ENVIRONMENT

Nitrogen in the environment

Excess nitrogen causes problems in developed nations, but nitrogen-poor soils threaten food security elsewhere

By **Carly J. Stevens**

Human activities have greatly perturbed the global nitrogen cycle. Planetary boundaries, which describe a safe operating space for humanity, have already been exceeded for the nitrogen cycle (*1*). In some parts of the world, excess nitrogen has negative impacts on biological diversity, human health, and climate. However, in other parts of the world, nitrogen shortages mean that food needs cannot be met. This large-scale disturbance of the nitrogen cycle presents considerable challenges that require wide-scale adoption of locally appropriate nitrogen management approaches.

Nitrogen is an abundant element on Earth; it makes up 78.1% of Earth's atmosphere and is an essential nutrient for all forms of life. Much of this nitrogen is in the form of unreactive nitrogen (N_2) gas and is not available for use by most living organisms. But a portion of it, fixed by natural or anthropogenic processes, is in a reactive form [Nr, which includes nitrogen oxides (NO_x), reduced nitrogen (NH_x), nitrous oxide (N_2O), nitric acid (HNO_3), and other organic and inorganic forms] available for use by living organisms. Over the past century, the amount of Nr from human activities has increased to such an extent that it now exceeds natural fixation, resulting in a more than doubled global cycling of nitrogen (anthropogenic Nr production, 210 Tg N per year; natural Nr production, 203 Tg N per year) (*2*). As a consequence of this increase in nitrogen fixation, nitrogen pollution of air, water, and soils has become a major cause for concern in many parts of the world (see the box).

INEQUALITIES OF NITROGEN USE

A major cause of nitrogen pollution in the developed world is food production. Pollutant Nr, released to the environment during food production and consumption, stems from a

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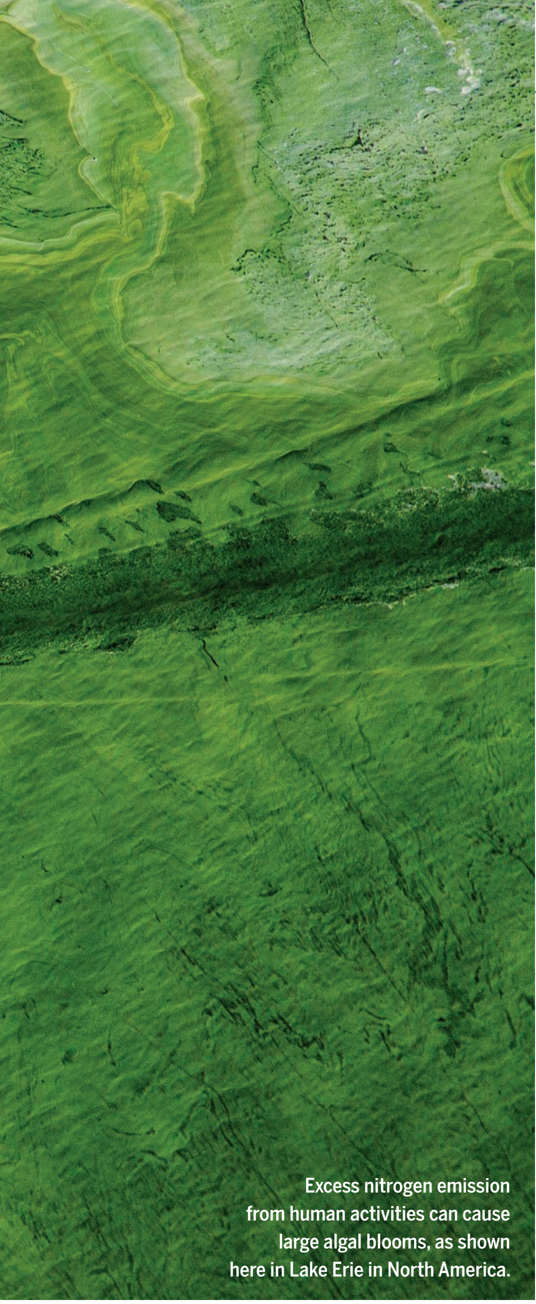

Excess nitrogen emission from human activities can cause large algal blooms, as shown here in Lake Erie in North America.

ILLUSTRATION: ADAM SIMPSON/HEART AGENCY

range of issues, including the overuse of fertilizers, poor management of animal wastes, overconsumption of protein, and food waste. Between 1961 and 2007, both fertilizer nitrogen inputs and grain yields increased globally, but the amount of added nitrogen recovered in the harvested crops remained relatively unchanged at around 40%. This means that the amount of nitrogen lost to the environment has increased steadily (*3*).

However, there are considerable inequalities in nitrogen use globally. In countries outside the Organisation for Economic Co-operation and Development (OECD) and major emerging economies, the amount of nitrogen taken up by crops remains low. Not only are there insufficient fertilizers, the nutrients that are available are often used inefficiently (*3*). Sub-Saharan Africa provides a perfect example. Here, nutrient-poor soils were yielding an average of 1 metric ton (MT) ha^{-1} for grain crops in 2012, with fertilizer use averaging 9 kg ha^{-1} of cultivated land. By contrast, in Asia, where there are major emerging economies, crop yield reached 4.5 MT ha^{-1}, but this was achieved with fertilizer application averaging 96 kg ha^{-1} (*4*). Shortages of nitrogen clearly lead to large problems in meeting population demands for food. These problems are just as difficult to address as the problems that nitrogen pollution causes in other parts of the world.

CONSEQUENCE OF INCREASED NR AVAILABILITY

One of the major consequences of increased Nr availability has been an increase in atmospheric deposition of Nr. Between 1900 and 1980, deposition of oxidized nitrogen [such as NO_x and N_2O] in Europe increased by three to four times, whereas deposition of reduced nitrogen [such as ammonia (NH_3)] doubled (*5*). Craine *et al.* have recently shown that the nitrogen concentrations in plant tissues—often considered an indicator of the amount of nitrogen taken up by plants or their nitrogen status—declined globally between 1980 and 2017 despite globally increasing availability of Nr (*6*). This reduction in nitrogen content seems to indicate that there is less nitrogen available for the plants than there was in the past. Although nitrogen deposition has declined in some developed countries since 1980, this is not a global trend, making this depletion of plant nitrogen reserves hard to reconcile with increased Nr emissions. The authors suggest that this is caused by increased levels of carbon dioxide (CO_2) and longer growing seasons, which allows greater levels of biomass production.

Stable isotope studies can provide information on the sources of nitrogen in plant tissues. Stable isotopes are measured as a ratio of the heavy and light isotopes in a sample; atmospherically deposited sources of nitrogen would typically be light (called the Haber-Bosch effect) (*7*). A decline in the nitrogen stable isotope ratio ($\delta^{15}N$) may thus indicate increased atmospheric deposition. Indeed, in a recent modeling study, Yang and Gruber found increases in isotopically light nitrogen in global oceans (*7*); Mii and Sigman reported similar observations in coral at a remote reef (*8*). Craine *et al.* (*6*) also observe a decline in $\delta^{15}N$, although the data are highly variable and changes are small. Thus, plant nitrogen concentrations are declining despite increasing atmospheric deposition.

Craine *et al.* (*6*) question whether humanity has exceeded a true planetary

TOMORROW'S EARTH

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Two sides of nitrogen

In many parts of the world, an excess of fixed nitrogen is causing environmental and health problems, but in some developing countries, insufficient nitrogen causes food shortages.

EXCESS NITROGEN

Causes

High emissions from agriculture, in particular fertilizer and animal waste

High combustion of fossil fuels

Effects

Reduced biodiversity across multiple trophic levels

Increased greenhouse gas emissions

Poor air quality and polluted water that impact human health

Polluted inland and coastal waters from leaching and atmospheric deposition

Enriched and acidified soils, resulting in changes to biology and chemistry

Increased formation of air pollutants in the atmosphere, including ozone

Examples of preventative measures

Better management of animal waste in agriculture to reduce emissions

Precision agriculture to reduce fertilizer inputs

Changes to human diet to reduce high-nitrogen-footprint foods such as pork

Increased use of alternative energy sources

Reduced use of fossil fuels in transport

Chemical scrubbing of industrial emissions to remove reactive nitrogen

INSUFFICIENT NITROGEN

Causes

Poor fertility soils

Insufficient availability of fertilizers for agriculture due to cost

Ineffective use of fertilizers

Reduced effectiveness of nitrogen additions due to poor soil condition

Effects

Low crop yields

Insufficient food production

Nitrogen can still be a pollutant owing to poor nitrogen management

Examples of preventative measures

Increased availability of fertilizers

Education for farmers regarding how to use fertilizers effectively

Education for farmers regarding soil management boundary for nitrogen availability because plant tissue nitrogen is falling. However, the extensive damage done to ecosystems supports the argument that we have indeed exceeded a planetary boundary. Atmospheric deposition of nitrogen has increased to levels where it has become a major driver of plant productivity globally (*9*) and is an important driver of species richness and composition at a continental scale (*10*). Many field experiments with simulated deposition have demonstrated considerable inertia in the recovery of soil chemistry and species composition when amounts of nitrogen addition are reduced.

For example, Bowman *et al.* have shown that in an alpine grassland in the Rocky Mountains of the United States, 12 years of simulated Nr deposition resulted in significant changes in species composition, including the decline of a previously dominant sedge and increases in other species (*11*). The study also found changes in fungal-to-bacterial ratio, nitrification in the soil, soil pH, toxic metal concentrations, and cation concentrations. Nine years after Nr applications were stopped, many of these soil variables had not returned to baseline levels, nor had biota. This type of finding is not uncommon, and it is possible, given the lack of recovery observed in some communities, that alternative stable states may have been reached in some habitats.

ADDRESSING EXCESSES AND SHORTAGES

Realization of the extent of the damage caused by nitrogen deposition, together with co-benefits from other areas of environmental policy, is beginning to result in reductions in nitrogen emissions and deposition. Deposition of oxidized nitrogen, which is mainly produced by combustion processes, peaked in Europe in the 1980s and has since declined, mainly owing to policies to reduce air pollution and as a co-benefit from reductions in carbon emissions. Declines in the deposition of reduced nitrogen, which is mainly produced by agriculture, have been much smaller (*5*). This lack of progress with reduced nitrogen emissions is partly because emissions from agriculture are less regulated in many countries than are emissions from industry and transport. Similar trends have been observed in the United States (*12*).

Further reductions in the creation of Nr will require wide-ranging changes to agricultural practices and to attitudes toward food. Li *et al.* have highlighted the environmental pressures that the food production system places on the environment. If humanity is to stay within planetary boundaries, including the boundary for nitrogen, we must change our diets, combined with technological improvements and reductions in food waste (*13*). Meat consumption, in particular, drives the human nitrogen footprint, because large amounts of Nr are lost to the environment during meat production. Globally, meat consumption continues to grow, but there is some evidence that in some high-income countries, meat consumption per capita is beginning to decline (*14*).

Earth's nitrogen cycle has been hugely perturbed at a global scale, and there is an urgent need to address the problem of excess Nr in our environment. There are many potential approaches that can be taken to reduce Nr inputs further, such as technical solutions to agricultural and industrial emissions and changes in practice in polluting sectors. This might include better storage of animal waste, precision agriculture to reduce fertilizer inputs, and gas scrubbing to remove nitrogen from industrial emissions. However, measures such as these need to be widely adopted and supported with legislative limits.

There is also an urgent need to address the lack of Nr in many regions of the world to ensure that food production is sufficient to meet requirements. The lack of nitrogen is a complex problem with many societal considerations, and there is considerable debate around the role inorganic fertilizers should play (*4*).

Balancing these two contrasting issues presents a big challenge to the communication of Nr as an environmental problem to the public and is one that can only be addressed through collaboration between natural and social scientists, governments, and nongovernmental organizations. Nr excesses and shortages are set to continue to be major environmental issues into the future. Increasing awareness, changing behaviors, and increasing regulation, particularly to reduce nitrogen emissions, must all come together to address this global problem. ■

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CLIMATE

How do aerosols affect cloudiness?

Cloud-aerosol interactions can be determined more accurately by isolating aerosol effects

By **Yousuke Sato**[1,2] *and* **Kentaroh Suzuki**[3]

Aerosols are tiny particles suspended in the atmosphere that originate from sources such as agricultural waste, forest fires, sea spray (see the photo), desert dust, and industrial pollution. They alter the energy balance of Earth's climate system through direct reflection and absorption of solar radiation as well as through modulating cloud properties by serving as nuclei for cloud particles. As a result of such aerosol-cloud interactions (*1*), cloud particle size tends to fall with increasing aerosol number concentration and rain formation is suppressed. However, it has been difficult to determine the overall cloud response to these interactions and the resulting climate effect. On page 599 of this issue, Rosenfeld *et al.* (*2*) report that the cloud response to the interaction is much larger than previously estimated (see the figure).

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