# Invited Feature

## Denitrification Across Landscapes and Waterscapes[1]

Humans have now altered the nitrogen (N) cycle to a greater extent than any other major biogeochemical element. At the global scale, fertilizer production, fossil fuel combustion, and the widespread cultivation of leguminous crops now cause more atmospheric $N_2$ to be fixed into chemically and biologically reactive forms than all natural processes on land combined. At regional scales, the transformations are even more dramatic: in large portions of the United States, Europe, and eastern Asia, inputs of human-derived reactive nitrogen are now an order of magnitude above those occurring prior to the 20th century. Such changes are not only large, they have been exceptionally rapid; consider that the relative increase in anthropogenic N fixation over the past 50 years has been at least five times greater than that observed in atmospheric $CO_2$.

Such changes to the N cycle are not entirely detrimental. The bulk of human-created reactive N helps sustain levels of agricultural production that are essential to a burgeoning human population, and even today, increased fertilizer use in some regions would clearly have significant public health benefits. Increased atmospheric N deposition may also contribute to anthropogenic $CO_2$ storage (though recent studies suggest this effect is not large). However, excess reactive N throughout much of the world has a suite of negative environmental and human health consequences. These include contributions to air pollution, soil and water acidification, coastal eutrophication and associated fisheries damage, losses of biodiversity, and increases in the frequency of a variety of human ailments.

The necessity of N to modern agriculture, and the growing environmental and societal concerns around its high levels of use, has stimulated considerable research on the fate of excess N in the environment. However, despite decades of such effort, we still have poorly constrained quantitative estimates of a critical piece of the N cycle: denitrification. Once an atom of reactive N enters the environment, it can have a cascade of consequences that can only be halted by conversion back to atmospheric $N_2$. This conversion largely occurs via the process of denitrification, in which nitrogen oxides serve as the terminal electron acceptor of anaerobic respiration by a range of microorganisms. The existence of denitrification has been known for over a century, and today it is widely used to help mitigate N pollution in both agricultural and sewage treatment settings. Yet, at scales ranging from local to global, denitrification is typically the greatest unknown in any attempt to balance the N cycle, a fact that restricts our ability to both manage and predict the consequences of an increasingly N-rich world.

This Invited Feature attempts to synthesize our current knowledge of denitrification in terrestrial and aquatic ecosystems, with an emphasis on recent advances and future opportunities in both measurement and modeling techniques. The papers that follow emerged from a May 2004 workshop entitled "Advanced Approaches to Quantify Denitrification." The meeting was held in Woods Hole, Massachusetts, USA, under the auspices of the International Nitrogen Initiative (INI), and the societal importance of the topic is reflected by the fact that the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), the Environmental Protection Agency (EPA), and the National Oceanic and Atmospheric Administration (NOAA), as well as the International Global Atmospheric Chemistry offices in Europe (EU Network ACCENT) and Asia (Tapei, Institute of Earth Science), all provided support.

The first paper by Davidson and Seitzinger is a more comprehensive introduction to the Invited Feature, and it outlines three major obstacles to progress in denitrification research. Two of these arise from aspects of the process itself: both the dominance of $N_2$ in the atmosphere and the substantial temporal and spatial heterogeneity that is characteristic of denitification hinder

[1] Reprints of this 153-page Invited Feature are available for $10.00 each, either as PDF files or as hard copy. Prepayment is required. Order reprints from the Ecological Society of America, Attention: Reprint Department, 1707 H Street, N.W., Suite 400, Washington, DC 20006 USA (e-mail: esaHQ@esa.org).

measurement and scaling efforts. The third, however, has a more tractable solution. Davidson and Seitzinger argue that a lack of communication and technology transfer among the scientific disciplines concerned with denitrification has slowed progress, and the Woods Hole workshop sought to begin tackling that problem. Thus, this issue contains four review papers that reflect the coordinated efforts of scientists representing multiple disciplines.

The first of these, by Seitzinger et al., takes on the challenge of synthesizing denitrification estimates and controls across terrestrial, freshwater, and marine systems. The paper organizes these disparate realms along a continuum in which nitrate production and consumption are progressively decoupled. The second review by Groffman et al. addresses the diversity of modern methods for measuring denitrification, discusses the merits and limitations of each, and highlights opportunities for improvement, especially in terrestrial ecosystems. Boyer et al. then follow with a review of commonly used denitrification modeling techniques. They point out that most terrestrial and aquatic models suggest a major role for denitrification in the N cycle even at the largest of scales, but that model uncertainties are typically large, and the substantial measurement challenges outlined in the prior reviews often thwart model validation or development. Finally, Wallenstein et al. review recent molecular analyses of denitrifier communities and outline a research agenda for improving our knowledge of how such community structure determines rates of $N_2$ production.

The Invited Feature then concludes with four site-specific papers that exemplify both current methods and limitations to denitrification research. Two of these are from upland terrestrial ecosystems, which pose some of the greatest unknowns in regional denitification rates. Perez et al. describe a new approach to differentiating between nitrification and denitrification sources of $N_2O$ that is based on a combination of isotopomeric and traditional isotopic measurements of the gas. This approach is perhaps most useful for helping to resolve some pervasive uncertainties in $N_2O$ budgets, but it also holds promise for providing additional insight into denitrification rates. Wallenstein and colleagues then explore such rates across a set of fertilized, whole-tree harvested plots in a West Virginia forest and suggest that tree harvesting has lowered denitrification rates and made soils less prone to N saturation than those found in mature, undisturbed forests.

The final two papers of this feature focus on denitrification in aquatic sediments of the Mississippi River Basin, a region that receives enormous inputs of anthropogenic reactive N. Using a modest-sized reservoir in Illinois, David and colleagues demonstrate how reservoir-based denitification can substantially reduce nitrate loading to streams and rivers, and by extension, to the Gulf of Mexico. Finally, Smith et al. use both membrane inlet (MIMS) and isotope ratio (IRMS) mass spectrometry to measure denitrification in sediments from nitrate-rich streams of the upper Mississippi Basin, and provide evidence that there is good agreement between the two techniques.

The papers presented here are an important and timely synthesis of denitrification research, but they represent only a small step toward a much more challenging goal. The scale and pace of change in the nitrogen cycle demands that we move beyond just understanding its controls, and toward a better ability to maximize the benefits of human-fixed $N_2$ while also minimizing its collateral damages. Progress toward such a goal requires a much improved ability to measure and model denitrification. Our hope is that the papers presented here will help take us closer to meeting that challenge.

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