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Opportunities in Nitrogen Management Research: Improving Applications for Proven Technologies and Identifying New Tools for Managing Nitrogen Flux and Input in Ecosystems

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The presence and distribution of undesirable quantities of bioavailable nitrogenous compounds in the environment are issues of long-standing concern. Importantly for us today, deleterious effects associated with high levels of nitrogen in the ecosystem are becoming everyday news events. Excess nitrogen in the environment is associated with many large-scale environmental concerns, including eutrophication of surface waters, toxic algae blooms, hypoxia, acid rain, and global warming. Unfortunately, releases of nitrogen associated with anthropogenic activities are expected to rise throughout the foreseeable future. Whereas our current technologies for managing nitrogen in the environment are stressed, it is reasonable to project that they are likely to fail under the increased loads of nitrogen that are projected for the future. The potential scale of the undesirable consequences are such that it is prudent for us to consider reasonable management and research responses now. This Issue Paper describes a proposed three-part research and management program that is a measured response to concerns about nitrogen pollution, particularly in the eastern United States. The program describes: 1) steps to be taken with regard to landscape management that will improve our knowledge of nitrogen release and management as it relates to land use; 2) investigations needed that will improve our understanding of the factors that prevent full implementation of nitrogen management technology in the high use landscapes that comprise 35.2% of the land cover in the eastern United States; and, 3) research that is needed to help uncover cause-and-effect relationships among trophic levels that will provide new tools for managing nitrogen, especially on low use landscapes that comprise 64.8% of the land cover in the eastern United States.

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Nitrogen is added to ecosystems in enormous quantities through anthropogenic activities (Smil, 1990; Vitousek et al., 1997). Further, these additions have been increasing; a trend that is projected to continue (Brimblecombe and Stedman, 1982; Galloway et al., 1994; U.S. EPA, 1995; Vitousek et al., 1997). Because nitrogen is frequently a limiting nutrient for plants and animals, increased quantities of nitrogen in the ecosystem alters competitive relationships among terrestrial and aquatic organisms. This phenomenon is usually manifested as eutrophication, but acidification of forested watersheds and nitrate pollution to ground water are also symptomatic (e.g., Baker ,1992; Likens, 1992; Wedin and Tilman, 1996; Asner et al., 1997). Excess nitrogen is not tightly retained by ecosystems but is highly mobile (e.g., Vitousek et al., 1997) and it occurs in ecosystems under a variety of guises (i.e., nitrogen species; NO^3, NH^4, NO^2, DON, TN, etc.), each of which varies in its mobility and potential for use by organisms and expression in site biogeochemistry. Therefore, concern about nitrogen management in ecosystems is focused not only on the amount of nitrogen present but also its transport and cycling.

Nitrogen, particularly nitrate, easily moves from terrestrial ecosystems into surface and ground waters, including lakes, streams, rivers, and estuaries (e.g., Kahl et al., 1993; Peterjohn et al., 1996). As nitrogen concentrates in surface and ground water sinks, increasingly frequent observations of undesirable effects associated with eutrophication, algae blooms, hypoxia, and toxicity are observed (Kelly et al., 1990; Likens,1992; Glibert and Terlizzi, 1999). Today, acid rain phenomena in North America are largely associated with excess nitrogen (Aber et al., 1989; Gilliam et al., 1996). Finally, nitrogen affects plant growth, and therefore interacts with atmospheric CO_2 (Shaver et al., 2000). Wedin and Tilman (1996) have suggested that increasing amounts of nitrogen in the environment may be associated with global warming and climate change (see also Vitousek et al., 1997; Shaver et al., 2000).

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While the aforedescribed risks associated with anthropogenic nitrogen are recognized, management options for containing and mitigating them are poorly developed. In order 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 ecosystems and the atmosphere be developed. The scope and magnitude of the nitrogen problem is such that there are many research needs and many opportunities for management intervention. It appears that a three-part nitrogen risk management research program, integrating basic and applied research, will contribute substantially to development of a multi-scale management approach that will maximize nitrogen retention and sequestration in terrestrial and managed landscapes, thereby reducing loadings to aquatic ecosystems.

The description of the research program that follows results from an expectation that the ability of terrestrial and freshwater aquatic ecosystems to optimally retain, sequester, and transform nitrogen can be manipulated, indeed enhanced, through application of appropriate management technologies. This research program would seek to identify those technologies, and identify opportunities for application of existing techniques. This view, that management of nitrogen will be accomplished through management of terrestrial and freshwater aquatic ecosystems, necessarily neglects the impact of direct atmospheric deposition. This particular source of nitrogen input must be managed at the point of production or (as described herein) after it is deposited in terrestrial or aquatic ecosystems. Terrestrial and freshwater ecosystems represent important points in the nitrogen cycle that are amenable to management, and that, if successful when managed together, can produce measurable benefits to water quality and aquatic resources in both freshwater and estuarine ecosystems.

Research Program

While it is possible to conduct research on a problem as pervasive and interrelated with biotic interactions as nitrogen in many subject areas, in many landscapes, and over multiple spatial and temporal scales, it appears that there is good potential to provide measurable changes to the flux and input of nitrogen through and into the environment, particularly in aquatic ecosystems, through a research program that conducts applied and basic research in three areas.

Area 1 – Landscape Management

GIS technology is rapidly reaching a level of sophistication sufficient to characterize watershed and landscape physical, biological, and chemical parameters. Where it is possible to characterize it is also possible to plan and manage. This proposed research area would seek to develop landscape management techniques and recommendations to guide planners' decisions regarding appropriate zoning, development, and land use. The research would characterize and model physical and remotely sensed properties of landscapes and watersheds, and associate these properties with concentrations of nitrogen ions in terrestrial and aquatic ecosystems. These characterizations and models would allow planners to identify potential landscapes and watersheds at risk from eutrophication and acidification to facilitate proactive land use planning. The characterizations and models would allow identification of landscapes and watersheds that are potentially highly perturbed by excess nitrogen, thereby facilitating efficient targeting of restoration and management actions. The characterizations and models would allow identification of landscape and watershed attributes that are highly correlated with risk from excess nitrogen, thereby providing clear guidance for prescription of specific restoration and management techniques and suggesting research themes for investigating methodologies of maximizing and optimizing landscape and watershed retention, sequestration, and transformation capability for nitrogen (e.g., Magill et al., 1996; Mander et al., 2000).

The following research tasks need to be addressed in this area:

Task 1.1 *Characterize and Model the Relations of Watershed and Upstream Land Uses and Physical and Biological Properties to the Concentration and Load of Targeted Nitrogen Ions in Terrestrial and Aquatic Ecosystems – Including Estuaries, Lakes, Rivers, Streams, Ground Water, and Sediment.*

Water that is present in or entering the lakes, rivers, streams, and ground water of a watershed is the product of a large spatial and temporal scale integration that reflects the types and distribution of land uses at large in the watershed and the physical, and biological interactions occurring therein.

Task 1.2 *Associate Characterizations and Models of Nitrogen Ion Concentrations and Loads in Watersheds from Task 1.1 with Known and Predicted Exposure Risk Levels for Biota and Health to Identify Watersheds and Landscapes that are Currently Adversely Affected by Excess Nitrogen and Those that are at Risk Attributable to Increasing Amounts of Nitrogen.*

Where an important goal of risk management is to predict and prevent future problems and to mitigate effects in already heavily impacted watersheds, an important priority is to develop and refine models that work in currently heavily impacted watersheds and those soon to be at risk from further nitrogen deposition.

Task 1.3 *Identify Watershed and Landscape Land Use and Physical and Biological Parameters that are Highly Correlated with Nitrogen Ion Concentrations and Loads in Terrestrial and Aquatic Ecosystems.*

Where reduction of adverse effects can be most rapidly achieved when cause and effect are known and consequences are certain, identification of non-optimum land use practices that may heavily impact at-risk watersheds is a priority.

Task 1.4 *Prescribe Watershed and Landscape Specific Restoration and Management Actions, Regarding Manipulation of Parameters Identified in Task 1.3, to Contain and/or Reduce Risks Associated with Excess Nitrogen Concentration and Loading.*

The nature of the nitrogen problem is such that prevention at the source is frequently not an economically or socially desirable option; therefore, containment of the effects of nitrogen release is desirable through implementation of appropriate risk reduction technologies remote from the point of release.

Task 1.5 *Identify and Prioritize Research Questions and Tasks Indicated by the Results of Task 1.3 that Hold Substantial Probability of Providing Measurable Refinements and Improvements to the Techniques Prescribed by Task 1.4.*

Through adaptive management, apply the skills developed through an increasing level of management activity and research to finding new and more effective and efficient means for managing excess nitrogen in watersheds.

Advances in this research area will provide managers and planners with coarse-scale correlative-tools that have a substantial probability of providing measurable reductions to the rate of flux and amount of nitrogen leaching to surface and ground waters, and estuaries. These coarse-scale tools can reasonably be expected to provide immediate management benefits. However, the ultimate ability of management actions prescribed based upon correlative tools to produce a large widespread benefit is unclear. The ability of prescribed management actions can certainly be improved and optimized through phased implementation of improvements to correlative tools that are based upon cause-and-effect knowledge of the system.

Area 2 – Management of High Use Landscapes

Problems associated with excess nitrogen have been recognized for decades and are frequently associated with increasing land use intensity and economic activity (i.e., urbanization and row cropping). These problems include, but are not limited to, economic loss attributable to excess fertilization, septic field failure, acid rain, eutrophication of aquatic ecosystems, and pollution from municipal sewage outfalls. Cover of high use lands increased 34.3% between 1982 and 1997 in the eastern United States from 60.4 to 81.1 million acres whereas cover of cropped lands decreased 9.9% during the same period (USDA, 2000). Together, developed and cropped lands accounted for 35.2% of the land cover in the eastern United States in 1997 (USDA, 2000). Impacts to watersheds of nitrogen from these high use lands are well known and must be accounted for. Because problems have been associated with nitrogen for many years, numerous techniques have been developed to minimize, or in some cases eliminate, nitrogen leaching from high use lands to the environment.

Prescription and regulation of nitrogen management techniques is not centralized, but falls within the authority of numerous federal, state, and local agencies and governments. Frequently, application of known techniques at any given local site occurs as a matter of opportunity when willing landowners interact with knowledgeable managers and planners. This loosely organized system leaves significant opportunity for the identification of high use watersheds and landscapes where application of known nitrogen management techniques is under-utilized.

The following research tasks need to be addressed in this area:

Task 2.1 *Inventory and Organize in a Central Database All Known Sources of Nitrogen that are Associated with High Use Landscapes, including Urbanized, Agricultural, Industrial, and Recreational Areas. Concurrently, Inventory and Organize in a Central Database Management Methods and Measurements of Effectiveness for Nitrogen Management in these Landscapes.*

Historically, it has only been poorly recognized that land use practices and nitrogen release are related; therefore, knowledge of land uses and expected contributions to the nitrogen problem is excessively dispersed, in the literature, among professionals, and among management agencies. There appears to be an opportunity to achieve significant economy of scale improvements for the organization of nitrogen data and information.

Task 2.2 *Inventory and Model Relationships Among Physical, Biological, Social, Economic, and Demographic Parameters on a Watershed Specific Basis, to the Distribution of Known Sources of Nitrogen (Task 2.1) in Conjunction with the Distribution of the Application of Management Methods (Task 2.2).*

Management of nitrogen falls to no single entity or agency. Therefore, many opportunities exist for the application of state-of-the-art management interventions where currently inadequate or absent interventions are accepted.

Task 2.3 *Rank, Prioritize, and Identify Watersheds Along a Gradient of Discordance Between the Distribution of Sources of Nitrogen and the Distribution of the Application of Management Methods Determined in Task 2.2.*

With the strong intent to improve the situation, we should identify watersheds that are substantive contributors to the nitrogen problem where even current management technologies are not being used.

Task 2.4 *Provide Watershed Specific Recommendations in High Priority Watersheds Identified in Task 2.3 to Local Managers and Planners - in Ecological, Engineering, Environmental, Economic, and Social Sciences – for Application of Known Nitrogen Management Methods for High Use Landscapes.*

It is reasonable to expect that local economic and social factors may be correlated with utilization of current nitrogen management technologies. These factors should be identified so that programs can be developed to help local stakeholders improve their environment and contribute to national and or regional nitrogen management goals.

Advances in this research area will help to relieve adverse impacts to watersheds in high use landscapes while concurrently contributing to measurable downstream improvements of water quality and habitat for aquatic biota in receiving waters, particularly estuaries. Because nitrogen management techniques already exist for many anthropogenic sources of nitrogen in high use landscapes, measurable reductions to the rate of flux and amount of nitrogen leaching to surface and ground water in these landscapes should be able to be realized through identification of under-utilized targets for technique application.

Area 3 – Management Techniques for Low Use Landscapes

Despite the recognition that excess nitrogen in the environment has notable undesirable properties, and despite decades of research and management practice aimed at minimizing and eliminating nitrogen leaching from its point of production or release, we currently face a substantial and apparently growing problem related to excess nitrogen. One explanation for this is that ecosystems are slowly losing their ability to optimally retain, sequester, and transform nitrogen. Thus, nitrogen is more readily leaching to surface and ground waters, and estuaries. By a large majority, most of the land where the ability of the ecosystem to process nitrogen may be degraded occurs in low use landscapes, including parklands, wilderness, grazing lands, and forests. Together, these land uses accounted for 68.8% of the land cover in the eastern United States during 1997 (USDA, 2000).

The ability of these lands to retain and sequester nitrogen is not well understood, although it is clear that increasing the amount of nitrogen input to these landscapes frequently leads to a decreasing ability of these landscapes to optimally retain, sequester, and transform nitrogen. Thus, the more nitrogen that is added, the less is retained.

This being the case, it is clear that our ability to reduce uncertainty regarding nitrogen management results attainable from Research Areas 1 and 2 can be greatly enhanced through an improved understanding of the contribution of low use landscapes to nitrogen management. Further, there is every reason to expect that management techniques and prescriptions can be developed for low use landscapes that will maximize and enhance their ability to retain, sequester, and transform nitrogen, especially nitrogen inputs attributable to atmospheric deposition.

The following research tasks need to be addressed in this area:

Task 3.1 *Measure the Ability of Landscapes and Vegetative Communities from Multiple Ecological Settings, and their Associated Consumer, Decomposer, and Microbial Communities, to Retain, Sequester, and Transform Nitrogen, and Measure their Retention, Sequestration, and Transformation Responses to Increased Levels of Nitrogen Flux and Input.*

Measures of the basic ability of ecosystems to assimilate and process nitrogen, and their ability to respond and adapt to greater levels of nitrogen input are notably lacking but certainly needed.

Task 3.2 *Measure the Interaction of Landscapes and Vegetative Communities with Producer, Consumer, Decomposer, and Microbial Activity Relative to the Ability of Landscapes and Vegetative Communities to Retain, Sequester, and Transform Nitrogen.*

An ability to understand and manipulate nitrogen cycling through the ecosystem, at the level of cause-and-effect relationships, would provide powerful tools for predicting watershed susceptibility to increased amounts of nitrogen and more importantly, for development of new nitrogen management tools for a wide variety of landscapes under many types of land use.

Task 3.3 *Provide Management Recommendations for Landscapes and Vegetative Communities Resulting from Tasks 3.1 and 3.2, for Manipulating Sites to Optimize and Maintain Nitrogen Retention, Sequestration, and Transformation.*

With an improved understanding of the cause-and-effect relationships underlying nitrogen cycling, it would be possible to tailor management interventions that will be optimum in specific watersheds in association with specific land uses.

Task 3.4 *Obtain Metrics for Projecting with Confidence how Site Succession will Affect Nitrogen Retention, Sequestration, and Transformation Characteristics and Identify Indicator and Monitoring Criteria that can Predict Site Senescence.*

Ecosystems change with time. Where it is desirable to predict future conditions, the ability to predict and therefore manage nitrogen in ecosystems must account for succession in ecological communities.

Task 3.5 *Develop Techniques and Methods for Manipulating Producer, Consumer, Decomposer, and Microbial Individuals, Populations, and Communities to Manage for Maintained Native Biodiversity on Landscapes and Watersheds to Concurrently Maximize Nitrogen Retention, Sequestration, and Transformation Characteristics.*

It is desirable that we integrate nitrogen management with interrelated environmental concerns, most particularly native species management, in an effort to increase management effectiveness and benefit.

Advances in this research area, while of a basic scientific nature, hold the promise of allowing spatially extensive low use landscapes to maintain and improve their ability to retain, sequester, and transform nitrogen. In this regard, they can serve as nitrogen sinks – offsetting to some extent the degraded ability of even the best-managed high use landscapes to use nitrogen. Just as the manipulation of plants, regarding their ability to produce food, has provided the foundation for the green revolution, so is it reasonable to expect that analogous manipulations of plants and other biota – including individuals, populations, and communities – can produce desirable outcomes for nitrogen management.

Conclusion

The research program for nitrogen management described herein constitutes a reasonable – measured response – to an environmental problem that is just beginning to be fully understood. A program of combined applied and basic research in the Ecological, Engineering, Environmental, Economic, and Social Sciences is described that will identify landscapes and watersheds at risk from excess nitrogen and prescribe management responses in both high and low use landscapes. The program will indicate fruitful directions for future research, leading to the development of techniques and methods for manipulating producers, consumers, decomposers, and microbial communities for the purpose of maximizing and optimizing landscape and watershed nitrogen retention, sequestration, and transformation ability.

Notice

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