Local and Global Effects of Human-Induced Alterations to the Nitrogen Cycle

Waquoit Bay National Estuarine Research Reserve Science and Policy Bulletin Series

Introduction

Many of us living on Cape Cod are concerned about the degraded quality of our coastal waters and the loss of associated fish and shellfish habitat. We know that excessive nitrogen delivery to coastal waters is a significant contributor to the water quality deterioration. Recent papers in the scientific literature identify coastal water degradation as but one effect of a much larger problem—that of large scale alteration of the global nitrogen cycle by human activities. Whereas the scarcity of biologically available nitrogen limited the growth of living things for millions of years, recent technological advances have resulted in significant increases in the amount of nitrogen cycling on Earth and its atmosphere. Furthermore, the nitrogen is transported over vast geographic distances. The increase in available nitrogen and the movement of that nitrogen from one region to another affect the functioning of terrestrial, freshwater and marine ecosystems on Earth.

The Local Connection: Eutrophication of Coastal Water

During the past decades, people on Cape Cod (and coastal areas worldwide) have witnessed deteriorating water quality in estuaries, bays, and other nearshore waters. Reports of increasingly murky water, algae blooms, and declining numbers of valued fish and shellfish come from seaside dwellers who supply anecdotal evidence and scientists whose research provides empirical evidence.

The poorer water quality is attributed in large part to an increase in the supply of nitrogen, the nutrient that most often limits growth in coastal waters. Nitrogen from septic systems, fertilizers, and the atmosphere travels via groundwater, rivers, and surface runoff to coastal waters where it stimulates the growth of simple plant-like organisms called algae (e.g., seaweed or macroalgae, and phytoplankton or microalgae). Overgrowth of algae decreases the amount of light that reaches the bottom, impeding the growth of submerged aquatic vegetation such as eelgrass. Eelgrass beds are important because they provide nursery, spawning, and feeding grounds for many species. Scallops, blue crabs, and winter flounder are among the species that frequent eelgrass meadows. When too little light reaches the bottom, eelgrass dies and the habitat for valued species is lost. Increased amounts of algae also indirectly affect the amount of oxygen dissolved in the water. Night-time respiration by the algae and consumption of the large amounts of algae by decomposers can deplete the levels of oxygen in the water column. Under certain weather conditions, massive fish and shellfish kills occur. This cascading sequence of effects resulting from an excessive supply of nutrients to water is called eutrophication.

The Relationship Between Coastal Development and Eutrophication

The increased delivery of nitrogen to coastal waters is directly related to changes in land use on coastal watersheds, because as coastal development increases so do the number of septic systems, fertilizer use, and other activities that contribute nitrogen. The relationship between development and nitrogen was demonstrated on Cape Cod where the concentration of nitrate-nitrogen in groundwater was positively related to the density of houses (Fig. 1). As Cape towns continue to experience rapid growth rates (Fig. 2), we can expect the concentration of nitrogen in groundwater to increase.

In many areas, rivers are the major conduits of nitrogen from watersheds to coastal waters. Several studies show that concentrations of nitrogen in rivers in the United States and Europe are increasing. As with the relationship between housing density and groundwater nitrogen concentrations, nitrate concentrations in the major rivers of the Earth are positively related to the density of human populations in their watersheds.

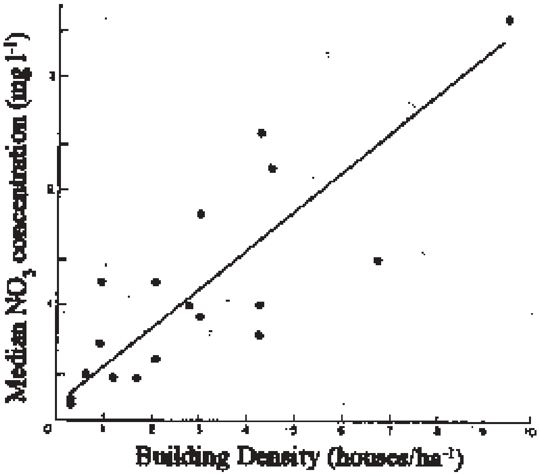

Figure 1. Nitrate concentration in groundwater below areas of Cape Cod having different densities of buildings. (From Valiela et al. 1992, data of Persky, 1986.)

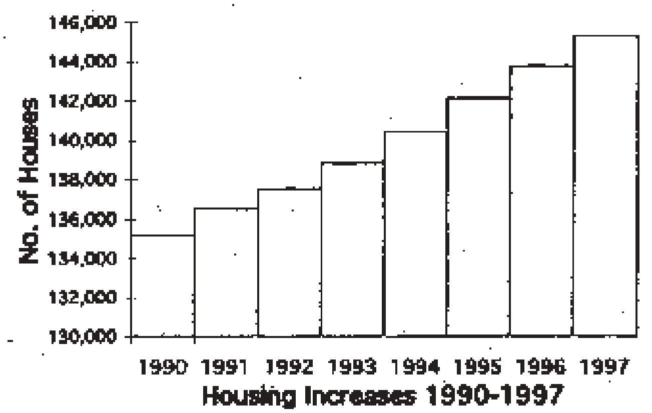

Figure 2. Housing units in Barnstable County, Cape Cod, MA, 1990-1997. 1990 data from U.S. census; all other from reports of Town Building Inspectors. Data courtesy of Marilyn Fifield of the Cape Cod Commission.

Cape Cod is not the only coastal community experiencing rapid population growth. Coastal counties are growing faster than inland counties throughout the United States (Fig. 3). On a global scale, coastal areas also are the most densely populated; approximately 50% of the people in the world now live within 125 miles of a coast.

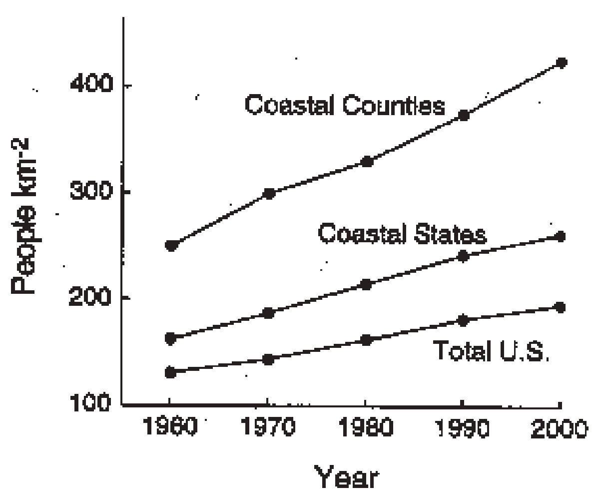

Figure 3. Population density in coastal counties, coastal states and the United States from 1960 to projections for 2010. (Data from Culliton et al. 1990.)

The Nitrogen Cycle

Eutrophication of water is not the only effect of excess available nitrogen. Too much nitrogen also increases acidity of soils and water, adds to the greenhouse effect, and contributes to photochemical smog. Why are we seeing these deleterious effects now? Recent papers in the scientific literature reveal that humans have increased the amount of usable nitrogen cycling on Earth. To understand why the increased supply of nitrogen can create problems, it is useful to know something about the nitrogen cycle.

The element nitrogen is essential to all life; it is a fundamental component of proteins, genes, and chlorophyll. After hydrogen, carbon and oxygen, nitrogen is the most plentiful element in our bodies. Nitrogen also is abundant in the Earth's atmosphere. About 78% of the atmosphere is dinitrogen gas (N_2) which is two nitrogen atoms bound together with three strong covalent bonds. However, most living things can not make use of N_2; most organisms can only use nitrogen when it is bound to other elements like hydrogen (e.g., in ammonium, NH_4) or oxygen (e.g. in nitrate, NO_3).

A few kinds of bacteria possess special enzymes that allow them to break the bonds of N_2 and to combine nitrogen with other elements to make compounds that can be used by other organisms. These bacteria include some that live in the roots of leguminous plants and others that live in surface water. Lightning also can break apart N_2. The process of making nitrogen biologically available is called nitrogen fixation. Once fixed, nitrogen-containing compounds recycle through plants, animals, soils, and water. Some kinds of bacteria change fixed nitrogen back to dinitrogen gas in a process called denitrification.

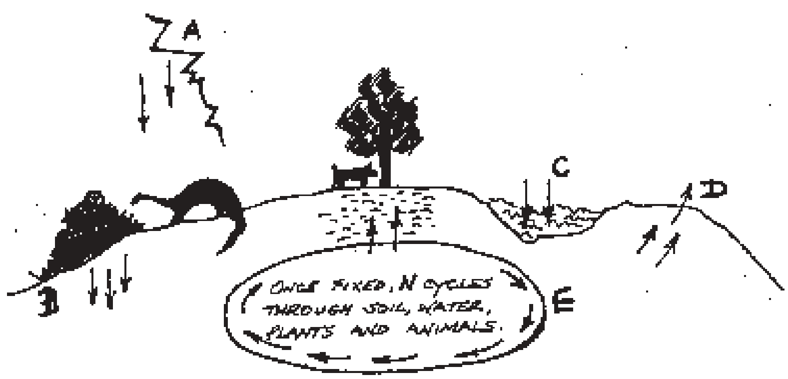

Figure 4. Prior to this century a small amount of nitrogen was fixed each year by lightning (A), by some free-living bacteria in soils and others inhabiting roots of certain plants (B), and by bacteria living in some surface waters (C). A small amount of fixed nitrogen was changed back to N_2 gas (D) through denitrification. A much larger quantity of previously fixed nitrogen cycled through organisms, soils, water and air (E).

Nitrogen: as a Limiting Nutrient

If an element is essential to all life and in short supply, its availability can limit the growth of living things. For millennia, the scarcity of fixed nitrogen was a major factor that constrained the growth rates and structured the distribution and abundance of living things on Earth (Fig. 4). In coastal waters for example, scientists believe the historic scarce supply of available nitrogen limited the growth of plants and algae. Today, as more nitrogen is released to coastal waters, there is more growth of plants and algae.

Human Alteration of the Nitrogen Cycle

Scientists estimate that before this century, bacteria and lightning were responsible for the fixation of about 90-140 million metric tons of new nitrogen per year (1 metric ton = about 2200 pounds); of that amount, only 5-10 million metric tons were fixed by lightning, the rest was from bacterial action.

During the past few decades we have found the keys to unlock the vast reservoir of nitrogen in the atmosphere and of nitrogen that was long buried in coal and oil deposits within the Earth. The result, scientists estimate, is that humans have more than doubled the amount of fixed nitrogen cycling on the planet (Fig. 5). How have we accomplished this? Historically, crops were fertilized using manure and other composted organic matter. This type of soil amendment recycles already available nitrogen. In 1913, the German, Fritz Haber, discovered how to synthesize ammonia (NH_3) by combining hydrogen gas and nitrogen gas at high temperature and pressure. Initially, this discovery helped the Germans to make explosives during World War I. Later, the technology, known as the Haber or Haber-Bosch process, gave birth to the artificial fertilizer industry and set the stage for the Green Revolution. Today, industrial fixation of nitrogen adds about 80 million metric tons of new nitrogen each year, which is then used as fertilizer and released to the environment.

Agricultural cultivation of legumes, such as peas, alfalfa, and soybeans, has increased with the availability of artificial fertilizers. Because legumes harbor nitrogen-fixing bacteria, their cultivation has indirectly led to an increase in nitrogen fixation. Cultivation of some other crops, including rice, also results in additional fixation of nitrogen. Scientists estimate that 40 million metric tons of nitrogen are fixed each year through cultivation of such crops.

Burning fossil fuels liberates the fixed nitrogen within coal and oil from what was essentially permanent storage within the Earth, making it available again. A small amount of atmospheric N_2 also is fixed during high-temperature combustion of fossil fuels. More than 20 million metric tons of fixed nitrogen is released into the atmosphere each year from burning fossil fuels in automobiles, power plants, factories, homes, and in other equipment and machinery.

Burning forests, clearing land, and draining wetlands mobilize fixed nitrogen that had been bound up in plant matter. About 70 million metric tons of nitrogen are mobilized each year through these activities.

Figure 5. In addition to the nitrogen fixed by lightning (A), and the nitrogen historically fixed by bacteria inhabiting roots of certain plants and living in surface waters (C, D), humans have increased the amount of nitrogen cycling through, plants, animals, soils, water, and air. Today, large quantities of industrially produced synthetic fertilizers (B) are applied to legumes that harbor nitrogen-fixing bacteria (C). Fossil fuel combustion (F) emits nitrogen oxides to the atmosphere. Not depicted are other human activities that mobilize nitrogen stored in biomass.

Transport of Bioavailable Nitrogen

The consequences of the increased delivery of nitrogen to our coastal waters are most visible to us on Cape Cod in the form of degraded water quality. What is perhaps not understood is the connection between the local problem of eutrophication and the agricultural food chain. The largest source of nitrogen to the northeastern United States is agricultural products imported from areas such as the Midwest. There, fertilizers are applied to crops; some of the crops are fed to animals; eventually, the crops and animals are shipped to coastal areas where the majority of people live. Poised at the edge of the sea, we are at the end of the line of a sequence of events that originated hundreds or thousands of miles away.

In contrast to the Northeast, the Mississippi Basin is a major exporter of nitrogen. The Mississippi Basin exports nitrogen in agricultural products for distribution worldwide, and as a side effect of agricultural practices, the Basin exports nitrogen in riverine discharge to the Gulf of Mexico. As different areas of the United States and the world import and/or export agricultural products, large quantities of fixed nitrogen are transported around the globe.

The atmosphere is another pathway of nitrogen transport. Fossil fuel combustion emits nitrogen compounds that travel hundreds of miles or more before returning to Earth in acid rain or dry deposition. Some of the nitrogen compounds in the atmosphere originate in the agricultural food chain, because some of the nitrogen in fertilizers and in livestock manure vaporizes. Taken together, the increase, transport and redistribution of fixed nitrogen have the capability to alter many ecosystems worldwide.

Ecological Effects of Human Influence on the Nitrogen Cycle

Although on Cape Cod, eutrophication is the most obvious effect of an excess supply of nitrogen, there are other deleterious effects of too much nitrogen that affect the functioning of terrestrial and aquatic ecosystems, the atmosphere, and cycles of other essential nutrients.

Changes in Terrestrial Ecosystems

Scientists use the term nitrogen saturation to describe forest ecosystems where the plants can no longer use the excessive amounts of available nitrogen. Several effects ensue, including acidification of soils and leaching of important soil minerals such as calcium, magnesium and potassium. Such changes can affect metabolic processes, and ultimately plant and forest growth. Detrimental effects of nitrogen saturation on trees (yellowed leaves and needles, decreased growth) are more pronounced in many parts of Europe where rates of atmospheric deposition of nitrogen are much higher than in the US.

Changes in Freshwater Lakes and Streams

Direct deposition of atmospheric nitrogen in the form of nitric acid (HNO_3) or ammonium (NH_4) causes acidification of lakes and streams. Atmospheric nitrogen that falls on nitrogen-saturated vegetated lands also can leach through to surface water bodies. Many organisms cannot tolerate a change in the chemical balance of the water and die when the waters become too acidic. Unfortunately, legislation targeting acid deposition has focused on reducing sulfur dioxide emissions and has not addressed reducing nitrogen emissions.

Changes in Atmospheric Chemistry

The amount of nitrous oxide (N_2O) in the atmosphere is increasing 0.2-0.3% each year. Like CO_2, nitrous oxide is a greenhouse gas that traps the Earth's heat. N_2O is not reactive in the lower atmosphere; therefore its effects are long lasting. If it rises into the upper stratosphere, it enters into chemical reactions that result in the thinning of the ozone layer. N_2O also is an intermediate product of reactions of the nitrogen cycle. Thus, as human actions have increased the amount of nitrogen cycling through the living and non-living components of the Earth, the intermediate products, such as N_2O, have increased as well.

Nitric oxide (NO) concentrations in the atmosphere are increasing. NO is a highly reactive compound that contributes to the formation of photochemical smog. NO also is oxidized to nitric acid, a major component of acid rain. Burning of fossil fuels is the major source of human-derived nitric oxides.

Atmospheric ammonia (NH_3) concentrations are also increasing. Volatilization of ammonia from fertilizers and from livestock manure adds approximately 10 and 32 million metric tons, respectively, of nitrogen to the atmosphere each year. In the atmosphere, ammonia is the primary neutralizer of acids. Volatilized ammonia from livestock operations is considered a major contributor to coastal water eutrophication in some areas.

Effects on Biodiversity

Different kinds of plants have different requirements for sun, shade, water, and fertilizer. Changes in these environmental variables lead to changes in plant community structure, as species adapted to the new conditions outcompete others. In the Netherlands, where rates of atmospheric deposition of nitrogen are the highest on Earth, scientists have documented the conversion of heathlands, habitats that support a diverse number of species that are acclimated to the nutrient-poor sandy soils, to grassland habitats similar to some in Eurasia, where a few nitrogen-loving species dominate the plant community. Experiments have validated what scientists have observed in the natural world. In England, when scientists experimentally added nitrogen to some plant communities, a few nitrogen-loving species took over, leading to declines in numbers of other species.

Options: Think Globally, Act Locally

Although there is still much work to be done to understand and quantify some components of the global nitrogen cycle and human alterations to it (e.g., background rates of nitrogen deposition, rates of nitrogen fixation in the oceans, rates of denitrification), there are several areas where prompt action is needed.

Global Issues

As the human population continues to grow, so will demand for agricultural products. By the year 2000, the global production of fertilizer is expected to increase from today's rate of 80 million metric tons annually to more than 130 million metric tons. Although fertilizer use will increase, there are some ways to slow the rate of increase, and to decrease the amount of nitrogen leached to surface waters. Here are some options for citizens, policy-makers, and legislators to consider:

- <u>New Technology</u>
  Presently much of the fertilizer applied to crops is lost to volatilization and leaching. There are some promising new technologies for increasing the efficient delivery of fertilizers to plants. These include "precision agriculture" techniques that link application of fertilizers to the requirements of the growing plants. Information about such technologies should be transferred to farmers worldwide.

- <u>Organic Fertilizers</u>
  The use of organic fertilizers (composted manure and plant materials) recycles previously fixed nitrogen and does not introduce new nitrogen to the Earth.

- <u>Soil Nutrient Thresholds</u>
  Research is needed to establish threshold levels of soil nutrients that put aquatic systems at risk. Establishment of threshold levels will provide a foundation for regulations to protect water resources.

- <u>Wetlands</u>
  Wetlands are sinks for nitrogen. Wetlands restoration and construction are new techniques that could be applied more widely as a means to reduce nitrogen inputs to surface waters.

- <u>Buffer Zones</u>
  Vegetated buffer zones along river and stream banks reduce the amount of nutrients entering water.

- <u>New Plant Varieties</u>
  Industry should be encouraged to continue working to find plant varieties that require less fertilizer.

Fossil fuel combustion is the other major contributor to the increased supply of nitrogen.

- Efficient Combustion
  More efficient combustion techniques and reductions in emissions are critical to reduce the amount of nitrogen oxides that enter the atmosphere.

- Alternative Energy
  Encouragement of the development of alternative energy sources is another action that could lead to a reduction in fossil fuel use.

Local Issues

It is important to remember that decisions we make about land use in our watersheds affect the quality of our bays, ponds, and terrestrial ecosystems. Suggestions to reduce nitrogen inputs on Cape Cod include:

- Preserve Open Space
  Naturally vegetated lands do not add nitrogen to coastal waters. In fact, studies on Cape Cod by Valiela et al. (1997) show that forests, meadows, and grasslands take up more than 90% of the fixed nitrogen coming from the atmosphere, thereby reducing the amount that enters surface waters.

- Watershed Management Districts
  Watershed management districts are a tool communities can use to implement wastewater management options across a watershed. Development of such districts includes siting different kinds of disposal systems in different areas, depending on density of development, planned future growth areas, and the need to protect resources. It also includes developing regulations and regulatory authority for the maintenance of wastewater facilities, including advanced denitrifying on-site systems that often have pumps and other devices that require maintenance.

- Everyday Use of Fossil Fuels
  Consider reducing your use of fossil fuels–for example, ride a bicycle; use a people-power mower; turn down the thermostat; use fans instead of air conditioners.

- Landscape Design
  Landscape to conserve heat in winter and cool your home in summer. Landscape with plants acclimated to this climate as they will require no fertilizer. Leave part of your yard in natural vegetation.

- Local Comprehensive Plans
  Cape Cod communities are developing and implementing Local Comprehensive Plans (LCPs) to guide decisions about future growth. LCPs provide an excellent opportunity to examine and implement options to preserve or restore good coastal water quality.

- Emission Standards
  Support efforts to implement stricter emission standards for automobiles, power boats, lawn mowers, and other machines that use internal combustion engines.

- Wetlands and Vegetated Buffer Zones
  Strong support should be given to local efforts to preserve wetlands and riparian habitats.

Recommended Reading:

Issues in Ecology is a series of reports written for the lay person and produced by The Ecological Society of America. The science writer, Yvonne Baskin, does an excellent job of providing scientific information in a very readable form.

Issue Number 1, "Human Alteration of the Global Nitrogen Cycle: Causes and Consequences"

Issue Number 3, "Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen"

These are available from the Public Affairs Office, Ecological Society of America, 2010 Massachusetts Avenue, NW. Suite 400. Washington, DC 20036. Phone: 202-833-8773, email: esahq@esa.org, or from http://esa.sdsc.edu/.

For more information:

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Waquoit Bay NERR Science and Policy Bulletin Series: *No. 6. Local and Global Effects of Human-Induced Alterations to the Nitrogen Cycle. June, 1998.* Margaret A. Geist, author

The Waquoit Bay National Estuarine Research Reserve is part of the National Estuarine Research Reserve System, established by Section 315 of the Coastal Zone Management Act as amended. Additional information about the system can be obtained from the Estuarine Reserves Division of the Office of Ocean and Coastal Resources Management, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 1305 East-West Highway, Silver Spring, MD 20910.

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