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Human Alteration of the Global Nitrogen Cycle: Causes and Consequences

Photo by Nadine Cavender

Human Alteration of the Global Nitrogen Cycle: Causes and Consequences

SUMMARY

Human activities are greatly increasing the amount of nitrogen cycling between the living world and the soil, water, and atmosphere. In fact, humans have already doubled the rate of nitrogen entering the land-based nitrogen cycle, and that rate is continuing to climb. This human-driven global change is having serious impacts on ecosystems around the world because nitrogen is essential to living organisms and its availability plays a crucial role in the organization and functioning of the world's ecosystems. In many ecosystems on land and sea, the supply of nitrogen is a key factor controlling the nature and diversity of plant life, the population dynamics of both grazing animals and their predators, and vital ecological processes such as plant productivity and the cycling of carbon and soil minerals. This is true not only in wild or unmanaged systems but in most croplands and forestry plantations as well. Excessive nitrogen additions can pollute ecosystems and alter both their ecological functioning and the living communities they support.

Most of the human activities responsible for the increase in global nitrogen are local in scale, from the production and use of nitrogen fertilizers to the burning of fossil fuels in automobiles, power generation plants, and industries. However, human activities have not only increased the supply but enhanced the global movement of various forms of nitrogen through air and water. Because of this increased mobility, excess nitrogen from human activities has serious and long-term environmental consequences for large regions of the Earth.

The impacts of human domination of the nitrogen cycle that we have identified with certainty include:

- Increased global concentrations of nitrous oxide (N_2O), a potent greenhouse gas, in the atmosphere as well as increased regional concentrations of other oxides of nitrogen (including nitric oxide, NO) that drive the formation of photochemical smog;
- Losses of soil nutrients such as calcium and potassium that are essential for long-term soil fertility;
- Substantial acidification of soils and of the waters of streams and lakes in several regions;
- Greatly increased transport of nitrogen by rivers into estuaries and coastal waters where it is a major pollutant.

We are also confident that human alterations of the nitrogen cycle have:

- Accelerated losses of biological diversity, especially among plants adapted to low-nitrogen soils, and subsequently, the animals and microbes that depend on these plants;
- Caused changes in the plant and animal life and ecological processes of estuarine and nearshore ecosystems, and contributed to long-term declines in coastal marine fisheries.

National and international policies should attempt to reduce these impacts through the development and widespread dissemination of more efficient fossil fuel combustion technologies and farm management practices that reduce the burgeoning demand for and release of nitrogenous fertilizers.

Human Alteration of the Global Nitrogen Cycle: Causes and Consequences

by
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INTRODUCTION

This report presents an overview of the current scientific understanding of human-driven changes to the global nitrogen cycle and their consequences. It also addresses policy and management options that could help moderate these changes in the nitrogen cycle and their impacts.

THE NITROGEN CYCLE

Nitrogen is an essential component of proteins, genetic material, chlorophyll, and other key organic molecules. All organisms require nitrogen in order to live. It ranks fourth behind oxygen, carbon, and hydrogen as the most common chemical element in living tissues. Until human activities began to alter the natural cycle (Figure 1), however, nitrogen was only scantily available to much of the biological world. As a result, nitrogen served as one of the major limiting factors that controlled the dynamics, biodiversity, and functioning of many ecosystems.

The Earth's atmosphere is 78 percent nitrogen gas, but most plants and animals cannot use nitrogen gas directly from the air as they do carbon dioxide and oxygen. Instead, plants — and all organisms from the grazing animals to the predators to the decomposers that ultimately secure their nourishment from the organic materials synthesized by plants — must wait for nitrogen to be "fixed," that is, pulled from the air and bonded to hydrogen or oxygen to form inorganic compounds, mainly ammonium (NH_4) and nitrate (NO_3), that they can use.

The amount of gaseous nitrogen being fixed at any given time by natural processes represents only a small addition to the pool of previously fixed nitrogen that cycles among the living and nonliving components of the Earth's ecosystems. Most of that nitrogen, too, is unavailable, locked up in soil organic matter — par-

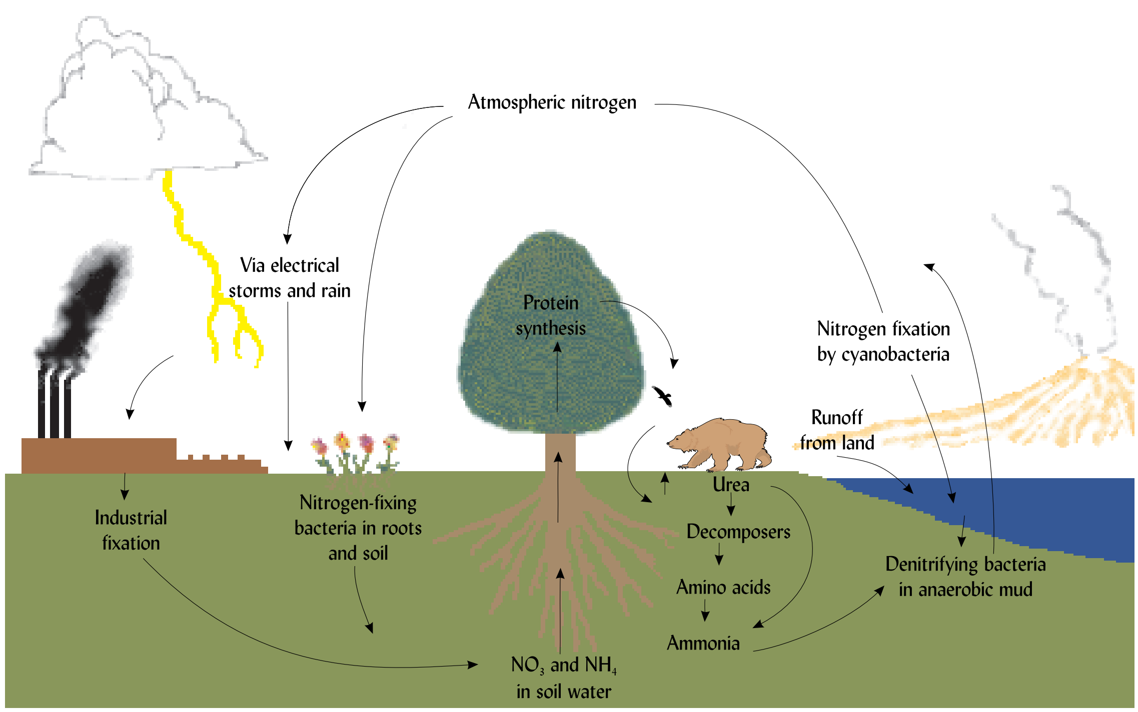

Figure 1-Simplified diagram of the nitrogen cycle. Adapted from *Environmental Science*, Third Edition by Jonathon Turk and Amos Turk, ©1984 by Saunders College Publishing, reproduced by permission of the publisher.

tially rotted plant and animal remains — that must be decomposed by soil microbes. These microbes release nitrogen as ammonium or nitrate, allowing it to be recycled through the food web. The two major natural sources of new nitrogen entering this cycle are nitrogen-fixing organisms and lightning.

Nitrogen-fixing organisms include a relatively small number of algae and bacteria. Many of them live free in the soil, but the most important ones are bacteria that form close symbiotic relationships with higher plants. Symbiotic nitrogen-fixing bacteria such as the Rhizobia, for instance, live and work in nodules on the roots of peas, beans, alfalfa and other legumes. These bacteria manufacture an enzyme that enables them to convert gaseous nitrogen directly into plant-usable forms.

Lightning may also indirectly transform atmospheric nitrogen into nitrates, which rain onto soil.

Quantifying the rate of natural nitrogen fixation prior to human alterations of the cycle is difficult but necessary for evaluating the impacts of human-driven changes to the global cycling of nitrogen. The standard unit of measurement for analyzing the global nitrogen cycle is the teragram (abbreviated Tg), which is equal to a million metric tons of nitrogen. Worldwide, lightning, for instance, fixes less than 10 Tg of nitrogen per year — maybe even less than 5 Tg. Microbes are the major natural suppliers of new biologically available nitrogen. Before the widespread planting of legume crops, terrestrial organisms probably fixed between 90 and 140 Tg of nitrogen per year. A reasonable upper bound for the rate of natural nitrogen fixation on land is thus about 140 Tg of N per year.

HUMAN-DRIVEN NITROGEN FIXATION

During the past century, human activities clearly have accelerated the rate of nitrogen fixation on land, effectively doubling the annual transfer of nitrogen from the vast but unavailable atmospheric pool to the biologically available forms. The major sources of this enhanced supply include industrial processes that produce nitrogen fertilizers, the combustion of fossil fuels, and the cultivation of soybeans, peas, and other crops that host symbiotic nitrogen-fixing bacteria. Furthermore, human activity is also speeding up the release of nitrogen from long-term storage in soils and organic matter.

Figure 2-Nitrogen is the major factor limiting many terrestrial ecosystems, including most of those in the temperate zone, such as this oak savannah. The number and identities of the plant and animal species that live in such terrestrial ecosystems, and the functioning of the ecosystem, depends on the rate of nitrogen supply to the ecosystem.

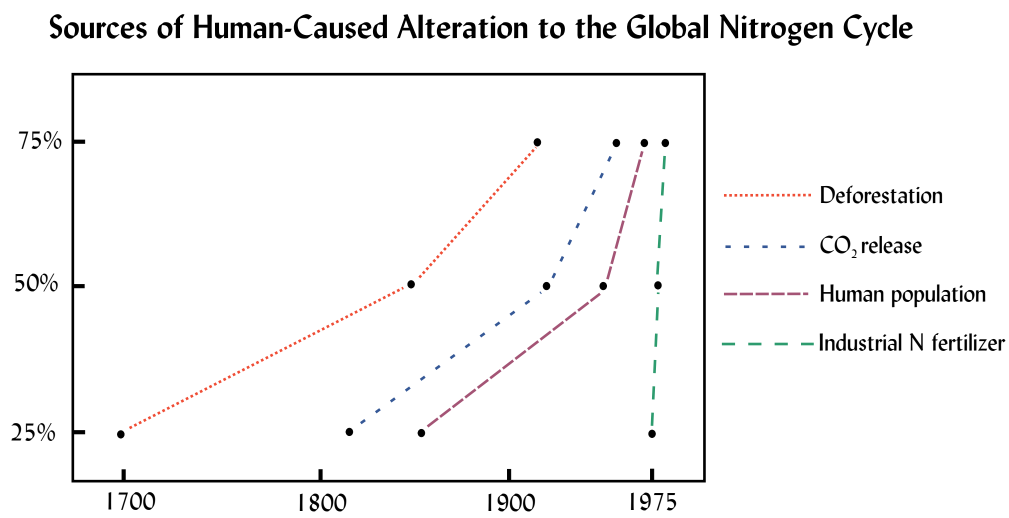

Figure 3-The pace of many human-caused global changes has increased starkly in modern history, but none so rapidly as industrial production of nitrogen fertilizer, which has grown exponentially since the 1940s. The chart shows the year which changes in human population growth, carbon dioxide release, deforestation, and fertilizer production had reached 25%, 50%, and 75% of the extent seen in the late 1980s. Revised from Kates et al. (1990).

Nitrogen Fertilizer

Industrial fixation of nitrogen for use as fertilizer currently totals approximately 80 Tg per year and represents by far the largest human contribution of new nitrogen to the global cycle (Figure 3). That figure does not include manures and other organic nitrogen fertilizers, which represent a transfer of already-fixed nitrogen from one place to another rather than new fixation.

The process of manufacturing fertilizer by industrial nitrogen fixation was first developed in Germany during World War I, and fertilizer production has grown exponentially since the 1940s. In recent years, the increasing pace of production and use has been truly phenomenal. The amount of industrially fixed nitrogen applied to crops during the decade from 1980 to 1990 more than equaled all industrial fertilizer applied previously in human history.

Until the late 1970s, most industrially produced fertilizer was applied in developed countries. Use in these regions has now stabilized while fertilizer applications in developing countries have risen dramatically. The momentum of human population growth and increasing urbanization ensures that industrial fertilizer production will continue at high and likely accelerating rates for decades in order to meet the escalating demand for food.

Nitrogen-Fixing Crops

Nearly one third of the Earth's land surface is devoted to agricultural and pastoral uses, and humans have replaced large areas of diverse natural vegetation with monocultures of soybeans, peas, alfalfa, and other leguminous crops and forages. Because these plants support symbiotic nitrogen-fixers, they derive much of their nitrogen directly from the atmosphere and greatly increase the rate of nitrogen fixation previously occurring on those lands. Substantial levels of nitrogen fixation also occur during cultivation of some non-legumes, notably rice. All of this represents new, human-generated stocks of biologically available nitrogen. The quantity of nitrogen fixed by crops is more difficult to analyze than industrial nitrogen production. Estimates range from 32 to 53 Tg per year. As an average, 40 Tg will be used here.

Fossil Fuel Burning

The burning of fossil fuels such as coal and oil releases previously fixed nitrogen from long-term storage in geological formations back to the atmosphere in the form of nitrogen-based trace gases such as nitric oxide. High-temperature combustion also fixes a small amount of atmospheric nitrogen directly. Altogether, the operations of automobiles, factories, power plants, and other combustion processes emit more than 20 Tg per year of fixed nitrogen to the atmosphere. All of it is treated here as newly fixed nitrogen because it has been locked up for millions of years and would remain locked up indefinitely if not released by human action.

Mobilization of Stored Nitrogen

Besides enhancing fixation and releasing nitrogen from geological reservoirs, human activities also liberate nitrogen from long-term biological storage pools such as soil organic matter and tree trunks, contributing further to the proliferation of biologically available nitrogen. These activities include the burning of forests, wood fuels, and grasslands, which emits more than 40 Tg per year of nitrogen; the draining of wetlands, which sets the stage for oxidation of soil organic matter that could mobilize 10 Tg per year or more of nitrogen; and land clearing for crops, which could mobilize 20 Tg per year from soils.

There are substantial scientific uncertainties about both the quantity and the fate of nitrogen mobilized by such activities. Taken together, however, they could contribute significantly to changes in the global nitrogen cycle.

Human Versus Natural Nitrogen Fixation

Overall, fertilizer production, legume crops, and fossil fuel burning deposit approximately 140 Tg of new nitrogen into land-based ecosystems each year, a figure that equals the upper estimates for nitrogen fixed naturally by organisms in these ecosystems. Other human activities liberate and make available half again that much nitrogen. From this evidence, it is fair to conclude that human activities have at least doubled the transfer of nitrogen from the atmosphere into the land-based biological nitrogen cycle.

This extra nitrogen is spread unevenly across the Earth's surface: Some areas such as northern Europe are being altered profoundly while others such as remote regions in the Southern Hemisphere receive little direct input of human-generated nitrogen. Yet no region remains unaffected. The increase in fixed nitrogen circulating around the globe and falling to the ground as wet or dry deposition is readily detectable, even in cores drilled from the glacial ice of Greenland.

IMPACTS ON THE ATMOSPHERE

One major consequence of human-driven alterations in the nitrogen cycle has been regional and global change in the chemistry of the atmosphere (Figure 4) — specifically, increased emissions of nitrogen-based trace gases such as nitrous oxide, nitric oxide, and ammonia (NH_3). Although such releases have received less attention than increased emissions of carbon dioxide and various sulfur compounds, the trace nitrogen gases cause environmental effects both while airborne and after they are deposited on the ground. For instance, nitrous oxide is long-lived in the atmosphere and contributes to the human-driven enhancement of the greenhouse effect that likely warms the Earth's climate. Nitric oxide is an important precursor of acid rain and photochemical smog.

Some of the human activities discussed above affect the atmosphere directly. For instance, essentially all of the more than 20 Tg per year of fixed nitrogen released in automobile exhausts and in other emissions from fossil fuel burning is emitted to the atmosphere as nitric oxide. Other activities indirectly enhance emissions to the atmosphere. Intensive fertilization of agricultural soils can increase the rates at which nitrogen in the form of ammonia is volatilized and lost to the air. It can also speed the microbial breakdown of ammonium and nitrates in the soil, enhancing the release of nitrous oxide. Even in wild or unmanaged lands downwind of agricultural or industrial areas, rain or windborne deposition of human-generated nitrogen can spur increased emissions of nitrogen gases from the soils.

Nitrous Oxide

Nitrous oxide is a very effective heat-trapping gas in the atmosphere, in part because it absorbs outgoing radiant heat from the Earth in infrared wavelengths that are not captured by the other major greenhouse gases, water vapor and carbon dioxide. By absorbing and reradiating this heat back toward the Earth, nitrous oxide contributes a few percent to overall greenhouse warming.

Although nitrous oxide is unreactive and long-lived in the lower atmosphere, when it rises into the stratosphere it can trigger reactions that deplete and thin the stratospheric ozone layer that shields the Earth from damaging ultraviolet radiation.

The concentration of nitrous oxide in the atmosphere is currently increasing at the rate of two- to three-tenths of a percent per year. While that rise is clearly documented, the sources of the increase remain unresolved. Both fossil fuel burning and the direct impacts of agricultural fertilization have been considered and rejected as the major source. Rather, there is a developing consensus that a wide array of human-driven sources contribute systematically to enrich the terrestrial nitrogen cycle. These "dispersed sources" include fertilizers, nitrogen-enriched groundwater, nitrogen-saturated forests, forest burning, land clearing, and even the manufacture of nylon, nitric acid, and other industrial products.

The net effect is increased global concentrations of a potent greenhouse gas that also contributes to the thinning of the stratospheric ozone layer.

Nitric Oxide and Ammonia

Unlike nitrous oxide, which is unreactive in the lower atmosphere, both nitric oxide and ammonia are highly reactive and therefore much shorter lived. Thus

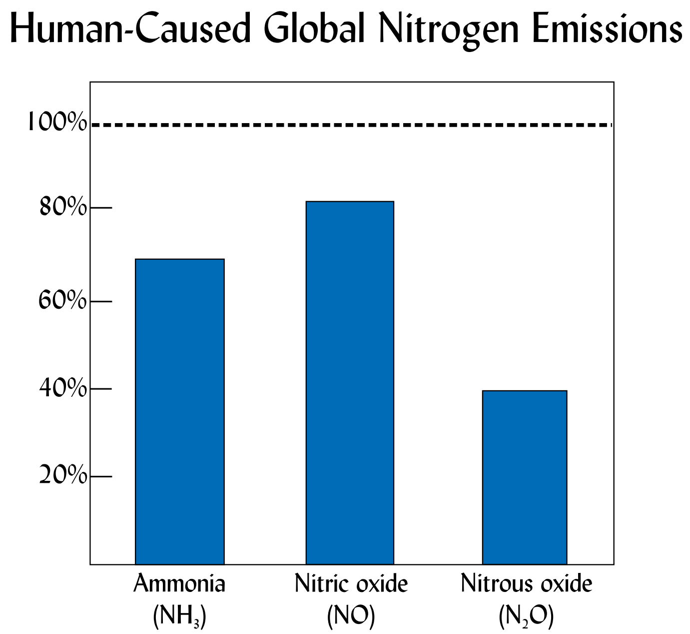

Figure 4-Human activities are responsible for a large proportion of the global emissions of nitrogen-containing trace gases, including 40% of the nitrous oxide, 80% or more of nitric oxide, and 70% of ammonia releases. The result is increasing atmospheric concentrations of the greenhouse gas nitrous oxide, of the nitrogen precursors of smog, and of biologically available nitrogen that falls from the atmosphere to fertilize ecosystems. Ammonia data are from Schlesinger and Hartley (1992), nitric oxide from Delmas et al. (in press), and nitrous oxide from Prather et al. (1995).

changes in their atmospheric concentrations can be detected only at local or regional scales.

Nitric oxide plays several critical roles in atmospheric chemistry, including catalyzing the formation of photochemical (or brown) smog. In the presence of sunlight, nitric oxide and oxygen react with hydrocarbons emitted by automobile exhausts to form ozone, the most dangerous component of smog. Ground-level ozone has serious detrimental effects on human health as well as the health and productivity of crops and forests.

Nitric oxide, along with other oxides of nitrogen and sulfur, can be transformed in the atmosphere into nitric acid and sulfuric acid, which are the major components of acid rain.

Although a number of sources contribute to nitric oxide emissions, combustion is the dominant one. Fossil fuel burning emits more than 20 Tg per year of nitric oxide. Human burning of forests and other plant material may add about 10 Tg, and global emissions of nitric oxide from soils, a substantial fraction of which are human-caused, total 5 to 20 Tg per year. Overall, 80 percent or more of nitric oxide emissions worldwide are generated by human activities, and in many regions the result is increased smog and acid rain.

In contrast to nitric oxide, ammonia acts as the primary acid-neutralizing agent in the atmosphere, having an opposite influence on the acidity of aerosols, cloudwater, and rainfall. Nearly 70 percent of global ammonia emissions are human-caused. Ammonia volatilized from fertilized fields contributes an estimated 10 Tg per year; ammonia released from domestic animal wastes about 32 Tg; and forest burning some 5 Tg.

EFFECTS ON THE CARBON CYCLE

Increased emissions of airborne nitrogen have led to enhanced deposition of nitrogen on land and in the oceans. Thanks to the fertilizer effects of nitrogen in stimulating plant growth, this deposition may be acting to influence the atmosphere indirectly by altering the global carbon cycle.

Over much of the Earth's surface, the lushness of plant growth and the accumulation of standing stocks of plant material historically have been limited by scanty nitrogen supplies, particularly in temperate and boreal regions. Human activity has substantially increased the deposition of nitrogen over much of this area, which raises important questions: How much extra plant growth has been caused by human-generated nitrogen additions? As a result, how much extra carbon has been stored in terrestrial ecosystems rather than contributing to the rising concentrations of carbon dioxide in the atmosphere?

Answers to these questions could help explain the imbalance in the carbon cycle that has come to be known as the 'missing sink.' The known emissions of carbon dioxide from human activities such as fossil fuel burning and deforestation exceed by more than 1,000 Tg the amount of carbon dioxide known to be accumulating in the atmosphere each year. Could increased growth rates in terrestrial vegetation be the 'sink' that accounts for the fate of much of that missing carbon?

Experiments in Europe and America indicate that a large portion of the extra nitrogen retained by forest, wetland, and tundra ecosystems stimulates carbon uptake and storage. On the other hand, this nitrogen can also stimulate microbial decomposition and thus releases of carbon from soil organic matter. On balance, however, the carbon uptake through new plant growth appears to exceed the carbon losses, especially in forests.

A number of groups have attempted to calculate the amount of carbon that could be stored in terrestrial vegetation thanks to plant growth spurred by added nitrogen. The resulting estimates range from 100 to 1,300 Tg per year. The number has tended to increase in more recent analyses as the magnitude of human-driven changes in the nitrogen cycle has become clearer. The most recent analysis of the global carbon cycle by the Intergovernmental Panel on Climate Change concluded that nitrogen deposition could represent a major component of the missing carbon sink.

Figure 5-Wild plants living in natural ecosystems, such as this lupine, a nitrogen-fixing plant, dominated the nitrogen cycle for millions of years. Human production of nitrogen fertilizer, burning of fossil fuels, and intensive cultivation of legume crops now adds as much nitrogen to terrestrial ecosystems as do all natural processes combined.

More precise estimates will become possible when we have a more complete understanding of the fraction of human-generated nitrogen that actually is retained within various land-based ecosystems.

NITROGEN SATURATION AND ECOSYSTEM FUNCTIONING

There are limits to how much plant growth can be increased by nitrogen fertilization. At some point, when the natural nitrogen deficiencies in an ecosystem are fully relieved, plant growth becomes limited by sparsity of other resources such as phosphorus, calcium, or water. When the vegetation can no longer respond to further additions of nitrogen, the ecosystem reaches a state described as "nitrogen saturation." In theory, when an ecosystem is fully nitrogen-saturated and its soils, plants, and microbes cannot use or retain any more, all new nitrogen deposits will be dispersed to streams, groundwater, and the atmosphere.

Nitrogen saturation has a number of damaging consequences for the health and functioning of ecosystems. These impacts first became apparent in Europe almost two decades ago when scientists observed significant increases in nitrate concentrations in some lakes and streams and also extensive yellowing and loss of needles in spruce and other conifer forests subjected to heavy nitrogen deposition. These observations led to several field experiments in the U.S. and Europe that have revealed a complex cascade of effects set in motion by excess nitrogen in forest soils.

As ammonium builds up in the soil, it is increasingly converted to nitrate by bacterial action, a process that releases hydrogen ions and helps acidify the soil. The buildup of nitrate enhances emissions of nitrous oxides from the soil and also encourages leaching of highly water-soluble nitrate into streams or groundwater. As these negatively charged nitrates seep away, they carry with them positively charged alkaline minerals such as calcium, magnesium, and potassium. Thus human modifications to the nitrogen cycle decrease soil fertility by greatly accelerating the loss of calcium and other nutrients that are vital for plant growth. As calcium is depleted and the soil acidified, aluminum ions are mobilized, eventually reaching toxic concentrations that can damage tree roots or kill fish if the aluminum washes into streams. Trees growing in soils replete with nitrogen but starved of calcium, magnesium, and potassium can develop nutrient imbalances in their roots and leaves. This may reduce their photosynthetic rate and efficiency, stunt their growth, and even increase tree deaths.

Nitrogen saturation is much further advanced over extensive areas of northern Europe than in North America because human-generated nitrogen deposition is several times greater there than in even the most extremely affected areas of North America. In the nitrogen-saturated ecosystems of Europe, a substantial fraction of atmospheric nitrate deposits move from the land into streams without ever being taken up by organisms or playing a role in the biological cycle.

In contrast, in the northeastern U.S., increased leaching of nitrates from the soil and large shifts in the nutrient ratios in tree leaves generally have been observed only in certain types of forests. These include high-elevation sites that receive large nitrogen deposits and sites with shallow soils containing few alkaline minerals to buffer acidification. Elsewhere in the U.S., the early stages of nitrogen saturation have been seen in response to elevated nitrogen deposition in the forests surrounding the Los Angeles Basin and in the Front Range of the Colorado Rockies.

Some forests have a very high capacity to retain added nitrogen, particularly regrowing forests that have been subjected to intense or repeated harvesting, an activity that usually causes severe nitrogen losses. Overall, the ability of a forest to retain nitrogen depends on its potential for further growth and the extent of its current nitrogen stocks. Thus, the impacts of nitrogen deposition are tightly linked to other rapidly changing human-driven variables such as shifts in land use, climate, and atmospheric carbon dioxide and ozone levels.

EFFECTS ON BIODIVERSITY AND THE SPECIES MIX

Limited supplies of biologically available nitrogen are a fact of life in most natural ecosystems, and many native plant species are adapted to function best under this constraint. New supplies of nitrogen showered upon these ecosystems can cause a dramatic shift in the dominant species and also a marked reduction in overall species diversity as the few plant species adapted to take full advantage of high nitrogen out compete their neighbors. In England, for example, nitrogen fertilizers applied to experimental grasslands have led to increased dominance by a few nitrogen-responsive grasses and loss of many other plant species. At the highest fertilization rate, the number of plant species declined more than five-fold. In North America, similarly dramatic reductions in biodiversity have been created by fertilization of grasslands in Minnesota and California (Figures 7, 8, and 9). In formerly species-rich heathlands across Western Europe, human-driven nitrogen deposition has been blamed for great losses of biodiversity in recent decades.

In the Netherlands, high human population density, intensive livestock operations, and industries have combined to generate the highest rates of nitrogen deposition in the world. One well-documented consequence has been the conversion of species-rich heathlands to species-poor grasslands and forest. Not only the species richness of the heath but also the biological diversity of the landscape has been reduced because the modified plant communities now resemble the composition of communities occupying more fertile soils. The unique species assemblage adapted to sandy, nitrogen-poor soils is being lost from the region.

Photo by John Aber

Figure 6-Deposition of nitrogen from the atmosphere is believed to be responsible for the yellowing and loss of needles from conifers and for cases of forest dieback, such as that shown here.

Losses of biodiversity driven by nitrogen deposition can in turn affect other ecological processes. Recent experiments in Minnesota grasslands showed that in ecosystems made species-poor by fertilization, plant productivity was much less stable in the face of a major drought. Even in non-drought years, the normal vagaries of climate produced much more year-to-year variation in the productivity of species-poor grassland plots than in more diverse plots.

EFFECTS ON AQUATIC ECOSYSTEMS

Historical Changes in Water Chemistry

Not surprisingly, nitrogen concentrations in surface waters have increased as human activities have accelerated the rate of fixed nitrogen being put into circulation. A recent study of the North Atlantic Ocean Basin by scientists from a dozen nations estimates that movements of total dissolved nitrogen into most of the temperate-zone rivers in the basin may have increased by two- to 20-fold since preindustrial times (Figure 10). For rivers in the North Sea region, the nitrogen increase may have been six- to 20-fold. The nitrogen increases in these rivers are highly correlated with human-generated inputs of nitrogen to their watersheds, and these inputs are dominated by fertilizers and atmospheric deposition.

Figure 7-Different rates of nitrogen addition lead to marked changes in the plant and insect species compositions and speicies diversity of these plots of grassland vegetation in Minnesota. Each plot is 4m x 4m (about 13 ft x 13 ft), and has received experimental addition of nitrogen (ammonium nitrate) since 1982.

For decades, nitrate concentrations in many rivers and drinking water supplies have been closely monitored in developed regions of the world, and analysis of these data confirms a historic rise in nitrogen levels in the surface waters. In 1,000 lakes in Norway, for example, nitrate levels doubled in less than a decade. In the Mississippi River, nitrates have more than doubled since 1965. In major rivers of the northeastern U.S., nitrate concentrations have risen three- to ten-fold since the early 1900s, and the evidence suggests a similar trend in many European rivers.

Again not surprisingly, nitrate concentrations in the world's large rivers rise along with the density of human population in the watersheds. Amounts of total dissolved nitrogen in rivers are also correlated with human population density, but total nitrogen does not increase as rapidly as the nitrate fraction. Evidence indicates that with increasing human disturbance, a higher proportion of the nitrogen in surface waters is composed of nitrate.

Increased concentrations of nitrate have also been observed in groundwater in many agricultural regions, although the magnitude of the trend is difficult to determine in all but a few well-characterized aquifers. Overall, the additions to groundwater probably represent only a small fraction of the increased nitrate transported in surface waters. However, groundwater has a long residence time in many aquifers, meaning that groundwater quality is likely to continue to decline as long as human activities are having substantial impacts on the nitrogen cycle.

High levels of nitrates in drinking water raise significant human health concerns, especially for infants. Microbes in an infant's stomach may convert high levels of nitrate to nitrite. When nitrite is absorbed into the bloodstream, it converts oxygen-carrying hemoglobin into an ineffective form called methemoglobin. Elevated methemoglobin levels — an anemic condition known as methemoglobinemia — can cause brain damage or death. The condition is rare in the U.S., but the potential exists whenever nitrate levels exceed U.S. Public Health Service standards (10 milligrams per liter).

Nitrogen and Acidification of Lakes

Nitric acid is playing an increasing role in the acidification of lakes and streams for two major reasons. One is that most efforts to control acid deposition — which includes acid rain, snow, fog, mist, and dry depos-

Figure 8-Native grasslands in Minnesota often contain 20 to 30 or more plant species per square meter, as does this plot. This plot is a "control" plot that received no nitrogen, and that retained its original plant diversity.

its — have focused on cutting emissions of sulfur dioxide to limit the formation of sulfuric acid in the atmosphere. In many areas, these efforts have succeeded in reducing inputs of sulfuric acid to soils and water while emissions of nitrogen oxides, the precursors of nitric acid, have gone largely unchecked. The second reason is that many watersheds in areas of moderate to high nitrogen deposition appear to be approaching nitrogen saturation, and the increasingly acidified soils have little capacity to buffer acid rain before it enters streams.

An additional factor in many areas is that nitric acid predominates among the pollutants that accumulate in the winter snowpack. Much of this nitric acid is flushed out with the first batch of spring meltwater, often washing a sudden, concentrated "acid pulse" into vulnerable lakes.

Adding inorganic nitrogen to freshwater ecosystems that are also rich in phosphorus can eutrophy as well as acidify the waters. Both eutrophication and acidification generally lead to decreased diversity of both plant and animal species. Fish populations, in particular, have been reduced or eliminated in many acidified lakes across Scandinavia, Canada, and northeastern United States.

Because the extent of nitrogen-saturated ecosystems continues to grow, along with human-caused nitrogen deposition, controls on sulfur dioxide emissions alone clearly will not be sufficient to decrease acid rain or prevent its detrimental effects on streams and lakes. European governments already have recognized the importance of nitrogen in acidifying soils and waters, and intergovernmental efforts are underway there to reduce emissions and deposition of nitrogen on a regional basis.

Eutrophication in Estuaries and Coastal Waters

One of the best documented and best understood consequences of human alterations of the nitrogen cycle is the eutrophication of estuaries and coastal seas (Figure 11 and 12). It is arguably the most serious human threat to the integrity of coastal ecosystems.

In sharp contrast to the majority of temperate-zone lakes, where phosphorus is the nutrient that most limits primary productivity by algae and other aquatic plants and controls eutrophication, these processes are controlled by nitrogen inputs in most temperate-zone estuaries and coastal waters. This is largely because the natural flow of nitrogen into these waters and the rate of nitrogen fixation by planktonic organisms are relatively low while microbes in the sea floor sediments actively release nitrogen back to the atmosphere.

When high nitrogen loading causes eutrophication in stratified waters — where a sharp temperature gradient prevents mixing of warm surface waters with colder bottom waters — the result can be anoxia (no oxygen) or hypoxia (low oxygen) in bottom waters. Both conditions appear to be becoming more prevalent in many estuaries and coastal seas. There is good evidence that since the 1950s or 1960s, anoxia has increased in the Baltic Sea, the Black Sea, and Chesapeake Bay. Periods

Figure 9-Nitrogen addition to this plot, located near that shown in Figure 8, led to the loss of almost all native prairie species and to dominance by the weedy European quackgrass. In 1982 this plot looked much like the one shown in Figure 8.

Comparison of Nitrogen Input in Various Aquatic Systems

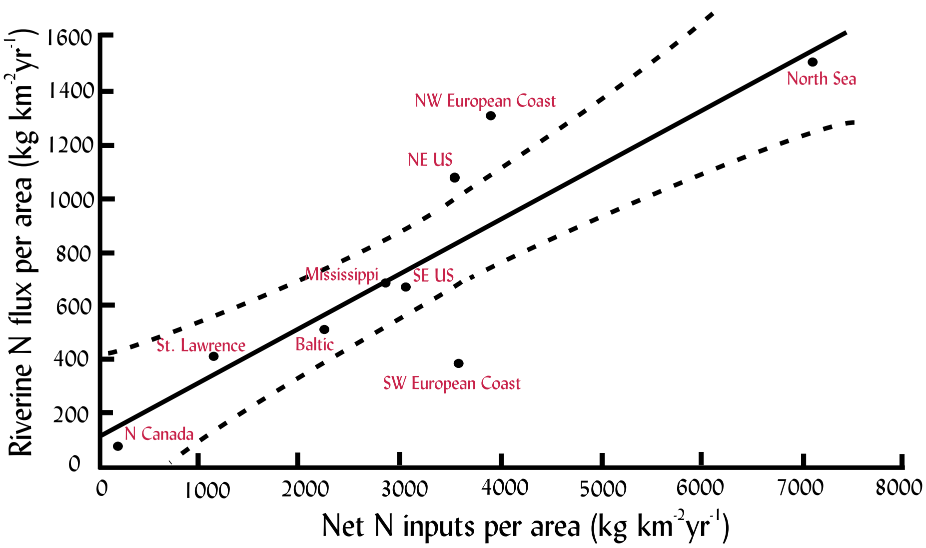

Figure 10-Movements of nitrogen into most of the temperate-zone rivers that empty into the North Atlantic Ocean have increased by two to 20-fold since preindustrial times. Nitrogen increases in these rivers are highly correlated with increasing human-generated nitrogen inputs into the watersheds, particularly fertilizer use and rising atmospheric deposition of nitrogen. Modified from Howarth et al. (1996).

of hypoxia have increased in Long Island Sound, the North Sea, and the Kattegat, resulting in significant losses of fish and shellfish.

Eutrophication is also linked to losses of diversity, both in the sea floor community — including seaweeds, seagrasses, and corals — and among planktonic organisms. In eutrophied waters, for example, “nuisance algae” may come to dominate the phytoplankton community. Increases in troublesome or toxic algal blooms have been observed in many estuaries and coastal seas worldwide in recent decades. During the 1980s, toxic blooms of dinoflagellates and brown-tide organisms caused extensive die-offs of fish and shellfish in many estuaries. Although the causes are not completely understood, there is compelling evidence that nutrient enrichment of coastal waters is at least partly to blame for such blooms.

MAJOR UNCERTAINTIES

Although this report has focused on what is known about human-driven changes to the global nitrogen cycle, major uncertainties remain. Some of these have been noted in earlier sections. This section, however, focuses on important processes that remain so poorly understood that it is difficult to distinguish human-caused impacts or to predict their consequences.

Marine Nitrogen Fixation

Little is known about the unmodified nitrogen cycle in the open ocean. Credible estimates of nitrogen fixation by organisms in the sea vary more than ten-fold, ranging from less than 30 to more than 300 Tg per year. There is some evidence that human alteration of the nitrogen cycle could alter biological processes in the open ocean, but there is no adequate frame of reference against which to evaluate any potential human-driven change in marine nitrogen fixation.

Changes in Limiting Resources

One consequence of human-driven changes in the global nitrogen cycle is a shift in the resources that limit biological processes in many areas. Large amounts of nitrogen are now deposited on many ecosystems that were once nitrogen deficient. The dominant species in these systems may have evolved with nitrogen limitation, and the ways they grow and function and form symbiotic partnerships may reflect adaptations to this limit. With this limit removed, species must operate under novel constraints such as now-inadequate phosphorus or water supplies. How are the performance of organisms and the operation of larger ecological processes affected by changes in their chemical environment for which they have no evolutionary background and to which they are not adapted?

Capacity to Retain Nitrogen

Forests and wetlands vary substantially in their capacity to retain added nitrogen. Interacting factors that are known to affect this capacity include soil texture, degree of chemical weathering of soil, fire history, rate at which plant material accumulates, and past human land use. However, we still lack a fundamental understanding of how and why nitrogen-retention processes vary among ecosystems — much less how they have changed and will change with time.

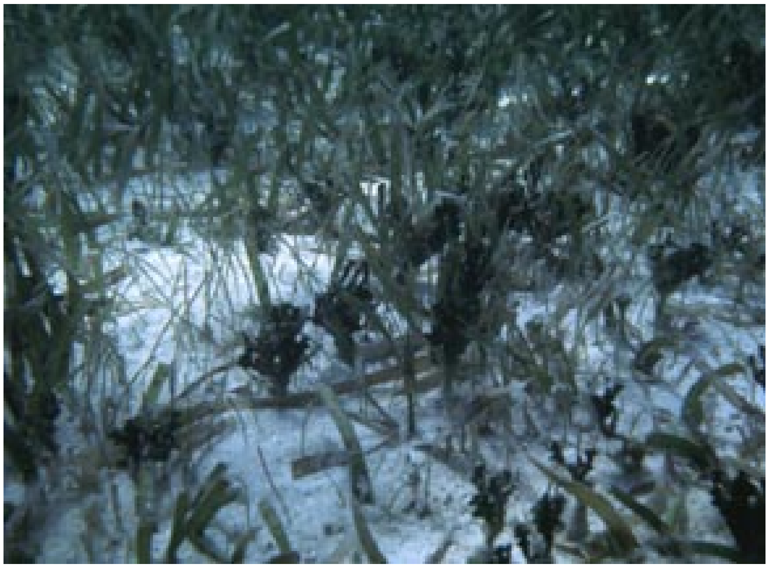

Photo by Robert Howarth

Figure 11-The bottom-dwelling plants of a marine ecosystem that received natural rates of nitrogen addition. Note the high diversity of these plants and their spacing.

Alteration of Denitrification

In large river basins, the majority of nitrogen that arrives is probably broken down by denitrifying bacteria and released to the atmosphere as nitrogen gas or nitrous oxide. Exactly where most of this activity takes place is poorly understood, although we know that streamside areas and wetlands are important. Human activities such as increased nitrate deposition, dam building, and rice cultivation have probably enhanced denitrification, while draining of wetlands and alteration of riparian ecosystems has probably decreased it. But the net effect of human influence remains uncertain.

Natural Nitrogen Cycling

Information on the rate of nitrogen deposition and loss in various regions prior to extensive human alterations of the nitrogen cycle remains patchy. In part, this reflects the fact that all of the Earth already is affected to some degree by human activity. Nevertheless, studies in remote regions of the Southern Hemisphere illustrate that there is still valuable information to be gathered on areas that have been minimally altered by humans.

FUTURE PROSPECTS AND MANAGEMENT OPTIONS

Fertilizer Use

The greatest human-driven increases in global nitrogen supplies are linked to activities intended to boost food production. Modern intensive agriculture requires large quantities of nitrogen fertilizer; humanity, in turn, requires intensive agriculture to support a growing population that is projected to double by the end of the next century. Consequently, the production and application of nitrogen fertilizer has grown exponentially, and the highest rates of application are now found in some developing countries with the highest rates of population growth. One study predicts that by the year 2020, global production of nitrogen fertilizer will increase from a current level of about 80 Tg to 134 Tg per year.

Curtailing this growth in nitrogen fertilizer production will be a difficult challenge. Nevertheless, there are ways to slow the growth of fertilizer use and also to reduce the mobility — and hence the regional and global impacts — of the nitrogen that is applied to fields.

One way to reduce the amount of fertilizer used is to increase its efficiency. Often at least half of the fertilizer applied to fields is lost to the air or water. This leakage represents an expensive waste to the farmer as well as a significant driver of environmental change. A number of management practices have been identified that can reduce the amounts of fertilizer used and cut losses of nitrogen to the air and water without sacrificing yields or profits (and in some cases, increasing them). For instance, one commercial sugar cane plantation in Hawaii was able to cut nitrogen fertilizer use by one third and reduce losses of nitrous oxide and nitric oxide ten-

Photo by Robert Howarth

Figure 12-The bottom-dwelling plants of a marine ecosystem that received high rates of nitrogen input. Note that there are few plant species, and that the leaves of these are covered with a thick layer of algae.

fold by dissolving the fertilizer in irrigation water, delivering it below the soil surface, and timing multiple applications to meet the needs of the growing crop. This knowledge-intensive system also proved more profitable than broadcasting fewer, larger applications of fertilizer onto the soil surface. The widespread implementation of such practices, particularly in developing regions, should be a high priority for agronomists as well as ecologists since improved practices provide an opportunity to reduce the costs of food production while slowing the rate of global change.

There are also ways to prevent the nitrogen that leaches from fertilized farmland from reaching streams, estuaries and coastal waters where it contributes to eutrophication. In many regions, agricultural lands have been expanded by channelizing streams, clearing riparian forests, and draining wetlands. Yet these areas serve as important natural nitrogen traps. Restoration of wetlands and riparian areas and even construction of artificial wetlands have been shown to be effective in preventing excess nitrogen from entering waters.

Fossil Fuel Burning

The second major source of human-fixed nitrogen is fossil fuel burning. It, too, will increase markedly as we enter the next century, particularly in the developing world. One study predicts that production of nitrogen oxides from fossil fuels will more than double in the next 25 years, from about 20 Tg per year to 46 Tg. Reducing these emissions will require improvements in the efficiency of fuel combustion as well as in the interception of airborne byproducts of combustion. As with improvements in fertilizer efficiency, it will be particularly important to transfer efficient combustion technologies to developing countries as their economies and industries grow.

CONCLUSIONS

Human activities during the past century have doubled the natural annual rate at which fixed nitrogen enters the land-based nitrogen cycle, and the pace is likely to accelerate. Serious environmental consequences are already apparent. In the atmosphere, concentrations of the greenhouse gas nitrous oxide and of the nitrogen-precursors of smog and acid rain are increasing. Soils in many regions are being acidified and stripped of nutrients essential for continued fertility. The waters of streams and lakes in these regions are also being acidified, and excess nitrogen is being transported by rivers into estuaries and coastal waters. It is quite likely that this unprecedented nitrogen loading has already contributed to

Photo by Nadine Cavender

Figure 13-Human activities, such as fertilizer production, growing legume crops, and burning of fossil fuels, are now of equal or greater magnitude than natural processes in the nitrogen cycle. Human domination of the nitrogen cycle impacts the functioning of many terrestrial and aquatic ecosystems, including seemingly pristine habitats such as this alpine ecosystem.

long-term declines in coastal fisheries and accelerated losses of plant and animal diversity in both aquatic and land-based ecosystems. It is urgent that national and international policies address the nitrogen issue, slow the pace of this global change, and moderate its impacts.

FOR FURTHER INFORMATION

This report summarizes the findings of our panel. Our full report, which is being published in the journal *Ecological Applications* (Volume 7, August 1997), discusses and cites more than 140 references to the primary scientific literature on this subject. From that list we have chosen those below as illustrative of the scientific publications and summaries upon which our report is based.

Aber, J.D. 1992. Nitrogen cycling and nitrogen saturation in temperate forest ecosystems. Trends in Ecology and Evolution 7:220-223.

Berendse, F., R. Aerts, and R. Bobbink. 1993. Atmospheric nitrogen deposition and its impact on terrestrial ecosystems. Pp. 104-121 in C.C. Vos and P. Opdam (eds), Landscape Ecology of a Stressed Environment. Chapman and Hall, England.

Cole, J. J., B. L. Peierls, N. F. Caraco, and M. L. Pace. 1993. Nitrogen loadings of rivers as a human-driven process. Pages 141-157 in M. J. McDonnell and S. T. A. Picket (eds.), Humans as Components of Ecosystems: The Ecology of Subtle Human Effects and Populated Areas. Springer-Verlag, NY.

DOE (Department of Environment, UK). 1994. Impacts of Nitrogen Deposition in Terrestrial Ecosystems. Technical Policy Branch, Air Quality Div., London.

Galloway, J. N., W. H. Schlesinger, H. Levy II, A. Michaels, and J. L. Schnoor. 1995. Nitrogen fixation: atmospheric enhancement-environmental response. Global Biogeochemical Cycles 9:235-252.

Howarth, R. W., G. Billen, D. Swaney, A. Townsend, N. Jaworski, K. Lajtha, J. A. Downing, R. Elmgren, N. Caraco, T. Jordan, F. Berendse, J. Freney, V. Kudeyarov, P. Murdoch, and Zhu Zhao-liang. 1996. Regional nitrogen budgets and riverine N & P fluxes for the drainages to the North Atlantic Ocean: Natural and human influences. Biogeochemistry 35: 75-139.

Nixon, S. W., J. W. Ammerman, L. P. Atkinson, V. M. Berounsky, G. Billen, W. C. Boicourt, W. R. Boynton, T. M. Church, D. M. Ditoro, R. Elmgren, J. H. Garber, A. E. Giblin, R. A. Jahnke, N. P. J. Owens, M. E. Q. Pilson, and S. P. Seitzinger. The fate of nitrogen and phosphorus at the land-sea margin of the North Atlantic Ocean. Biogeochemistry 35: 141-180.

NRC. 1994. Priorities for Coastal Ecosystem Science. National Research Council. Washington, D.C.

Prinn, R., D. Cunnold, R. Rasmussen, P. Simmonds, F. Alyca, A. Crawford, P. Fraser, and R. Rosen. 1990. Atmospheric emissions and trends of nitrous oxide deduced from 10 years of ALE-GAGE data. Journal of Geophysical Research 95:18,369-18,385.

Schindler, D. W. and S. E. Bayley. 1993. The biosphere as an increasing sink for atmospheric carbon:estimates from increasing nitrogen deposition. Global Biogeochemical Cycles 7:717-734.

Schlesinger, W. H. 1991. Biogeochemistry: An Analysis of Global Change. Academic Press, San Diego.

Smil, V. 1991. Population growth and nitrogen: an exploration of a critical existential link. Population and Development Review 17:569-601.

Tamm, C. O. 1991. Nitrogen in Terrestrial Ecosystems. Springer-Verlag, Berlin. 115 pp.

Tilman, D. 1987. Secondary succession and the pattern of plant dominance along experimental nitrogen gradients. Ecological Monographs 57(3):189-214.

Vitousek, P. M. and R. W. Howarth. 1991. Nitrogen limitation on land and in the sea: How can it occur? Biogeochemistry 13:87-115.

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This report presents the consensus reached by a panel of eight scientists chosen to include a broad array of expertise in this area. This report underwent peer review and was approved by the Board of Editors of Issues in Ecology. The affiliations of the members of the panel of scientists are:

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About the Science Writer

Yvonne Baskin, a science writer, edited the report of the panel of scientists to allow it to more effectively communicate its findings with non-scientists.

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This version of the report is also available electronically at http://www.sdsc.edu/~ESA/.

Also available for a small fee are reprints of our full report, published in the journal *Ecological Applications* (Volume 7, August 1997) with detailed citations to the original scientific literature. Contact the Ecological Society of America at the above listed address for more information.

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