrogen was due to denitrification losses. Finally, we wish to examine the fate of nitrogen applied to mature, well-established turfgrasses. Many of the studies on fertilizer fate were conducted on relatively new turf. All of these studies found very low levels of nitrate leaching; however, we wish to determine if this response holds for mature turf as well.

Several studies were completed in 2000. Two studies examining denitrification in the field found that denitrification, the anaerobic reduction of nitrate to nitrogen gas, occurs frequently in turf. Previous research in turf had indicated that denitrification does not occur except when soils are near saturation. Our research indicates that denitrification occurs routinely after rainfall or irrigation events and in large quantities following fertilizer applications. Denitrification appears to be a significant loss mechanism in turf because even though the loss rates are generally small, losses occur frequently throughout the growing season. Denitrification losses accounted for 5-15% of applied LFN; however, even with the ability to account for denitrification losses, our total recovery of LFN in soil, plant, and atmosphere averaged 61.2 to 68.4 %. While our research has indicated that denitrification occurs much more frequently than previously thought; it is not the answer for the incomplete recovery of LFN applied to turf. We believe other loss mechanisms must be occurring that we are not aware of and that account for the lack of complete recovery of LFN.

In 2000, we monitored denitrification under field conditions. During the course of the study, rainfall or irrigation fell on the plots 24 times and denitrification losses were measured 16 times. Even relatively light irrigation or rain events can result in some denitrification loss because small pockets within the soil can become anaerobic even though the entire soil profile is not saturated.

Research at Michigan State University monitored nitrate leaching from turf that has been maintained at two different fertility levels for the last two years. One area is fertilized at an annual rate of 2 lbs N/M/Yr. The other area is maintained at 6 lbs

lysimeters are 1 m^2 in surface area and 1.2 m deep and have been continuously monitored for the last two years for the concentration of nitrate in the drainage water. Earlier research has indicated that nitrate leaching from turf is negligible. However, in this study the 6 lbs N/M/Yr turf has shown steadily increasing rates of nitrate leaching with levels reaching 10-20 PPM nitrate from October 1999 through May of 2000. These levels are above the national drinking water standard. However, the 2 lb N/M/Yr, a more modest rate of nitrogen fertilization, continues to show low levels of nitrate leaching usually between 1-3 PPM, although even these levels are elevated compared to what previous research has indicated is likely from turf. This research emphasizes that turf is a perennial species and that long term view of its characteristics must be taken. The final study of this project was begun in the late fall of 2000 at MSU. This study will determine the fate of nitrogen on a mature turf at two different rates of annual nitrogen fertilization.

2000 Annual Report

Gaseous Losses of Nitrogen Applied to Kentucky Bluegrass Turf

Bruce Branham, Principal Investigator
Richard Mulvaney, Co-Principal Investigator
Brian Horgan, Graduate Student
University of Illinois
Department of Natural Resources and Environmental Sciences
Urbana, Il 61801
and
Kevin Frank, Co-Principal Investigator
Eldor Paul, Co-Principal Investigator
Ron Calhoun, Graduate Student
Michigan State University
Department of Crop and Soil Sciences
E. Lansing, MI 48824

Background

This project was designed to answer several questions that remain regarding the fate of applied nitrogen to turfgrass. The first question regards the lack of complete recovery of applied nitrogen. Every researcher who has studied nitrogen in term has been plagued by incomplete recovery of applied fertilizer nitrogen. Our hypothesis is that this incomplete recovery is due to loss by denitrification. Denitrification has been extensively studied in agricultural cropping systems but has received relatively little attention in turf. Denitrification is extremely difficult and expensive to study and this explains the relative lack of attention it has received in turf. In row crop systems, most denitrification occurs in the spring when frequent rains and large amounts of fertilizer create conditions that can lead to extensive denitrification losses. However, soil temperature is an important factor since denitrification is microbially mediated. Thus, loss rates in row crops would be potentially higher in the summer but in row crop agriculture irrigation and nitrogen are seldom applied in the summer. Agricultural soils rarely turn anaerobic in the summer and if they do, nitrate is generally not there in significant quantity to see large rates of denitrification losses. Turf soils in contrast, tend to be irrigated all summer and received monthly nitrogen applications. In addition, turf soils have a high organic matter content in the surface which can yield appreciable quantities of mineralized nitrogen during the summer months.

The second question this research project seeks to answer is the effect of age of the turf on the nitrogen dynamics. Recent research projects that have examined the fate of nitrogen in turf have usually involved recently established turfs that may respond differently to nitrogen than a more mature turf. A study was conducted at Michigan State University in 1991-93 that examined the fate of nitrogen on a Kentucky bluegrass sod that was established in 1991. The second portion of this project will conduct a study similar to the 1991 study but on a turf that has been established for almost 10 years. In addition, the lysimeters used in the original MSU study have been monitored for the last two years for nitrate leaching under two different nitrogen fertilization regimes. One half of the lysimeter area has been fertilized at an annual rate of 2 lbs N/M/Yr while the other half of the area has been fertilized at 6 lbs N/M/Yr. The lysimeters under each fertilization regime have been monitored continuously since that time.

Research Conducted in 2000

University of Illinois

Brian Horgan is a PhD student who began working on this project in January of 1998. He spent the first year preparing for these experiments. Several technical challenges had to be met before initiating the field studies with ^{15}N including the development of an air-tight lysimeter system; the development of a gas sampling system to permit atmospheric sampling 9 hours a day from the field installed lysimeters; learning and modifying the mass spectrometer that is used to differentiate $^{28}N_2$, $^{29}N_2$, and $^{30}N_2$; and development of a technique to determine the atmospheric volume which includes lysimeter headspace plus soil pore space.

Two experiments were conducted in 1999. Both were field studies designed to measure the denitrification losses from fertilizer applied to turf in the field. The experiments were initiated on May 20 and August 9 and concluded when dilution of labeled N was not detectable by mass spectrometric analysis, which occurred at approximately 4 to 6 weeks after fertilizer addition. These two experiments were discussed in last years report but we did not have the data on soil and plant distribution of applied nitrogen.

In calendar year 2000, several new experiments were conducted. First, we designed two studies to examine the issue of recovery of fertilizer nitrogen. The first study lasted for 24 hours and was simply a test of our ability to recover applied nitrogen from either bare soil or turf. The second test was a longer experiment conducted in the greenhouse so that leachate could also be conveniently collected.

The results we obtained in 1999 showed that denitrification occurs in turf after most rainfall or irrigation events. The addition of the ^{15}N labeled fertilizer allows us to not only monitor the loss of the fertilizer but to "see" the loss of total nitrogen from the system. This makes the use of ^{15}N a powerful tool to study denitrification. However, as the ^{15}N label decreases in the evolved denitrification products, our ability to "see" the other nitrogen being evolved is also lost. Therefore, we conducted a study in 2000 that made light, frequent additions of ^{15}N labeled fertilizer so we could observe total denitrification over the course of a month. In this study, two different fertilizer sources, KNO_3 and urea, were compared.

Progress and Results

The complete recoveries of labeled fertilizer nitrogen (LFN) for the spring and summer studies of 1999 are shown in tables 1-4. Tables 1 and 2 display the denitrification data collected in 1999. Points to be gleaned from these data are that the quantity of N_2O evolved is small relative to N_2. Losses of N_2O averaged 28% of total denitrification losses from summer experiment and 11% in the spring experiment. Losses by denitrification occur frequently following rain or irrigation events. The data in tables 1 and 2 show clearly that denitrification occurs frequently in turf and that the entire profile does not have to be anaerobic for denitrification to occur. Recovery of LFN, with estimates for denitrification, averaged 68.4 % for spring applied nitrogen and 61.7 % for the summer applied nitrogen. Clearly, denitrification is not the only factor responsible for lack of quantitative recovery. Nitrogen loss is significant and as yet unaccounted for conventional modes of loss.

Studies in 2000 focused on the lack of recovery problem and on further understanding dentrification in turf in the field. Our recovery studies began with a 24 hr experiment to see if we could get quantitative recovery with a short time frame for recovery. Our results showed that recovery in the field can be quantitative. LFN applied to bare soil yielded a recovery of 100.2 +/- 1.6 % while applications to turf yielded a recovery of 98.7 +/- 7.6 % (Table 5). The recovery from turf was more variable which may indicate that the plant community makes quantitative recovery more difficult. However, the main point to be gleaned from this study is that LFN losses are not occurring during the sample handling, drying, and preparation stages. This strongly implies that the losses of LFN are real and occurring through mechanisms we don't yet understand.

We developed a new hypothesis that the turfgrass plants themselves are responsible for the lack of LFN recovery. We theorized that the turf adds another layer of complexity into the system and opens new avenues to LFN loss that would not exist in bare soil. To test this hypothesis we took cores in the field, of both turf and bare soil, and moved them into the greenhouse where we could easily collect leachate as well as monitor for gas emission. This study was conducted during the summer of 2000. The results of this study (Table 6) did not support our hypothesis. Recovery from bare soil was 84% while recovery from turf averaged 91%. Leaching losses were nearly 20 % in bare soil but only 4.9 % from turf.

Loss of LFN by denitrification followed a pattern similar to what was observed with studies during 1999. Losses were significant immediately after fertilizer application and the majority of the evolved gas came from LFN. Gas loss decreased dramactically but still continued for the next 15 to 20 days. Denitrification losses were greater from turf than from bare soil. Loss of N_2O may be significant with the first denitrification event, but after that loss of N_2O quickly approaches zero.

The final study compared denitrification losses from two different fertilizer sources, KNO_3 or urea, and attempted to use these fertilizer applications to see the overall rate of denitrification in the total soil nitrogen pool. As long as the label in the evolved nitrogen gases is above 10% of the total N in the gas sample, applications of LFN can be used to monitor overall dentrification. In this study, we made weekly additions of 0.2 lbs N as ^{15}N labeled fertilizer to monitor dentrification within the turf. These studies were conducted in the field with gas monitoring from 8 AM through 5 PM.

These studies showed clearly showed two important points that were observed in other studies. First, gas loss occurs frequently following most rain or irrigation events. Denitrification losses are usually not large but they are fairly constant. Over the course of a growing season, these losses will become significant. Second, evolution of N_2O only seems to occur immediately after fertilizer addition. Interestingly, no loss of N_2O was observed from the urea fertilizer source. When nitrate is plentiful, such as immediately following an application of KNO_3, the microorganisms have so much material to choose from they can allow some N_2O to escape with reducing it further to N_2. However, under nitrate limiting conditions, the microorganisms seem to need to reduce all N_2O to N_2 in order to gain maximum energy from the process.

Michigan State University Results

The research project at MSU is moving into the active phase while the University of Illinois project winds down. Lysimeters have been installed at MSU to begin another nitrogen fate study on turf that has been grown under turf management conditions since 1991. In addition, the lysimeter plot area that was constructed during the first USGA sponsored nitrogen fate project in 1991, has been divided into two areas that have been maintained under different levels of nitrogen fertilziation since this project began in 1998. One half of the plot area has been fertilized with urea at an annual rate of 100 kg N/ha (2 lbs N/M) while the other one half has been fertilized at an annual rate of 300 kg N/ha (6 lbs N/M). Each fertilizer rate contains two of the large monolith lysimeters, each 1 m^2 in surface area and 1.2 m in depth, that have been monitored constantly over the last two years for nitrate levels in the drainage water. The results are quite interesting and are shown in figure 1.

The high N treatment has given yielded nitrate concentrations of greater than 10 PPM nitrate-nitrogen since September of 1999. With the exception of one sampling date, the low N treatments have always been below 4 PPM nitrate-nitrogen. When examined on a percentage of the total N applied, the high N treatment has leached a total of 65 kg N/ha or 12 % of the total applied. Conversely, the low N treatment has leached a total of 15 kg N/ha or 7 % of the total applied. Thus, we see that while turf is a good system, high levels of N fertilization will cause unacceptable levels of nitrate leaching.

Table 1. Field Study: Spring 1999 Denitrification Gas Loss Data†

Sampling date	Rainfall/ irrigation	N_2 Gas loss‡		N_2O Gas Loss	
		LFN	Total	LFN	Total
	(cm)	mg N m^{-2}			
20-May	0.51	9.43	10.51	4.54	4.68
21-May	3.18	4.26	5.45	0.22	0.24
22-May§	0	41.12	53.47	15.28	17.46
23-May	0.13	5.67	8.87	0.73	0.86
24-May	0	3.14	5.27	0	0
25-May	0	1.59	2.90	0	0
26-May	0	0	0	0	0
27-May	0	0.91	2.11	0	0
28-May	1.27	3.00	6.99	0	0
29-May	0	1.66	4.10	0	0
30-May	0.25	0.80	2.27	0	0
31-May	0	0.63	1.49	0	0
1-June	3.18	0.40	0.95	0	0
2-June	0	1.87	5.61	0	0
3-June	0	1.71	4.78	0	0
4-June	2.03	0.96	2.83	0	0
5-June	0	3.83	13.85	0	0
6-June	0	1.36	4.03	0	0
7-June	1.02	0.58	1.37	0	0
8-June	0	1.56	6.74	0	0
9-June	0	1.52	4.44	0	0
10-June	0	0.49	1.20	0	0
11-June	1.78	0.51	1.46	0	0
12-June	3.94	1.03	3.31	0	0
13-June	0.76	4.54	37.43	0.06	0.14
14-June	0	10.66	89.06	0.76	3.38
15-June	0	2.05	8.06	0	0
16-June	0	0.82	3.00	0	0
17-June	0	0	0	0	0
18-June	1.40	0	0	0	0
19-June	0	0	0	0	0
20-June	0	0	0	0	0
21-June	0	0.12	0.32	0	0
22-June	1.91	0	0	0	0
23-June	1.40	0.11	0.31	0	0
24-June	0	1.64	12.90	0	0
25-June	0	0.09	0.43	0	0
26-June	1.40	0.34	1.34	0	0
27-June	0.25	0.47	2.32	0	0
28-June	0	0	0	0	0
29-June	0	0	0	0	0
30-June	0	0	0	0	0

†Gas flux samples were collected from 0800 to1100, 1100 to 1400, and 1400 to 1700 from two replications in the field. Gas samples from a replication were summed and values reported are means of the two replications.

‡ LFN = ^{15}N-labeled fertilizer nitrogen evolved as N_2 or N_2O. Total = total N evolved as N_2 or N_2O. Nitrogen applied as 98.5 atom % ^{15}N-labeled KNO_3 at a rate of 4880.835 mg N m^{-2}.

§May 22, June 5, and June 14 gas flux samples were collected from 0800 to 1100, 1100 to 1400, 1400 to 1700 and 1700 to 0500 from two replications in the field. Gas samples from a replication were summed and values reported are means of the two replications.

Table 2. Field Study: Summer 1999 Denitrification Gas Loss Data†

Sampling date	Rainfall/ irrigation	N_2 Gas loss‡		N_2O Gas Loss	
		LFN	Total	LFN	Total
	(cm)	mg N m^{-2}			
9-August	1.02	51.28	54.57	47.52	48.62
10-August	0	8.40	11.04	1.68	0.86
11-August	0.25	3.07	4.70	0	0
12-August	8.89	14.29	21.22	10.15	13.54
13-August	1.27	98.23	141.17	12.19	16.48
14-August§	0	134.67	271.99	104.45	153.33
15-August	0	24.12	58.35	17.57	27.31
16-August	0	5.52	13.61	1.17	1.17
17-August	1.91	3.16	6.61	0	0
18-August	0	3.53	10.15	0	0
19-August	0	1.96	4.56	0	0
20-August	0	1.17	2.33	0	0
21-August	1.65	0.88	2.46	0	0
22-August	0	0.77	2.64	0	0
23-August	0.89	0.70	1.97	0	0
24-August	0.76	1.84	8.06	0	0
25-August	0	1.61	7.18	0	0
26-August	0	0.62	2.54	0	0
27-August	1.27	0.28	0.64	0	0
28-August	0	0	0	0	0
29-August	0	0.53	1.44	0	0
30-August	0	0.54	1.02	0	0
31-August	0	0	0	0	0
1-September	0.76	0	0	0	0
2-September	0	0	0	0	0
3-September	0	0	0	0	0
4-September	1.65	0	0	0	0
5-September	0	0	0	0	0

†Gas flux samples were collected from 0800 to1100, 1100 to 1400, and 1400 to 1700 from two replications in the field. Gas samples from a replication were summed and values reported are means of the two replications.

‡ LFN = ^{15}N-labeled fertilizer nitrogen evolved as N_2 or N_2O. Total = total N evolved as N_2 or N_2O. Nitrogen applied as 98.5 atom % ^{15}N-labeled KNO_3 at a rate of 4880.835 mg N m^{-2}.

§August 14 and 15, gas flux samples were collected from 0800 to 1100, 1100 to 1400, 1400 to 1700, and 1700 to 0500 from two replications in the field. Gas samples from a replication were summed and values reported are means of the two replications.

Table 3. Field Study: Partitioning of Labeled Fertilizer Nitrogen in the Soil, Plant, and Atmosphere.

Sample timing	Labeled fertilizer nitrogen† Gas‡ N_2	N_2O	Plant	Soil section 0-5	5-10	10-20	20-
	mg N m^{-2}						
			Spring				
0800-1100	161.87	14.18	1348.27	1324.22	221.68	170.50	25.28
1100-1400	254.36	37.00	1564.09	1283.52	227.85	158.17	45.94
1400-1700	217.67	28.06	1319.90	1217.23	221.06	134.43	44.17
			Summer				
0800-1100	598.13	287.97	1090.52	633.28	65.67	101.74	24.36
1100-1400	561.14	285.50	998.33	696.49	95.27	167.42	81.70
1400-1700	1041.80	245.73	1075.10	797.31	59.51	98.35	34.53

†Labeled fertilizer nitrogen values for soil and plant are reported as means of the two replications in the field and four replications in the laboratory. Total N applied as 98.5 atom % ^{15}N-labeled KNO_3 was 4880.835 mg N m^{-2}.
‡Gas flux values are means of two replications and are extrapolated to a 24-hr period.

Table 4. Field Study: Percent Recovered of LFN†

Season	Sample timing		
	0800-1100	1100-1400	1400-1700
		%	
Spring	66.9	73.2	65.2
Summer	57.4	59.1	68.7

† Percent labeled fertilizer recovery is calculated as the sum of gas flux (extrapolated to a 24-hr period), plant, and soil divided by the total amount of fertilizer-N applied. Total N applied was 4880.835 mg N m^{-2}.

Table 5. Recovery of LFN 24h after application to bare soil and a turfgrass system†

	LFN recovery‡	
Replication	Bare soil	Turfgrass system
	%	
1	102.3	90.3
2	99.9	109.2
3	98.5	96.6

†Labeled fertilizer nitrogen (LFN) was applied at 44.686 mg N using 2 atom % ^{15}N-labeled KNO_3.
‡LFN recovery was calculated as the sum of labeled fertilizer nitrogen in the plant and soil for the turfgrass system and from the soil for the bare soil system.

Table 6. Greenhouse study: Partitioning of labeled fertilizer nitrogen in the soil, plant, atmosphere, and leachate.†

Sample	Labeled fertilizer nitrogen‡							
	Gas§		Plant	Soil section (cm)				Leachate
	N_2	N_2O		0-5	5-10	10-20	20-	
	mg N m^{-2}							
Bare soil	215.59	142.49	NA	2003.84	316.14	303.10	159.21	966.70
Turf system	640.62	286.57	1441.93	1515.40	174.12	103.05	46.11	240.20

†Values reported are means of the two replications. Plots were fertilized with 98.5 atom % ^{15}N-labeled KNO_3 (4880.84 mg N m^{-2}). Values reported as NA=not applicable.
‡Labeled fertilizer nitrogen values for soil, plant, and leachate are reported as means of the two replications in the greenhouse and four replications in the laboratory.
§Gas flux values are means of two replications and are extrapolated to a 24-hr period.

Table7. Greenhouse study: Total and labeled fertilizer nitrogen N_2 gas loss from a turf system and bare soil†

Sampling date	Rainfall/ irrigation	Turf system‡ LFN	Turf system‡ Total	Bare soil LFN	Bare soil Total
	(cm)	mg N m^{-2}			
24-May	0.51	52.37	53.16	16.60	18.04
25-May	0	11.03	12.99	3.96	5.03
26-May	0.51	2.40	3.09	0.38	0.56
27-May	0	3.08	4.72	1.47	2.36
28-May	0	1.59	2.93	0.82	1.45
29-May	0.76	4.76	8.00	1.27	2.04
30-May	0	1.99	4.49	1.00	1.95
31-May	0	0.52	1.56	0.31	0.59
1-June	0	0.70	2.03	0.52	1.07
2-June	0.64	1.23	3.82	0.47	0.92
3-June	0	0.21	0.78	0.15	0.36
4-June	0	0	0	0	0
5-June	0	0	0	0	0
6-June	0.64	0.20	0.76	0	0
7-June	0	0	0	0	0
8-June	0.76	0	0	0	0
9-June	0	0	0	0	0
10-June	0	0	0	0	0
11-June	0	0	0	0	0
12-June	0	0	0	0	0
13-June	0	0	0	0	0

†Gas flux samples were collected from 1100 to 1400 from two replications in the greenhouse. Gas samples from a replication were summed and values reported are means of the two replications.
‡ LFN = ^{15}N-labeled fertilizer nitrogen evolved as N_2. Total = total N evolved as N_2. Plots were fertilized with 98.5 atom % ^{15}N-labeled KNO_3 (4880.835 mg N m^{-2}).

Table 8. Greenhouse study: Total and labeled fertilizer nitrogen gas loss as N_2O comparing a turf system and bare soil†

Sampling date	Rainfall/ irrigation	Turf system‡		Bare soil	
		LFN	Total	LFN	Total
	(cm)	mg N m^{-2}			
24-May	0.51	33.88	34.32	16.38	17.44
25-May	0	1.30	1.35	1.06	1.22
26-May	0.51	0	0	0	0
27-May	0	0	0	0	0
28-May	0	0	0	0	0
29-May	0.76	0.64	0.81	0.37	0.45
30-May	0	0	0	0	0
31-May	0	0	0	0	0
1-June	0	0	0	0	0
2-June	0.64	0	0	0	0
3-June	0	0	0	0	0
4-June	0	0	0	0	0
5-June	0	0	0	0	0
6-June	0.64	0	0	0	0
7-June	0	0	0	0	0
8-June	0.76	0	0	0	0
9-June	0	0	0	0	0
10-June	0	0	0	0	0
11-June	0	0	0	0	0
12-June	0	0	0	0	0
13-June	0	0	0	0	0

†Gas flux samples were collected from 1100 to 1400 from two replications in the greenhouse. Gas samples from a replication were summed and values reported are means of the two replications.
‡ LFN = ^{15}N-labeled fertilizer nitrogen evolved as N_2O Total = total N evolved as N_2O. Plots were fertilized with 98.5 atom % ^{15}N-labeled KNO_3 (4880.835 mg N m^{-2}).

Table 9. Effect of Fertilizers on Rates of Denitrification from Creeping Bentgrass†

		KNO_3				Urea			
		N_2		N_2O		N_2		N_2O	
Sampling date	Rainfall/ irrigation	LFN	Total	LFN	Total	LFN	Total	LFN	Total
	(cm)	mg N m^{-2}							
18-July§	0.51	9.01	9.13	6.14	5.88	0.86	1.08	0	0
19-July	0.38	1.66	1.66	0	0	0.77	1.13	0	0
20-July	0	1.10	1.16	0	0	0.70	0.80	0	0
21-July	0	0	0	0	0	0	0	0	0
22-July	0.38	0	0	0	0	0	0	0	0
23-July	0	0	0	0	0	0	0	0	0
24-July	0.38	0	0	0	0	0	0	0	0
25-July§	0.51	9.76	9.76	2.57	2.37	1.33	1.31	0	0
26-July	0	1.76	1.86	0	0	0.97	1.26	0	0
27-July	0	0	0	0	0	0	0	0	0
28-July	0.76	0	0	0	0	0	0	0	0
29-July	0.38	0	0	0	0	0	0	0	0
30-July	0.25	0	0	0	0	0	0	0	0
31-July	0	0	0	0	0	0	0	0	0
1-August§	0.51	5.70	5.90	1.10	0.92	1.82	2.21	0	0
2-August	0.86	3.07	3.59	0	0	3.58	5.19	0	0
3-August	1.65	0.84	1.04	0	0	2.00	3.76	0	0
4-August	0	0.93	0.99	0	0	1.24	2.12	0	0
5-August	0.64	0	0	0	0	0.59	1.19	0	0
6-August	0.64	0	0	0	0	0.22	0.41	0	0
7-August	0	0	0	0	0	0.29	0.48	0	0
8-August§	0.51	4.43	4.57	0.70	0.54	1.74	2.08	0	0
9-August	0.64	5.63	6.82	0	0	6.16	9.62	0	0
10-August	0	2.59	2.98	0	0	3.82	6.34	0	0
11-August	1.44	0	0	0	0	3.94	8.95	0	0
12-August	0.81	0	0	0	0	1.64	3.94	0	0
13-August	0.76	0.88	2.42	0	0	0	0	0	0
14-August	0	0	0	0	0	1.30	3.09	0	0
15-August§	0.51	2.95	3.19	0.36	0.23	2.04	3.12	0	0
16-August	1.02	3.56	5.02	0	0	3.91	6.67	0	0
17-August	0.51	1.69	3.62	0	0	2.10	4.84	0	0
18-August	1.27	0	0	0	0	2.88	8.85	0	0
19-August	0.89	0	0	0	0	1.46	4.60	0	0
20-August	0.76	0	0	0	0	0.83	2.53	0	0
21-August	0	0	0	0	0	2.16	4.19	0	0

†Gas flux samples were collected from 1100 to 1400 from two replications in the field. Gas samples from a replication were summed and values reported are means of the two replications.
‡ LFN = ^{15}N-labeled fertilizer nitrogen evolved as N_2 or N_2O. Total = total N evolved as N_2 or N_2O.
§Fertilizer application made using 49.97 atom % ^{15}N-labeled KNO_3 at a rate of 998.82 mg N m^{-2} and 46.8 atom % ^{15}N-labeled urea at a rate of 1991.23 mg N m^{-2}.

Figure 1. NO_3-N Concentration (1998-2000)

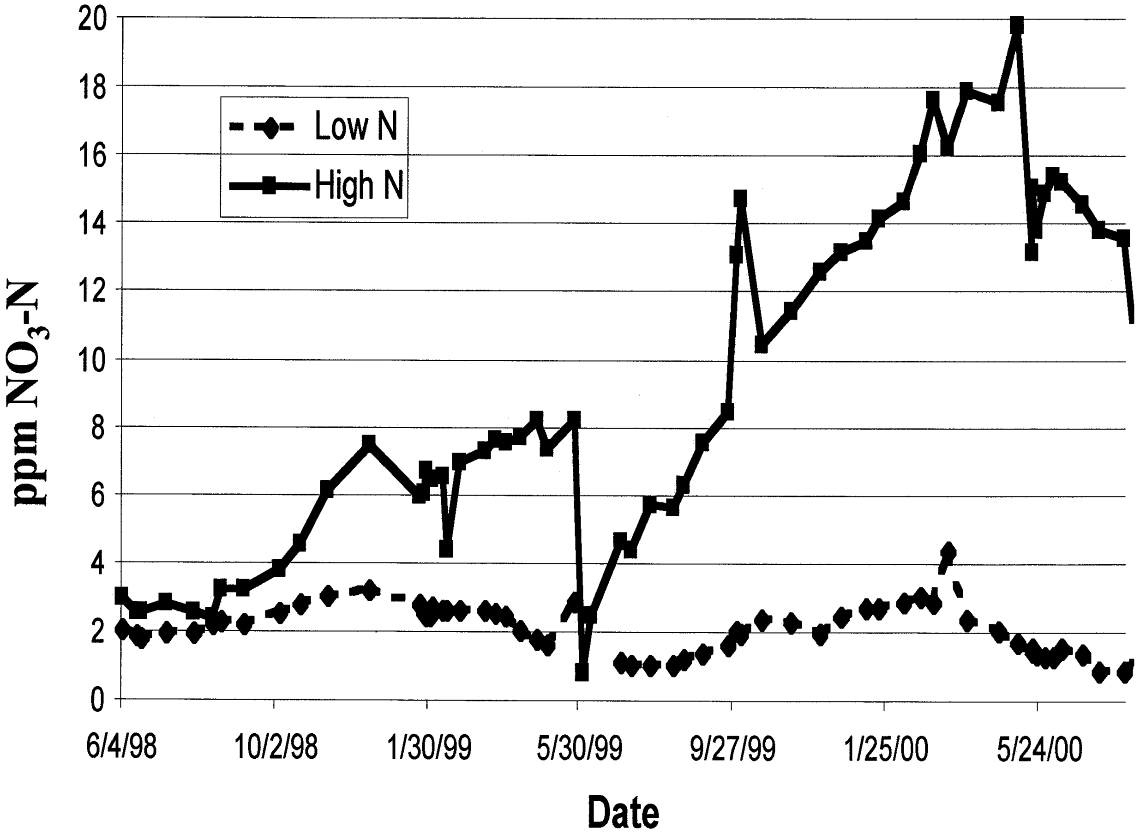

Figure 2. Total N Recovered (1998-2000)