Sources and Estimated Load of Bioavailable Nitrogen Attributable to Chronic Nitrogen Exposure and Changed Ecosystem Structure and Function

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Abstract

Bioavailable nitrogen is a limiting nutrient throughout the Eastern United States. Research demonstrates that exposure to large doses of nitrogen leads to deleterious environmental impacts. However, effects of chronic exposure to lower doses of nitrogen are not well known. Since 1998, we conducted an integrated multi-disciplinary study investigating ecosystem feedback associated with chronic exposure to low doses of nitrogen. In this nitrogen-limited ecosystem, the ability of the soil system to adapt to new nitrogen inputs was degraded by the first winter season when soil nitrate concentration (indicated by extract concentration) increased 590%. Increased concentrations of nitrate were especially evident on fertilized plots ($P<0.0001$) but also were measured on plots that were only fenced to manipulate herbivore abundance ($P=0.0443$). Changes to the plant, macro invertebrate, herbivore, and microbial communities each reduced ecosystem nitrogen use efficiency thereby producing a self-reinforcing positive feedback loop leading to conditions favoring greater concentrations of soil nitrate. Because all of these effects occur together, it is unclear whether the results seen in soil nitrogen chemistry are from one or some combination of them working together. What is clear however is that changes to trophic feedbacks associated with chronic exposure to low levels of bioavailable nitrogen resulted in an annual mean nitrogen excess of 105.6%. Although it was not our goal to measure mass balance for all nitrogen loss pathways, we estimate that ecosystems similarly exposed to excess or new sources of nitrogen may be at risk and are capable of leaching essentially all new nitrogen additions during seasons of dormancy. These experiments demonstrate that even the relatively small amount of nitrogen deposited in precipitation has the capacity to change multiple aspects of ecosystem structure and function.

Keywords: atmospheric deposition, bioavailable nitrogen, nitrate, ecosystem response, ecosystem management, trophic interactions

Introduction

Bioavailable nitrogen has been falling in the rain for decades in developed areas (e.g., Smil 1990, Vitousek et al. 1997). This is expected to continue indefinitely (Brimblecombe and Stedman 1982, Galloway et al. 1994, Vitousek et al. 1997). Only recently has attention been focused toward risks associated with low level exposure to nitrogen, such as that accompanying atmospheric deposition (Likens 1992). Nitrogen, particularly nitrate, easily moves from terrestrial ecosystems into surface and groundwaters, including lakes, streams, rivers, and estuaries (e.g., Baker 1992, Kahl et al. 1993, Peterjohn et al. 1996). To weigh risks and assess management options, it is important that a thorough understanding of the interactions and transport of nitrogen in terrestrial and aquatic

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ecosystems, and the atmosphere be developed (Jorgensen 2002).

The nitrogen cycle is well studied. Although many of the cycle's components are important to consider for nitrogen management, there are relative few that interact closely with atmospherically deposited nitrogen. In this study, we are most interested in those components that are directly affected by nitrogen deposition. Wedin and Tilman (1996) published data demonstrating that exposure to excess bioavailable nitrogen degrades ecosystems in a number of notable ways: 1) retained nitrogen decreases with increasing exposure, 2) biodiversity declines, and 3) plant C/N ratio declines. Of perhaps greater importance is the observation that most of the ecological response measured by Wedin and Tillman (1996) occurs in the first 100 kg/ha/yr of deposition. We call this the 'ecologically significant dose' (Figure 1).

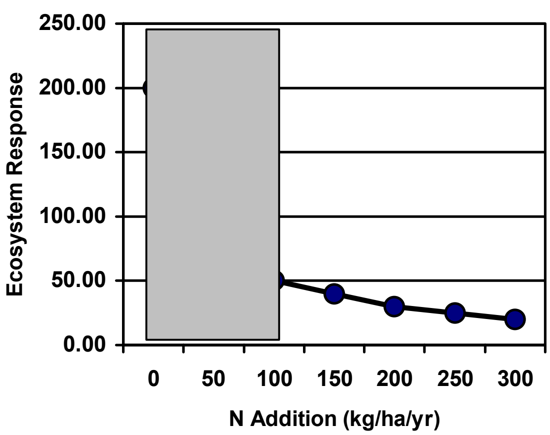

Figure 1. Data adapted from Wedin and Tilman (1996) demonstrating relationship between several ecosystem characteristics and nitrogen dose. Because most of the ecological response occurs with the first 100 kg of load, we call this the 'ecologically significant dose.'

Whereas atmospheric deposition in the Eastern United States is measured at approximately 10-30 kg/ha/yr NO_3 (National Atmospheric Deposition Program (NRSP-3)/National Trends Network 2002), it is evident that ecosystems throughout this region may be affected by exposure to atmospheric deposition of bioavailable nitrogen.

Ecosystems process deposition in a few ways. Deposition to terrestrial systems may be processed by biota (i.e., plants and/or microbes), escape to aquatic systems through runoff or percolation, or volatilize. Improved nitrogen management will occur where the probability of interaction with biota is high. The probability of interacting with biota changes in response to many environmental conditions, some of which (e.g., temperature and precipitation) are essentially outside of the scope of management intervention (Silva et al. 2002). But, many of the conditions are susceptible to management once their response is better understood (e.g., carbon availability).

Study Site

This study was conducted in southeastern Oklahoma at the Center for Subsurface and Ecological Assessment Research (CSEAR), operated by U.S. EPA, Robert S. Kerr Environmental Research Center, Ada, Oklahoma, USA. CSEAR is located in an area of interspersed old-field and oak-forest patches characteristic of the Cross Timbers ecotone, historically a mosaic of mixed grasslands and oak-dominated forest between the southern Great Plains and eastern deciduous forests of Texas, Oklahoma, and Kansas. Cultivation at CSEAR was abandoned at ca. 1950 and cattle grazing was halted in 1998.

Within a contiguous old-field, sixteen 40 x 40-m plots were established to investigate ecosystem interactions associated with additions of nitrogen and manipulations of herbivore populations. Plots were separated by a ca. 5-m mowed pathway. N availability and herbivory were manipulated in plots in a factorial experimental design such that 4 plots each received fertilizer only, herbivory manipulation only, a combination of fertilizer and herbivory manipulation, or neither. Plots were fertilized with granular 34% ammonium nitrate at an annual rate of 16.3 kg-N/ha/yr beginning in February 1999 and every 3 months thereafter. Herbivory was manipulated by a ≐2-m tall chain-link fence of 2.5-cm mesh that effectively excluded intermediate to large sized mammals while supporting greater abundance of small mammals inside fenced plots.

Methods

Two soil samples (separated by ≐10 m) were collected three times per quarter from each plot.* Samples were processed within 24 Hrs of collection. Samples were hand cleansed of gross contaminants (e.g., plant material, worms, stones) and homogenized. Two subsamples were taken from each sample. Subsamples were then extracted with 2-M KCl using a soil to extract ratio of 2:1 (Silva et al. 2003). Samples were centrifuged at 1800 rpm for 10 minutes at 15^{O}C and filtered using pretreated (with 2-M KCl and deionized water) Whatman 42 filter papers. Extractions were completed within two days of sampling. Filtrates were analyzed for mineral-N using LACHAT QuikChem FIA.

* Note: sampling during spring 1999 was done differently and is not included in these analyses; complete sampling from July-December 2001 was interrupted and are not included in these analyses; however, in both of these cases the data points that exist are consistent with the data and interpretations presented.

Results

In this nitrogen-limited ecosystem, extractable nitrate concentrations never averaged more than 1 mg/l during the growing season and were always less than 2 mg/l during the dormant season on control plots. The introduction of an additional 16.3 kg/ha/yr of N deposition was initially successfully processed.

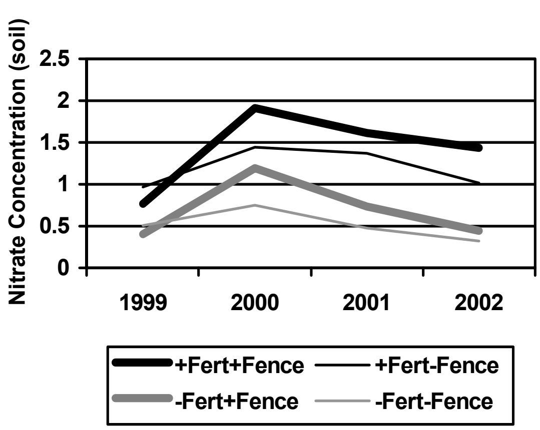

Figure 2. Soil nitrate concentration was consistently greater on fertilized plots. Concentration was also greater on fenced plots, apparently because of highly abundant small mammal populations in fenced plots.

However, this was short-lived and average soil nitrate concentration was 100.5% greater on fertilized plots (Figure 2. $P<0.0001$; $F_{1,360}=37.80$). Further, average nitrate concentration on fenced plots was 24.7% greater (Figure 2. $P=0.0443$; $F_{1,360}=4.07$).
The decline in total soil nitrate measured during 2001 and 2002 (Figure 2) is attributable to lower average concentration measured during winter when concentrations are greatest (Figure 3).

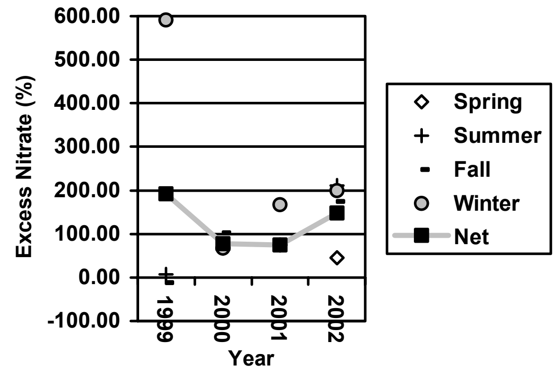

Figure 3. Excess nitrate on fertilized plots has changed dramatically throughout this experiment. This is primarily attributable to changes during winter. Amount of excess nitrate has increased during summer and fall, and stayed essentially the same during spring.

Average excess winter concentration declined from +590.6% during 1999 to +198.7% during 2002 (up from 2000 and 2001). At the same time, average excess concentration during spring remained essentially unchanged, but increased during summer from +6.8% in 1999 to +211.3% in 2002, and during fall from –11.3% in 1999 to +178.3% in 2002 (Figure 3). Mean excess nitrate concentration on fertilized plots was greatest in 1999 (+191.9%) and then declined to approximately +70% for 2000 and 2001, before increasing to +147.3% in 2002.

Excess soil nitrate concentration on fertilized plots ranged between +64.5% during spring to +135.4% during winter (Figure 4). Yearly average mean excess was +105.6%.

Our estimates lead us to expect that essentially all new deposition occurring during the dormant season (winter) is lost to watersheds and we are conducting further research better estimate this loss. However, that this loss is from lands that are considered undeveloped and at low risk is noteworthy.

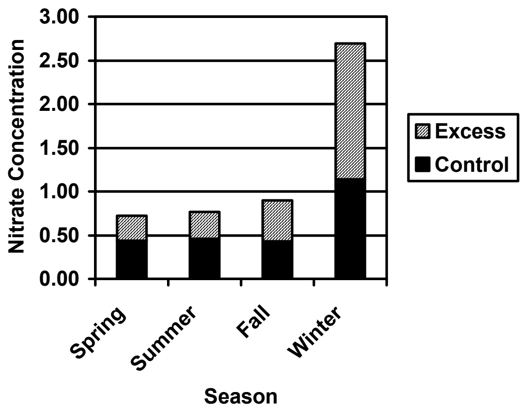

Figure 4. Excess soil nitrate peaks during winter. Averaged over a year, more than twice as much nitrate is available on fertilized plots compared to control plots.

Discussion

Our sites were unable to process the low amounts of nitrogen that we added. Although fertilization began in February 1999, differences among plot response to fertilization were not detectable until December when large differences were observed (Figure 3). Thus, fertilized plots successfully incorporated the initial nitrogen additions until the first dormant season when a substantial failure of the fertilized plots' ability to process nitrogen occurred. It appears to be this initial failure, or initial adaptation to new conditions, leading out of the dormant season that explains the relatively high concentrations measured during 2000 (Figure 2). Further adaptation may be lowering annual average soil nitrate concentration (Figure 2), but excess nitrate remains available during much of the year (Figure 3).

In this experiment, soil nitrogen chemistry is the final product of availability and trophic interactions. Elsewhere, we describe how chronic exposure to low doses of nitrogen on our study plots fundamentally change trophic/ecosystem interactions and lead to reduced nitrogen use efficiency (e.g., Jorgensen et al. 2002, Clark et al. 2003, Mayer et al. 2003, West et al. 2003). Although we expected change to site nitrogen processing to occur, we did not have a clear idea of how long it would take for them to be detectable. In fact, it took only a single growing season for changes to the soil's ability to adapt to nitrogen inputs to be evident and for changes to interactions among biota and ecosystem to be measurable.

This study demonstrates that even regions of the Eastern United States which receive seemingly modest or small amounts of atmospheric nitrate deposition may have undergone a long-term change to their ability to process further nitrogen inputs. Perakis and Hedin (2002) have hypothesized that current ecosystem nitrogen biogeochemistry in much of the Northern Hemisphere may be the product of an historical alteration to biogeochemical cycles that has not yet been identified or understood. We are currently investigating means of detecting such changes through insights from this research.

Finally, our data suggest that the inherent capacity of terrestrial ecosystems to process bioavailable nitrogen has been altered by past exposures to atmospherically deposited nitrogen. Although by themselves these data are insufficient to lead us to the conclusion that existing technologies will be unable to address currently observed environmental problems associated with nitrogen (e.g., Jorgensen 2002), they are consistent with that outcome.

Implications

This study provides evidence for several important phenomena:

1) soil nitrogen chemistry is altered after one growing season of exposure to low-level nitrate deposition.
2) soils are slow to adapt to new nitrogen inputs.
3) the ability of the ecosystem to respond to nitrogen inputs can be compromised by previous exposures.

Ecosystems may be at risk from doses of atmospherically deposited nitrate that are generally considered to be low or modest. As deposition of bioavailable nitrogen from the atmosphere can reasonably be expected to increase, it is prudent to identify and develop management options now to both restore ecosystems that are already compromised and to buffer affects to ecosystems that are at risk from new nitrogen inputs.

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