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NO SURE FIX

Prospects for Reducing Nitrogen Fertilizer Pollution through Genetic Engineering

Excess nitrogen fertilizer applied to farm fields pollutes our air and water and contributes to global warming. The biotechnology industry says it will genetically engineer plants to use nitrogen more efficiently, but it has yet to produce any crops capable of achieving this goal—despite increasing efforts over the past decade—and the future prospects are uncertain. More promising solutions, including traditional breeding and cover crops, deserve increased funding and attention.

Nitrogen is essential for life. It is the most common element in Earth's atmosphere and a primary component of crucial biological molecules, including proteins and nucleic acids such as DNA and RNA—the building blocks of life.

Crops need large amounts of nitrogen in order to thrive and grow, but only certain chemical forms collectively referred to as reactive nitrogen can be readily used by most organisms, including crops. And because soils frequently do not contain enough reactive nitrogen (especially ammonia and nitrate) to attain maximum productivity, many farmers add substantial quantities to their soils, often in the form of chemical fertilizer.

Unfortunately, this added nitrogen is a major source of global pollution. Current agricultural practices aimed at producing high crop yields often result in excess reactive nitrogen because of the difficulty in matching fertilizer application rates and timing to the needs of a given crop. The excess reactive nitrogen, which is mobile in air and water, can escape from the farm and enter the global nitrogen cycle—a complex web in which nitrogen is exchanged between organisms and the physical environment—becoming one of the world's major sources of water and air pollution.

The challenge facing farmers and farm policy makers is therefore to attain a level of crop productivity high enough to feed a growing world population while reducing the enormous impact of nitrogen pollution. Crop genetic engineering has been proposed as a means of reducing the loss of reactive nitrogen from agriculture. This report represents a first step in evaluating the prospects of genetic engineering to achieve this goal while increasing crop productivity, in comparison with other methods such as traditional crop breeding, precision farming, and the use of cover crops that supply reactive nitrogen to the soil naturally.

The Importance of Nitrogen Use Efficiency (NUE)

Crops vary in their ability to absorb nitrogen, but none absorb all of the nitrogen supplied to them. The degree to which crops utilize nitrogen is called nitrogen use efficiency (NUE), which can be measured in the form of crop yield per unit of added nitrogen. NUE is affected by how much

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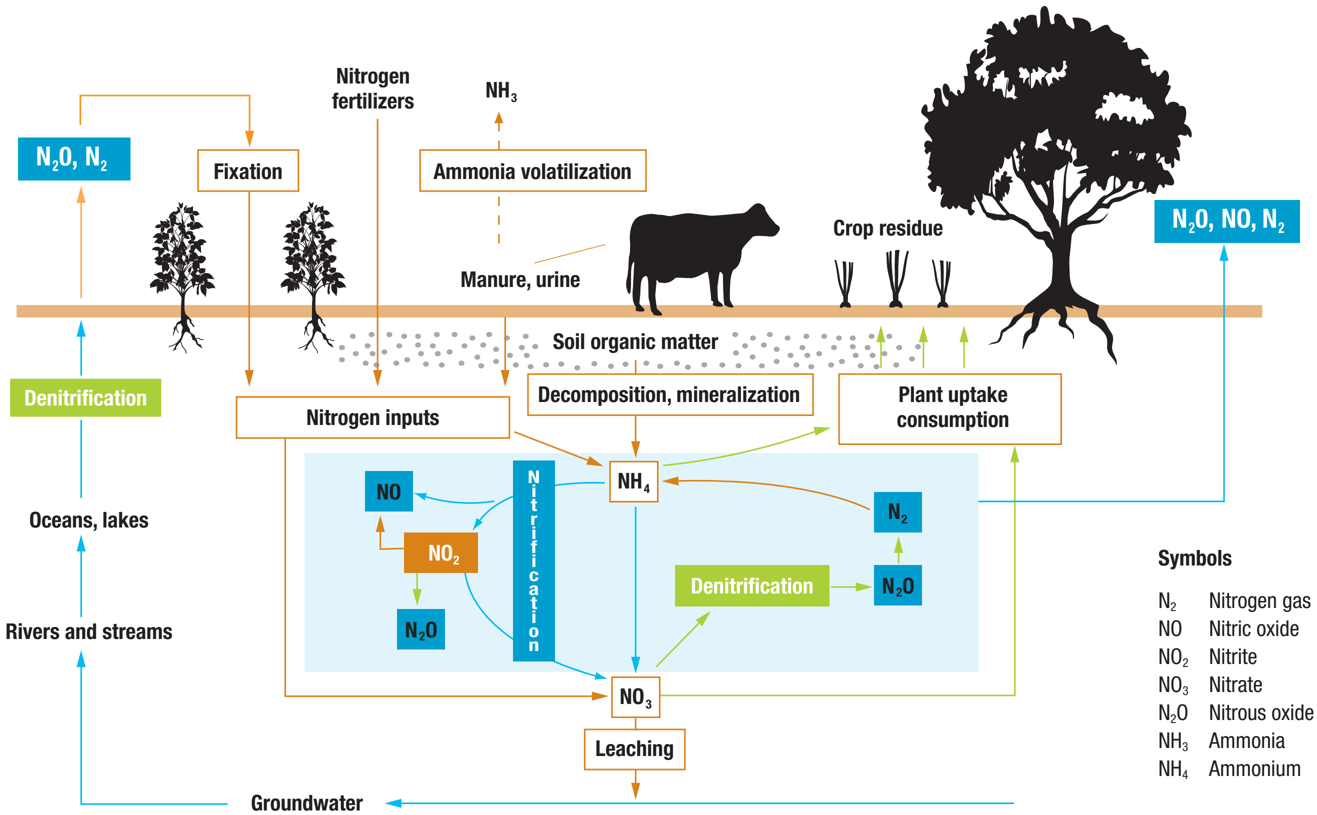
The Nitrogen Cycle



The nitrogen cycle is a highly complex, global cycle that continuously transforms nitrogen into various chemical forms. Industrial agriculture—with its inefficient use of synthetic fertilizers—alters this cycle by adding excessive amounts of reactive nitrogen to the local and global environments.

Source: Adapted from Government of South Australia, Primary Industries and Resources SA.

nitrogen is added as fertilizer, since excess added nitrogen results in lower NUE. Some agricultural practices are aimed at optimizing the nitrogen applied to match the needs of the crop; other practices, such as planting cover crops, can actually remove excess reactive nitrogen from the soil.

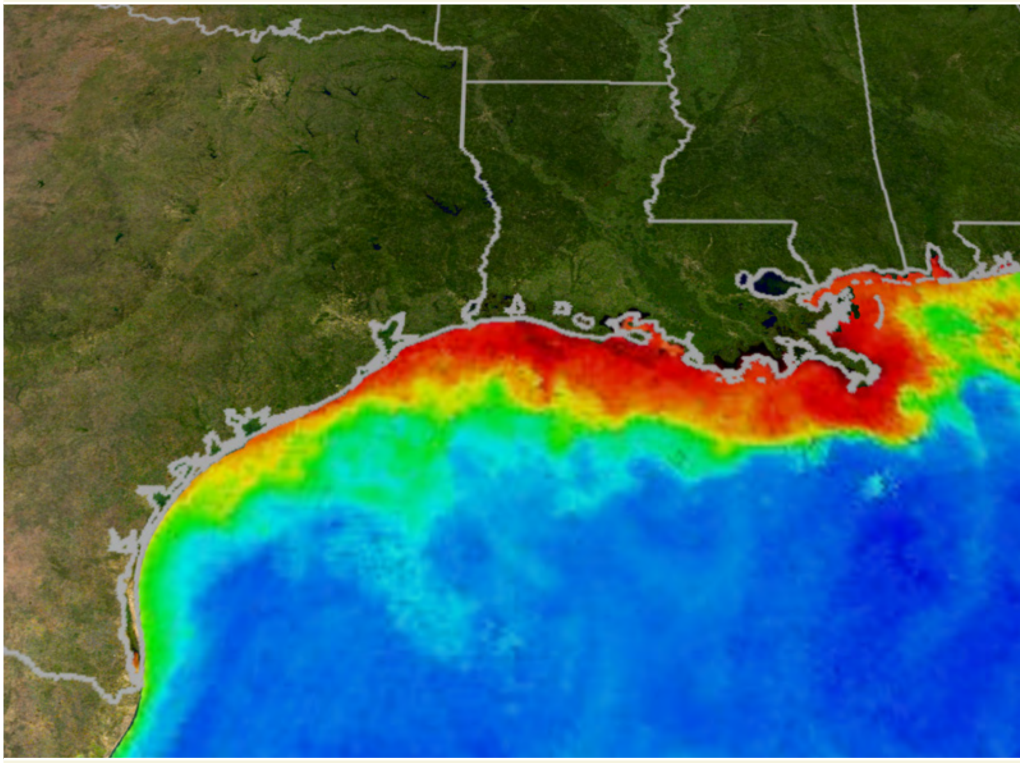
In the United States, where large volumes of chemical fertilizers are used, NUE is typically below 50 percent for corn and other major crops—in other words, much of the added reactive nitrogen is lost from farms. Some of this lost nitrogen is the largest contributor to the "dead zone" in the Gulf of Mexico—an area the size of Connecticut and Delaware combined, in which excess nutrients have caused microbial populations to boom, robbing the water of oxygen needed by fish and shellfish. Furthermore, nitrogen in the form of nitrate seeps into drinking water, where it can become a health risk (especially to pregnant women and children), and nitrogen entering the air as ammonia contributes to smog and respiratory disease as well as to acid rain that damages forests and other habitats. Agriculture is also the largest human-caused domestic source of nitrous oxide, another reactive form of nitrogen that contributes to global warming and reduces the stratospheric ozone that protects us from ultraviolet radiation.

Nitrogen is therefore a key threat to our global environment. A recent scientific assessment of nine global environmental challenges that may make the earth unfavorable for continued human development identified nitrogen pollution as one of only three—along with climate change and loss of biodiversity—that have already crossed a boundary that could result in disastrous consequences if not corrected. One important strategy for avoiding this outcome is to improve crop NUE, thereby reducing pollution from reactive nitrogen.

Can Genetic Engineering Increase NUE?

Genetic engineering (GE) is the laboratory-based insertion of genes into the genetic material of organisms that may be unrelated to the source of the genes. Several genes involved in nitrogen metabolism in plants are currently being used in GE crops in an attempt to improve NUE. Our study of these efforts found that:

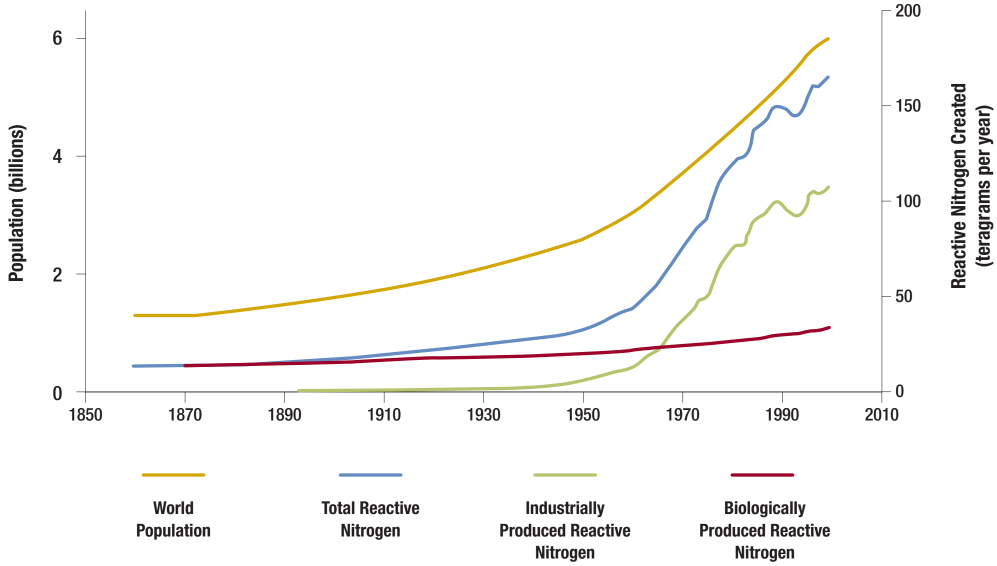
- Approval has been given for approximately 125 field trials of NUE GE crops in the United States (primarily corn, soybeans, and canola), mostly in the last 10 years. This compares with several thousand field trials each for insect resistance and herbicide tolerance.
- About half a dozen genes (or variants of these genes) appear to be of primary interest. The exact number of NUE genes is impossible to determine because the genes under consideration by companies are often not revealed to the public.
- No GE NUE crop has been approved by regulatory agencies in any country or commercialized, although at least one gene (and probably more) has been in field trials for about eight years.



NASA Goddard Space Flight Center

This satellite image shows the impact of nitrogen pollution in the Gulf of Mexico, which is caused by agriculture and other human activities in the Mississippi River basin. The excess nitrogen feeds large blooms of phytoplankton (the red and orange areas in the photo); when these phytoplankton die, their decomposition removes oxygen from the surrounding water, creating a “dead zone” in which fish, shellfish, and other marine life cannot survive.

Rise in Global Reactive Nitrogen Production



The amount of human-caused reactive nitrogen in the global environment has increased 11-fold since the nineteenth century and about eight-fold since the 1960s, which marked the beginning of the "green revolution" in agriculture. Agriculture is responsible for about 80 percent of the reactive nitrogen produced worldwide.

Source: Adapted from Galloway et al. 2003. © 2003, American Institute of Biological Sciences. Used by permission. All rights reserved.

- Improvements in NUE for experimental GE crops, mostly in controlled environments, have typically ranged from about 10 to 50 percent for grain crops, with some higher values. There have been few reports of values from the field, which may differ considerably from lab-based performance.
- By comparison, improvement of corn NUE through currently available methods has been estimated at roughly 36 percent over the past few decades in the United States. Japan has improved rice NUE by an estimated 32 percent and the United Kingdom has improved cereal grain NUE by 23 percent.
- Similarly, estimates for wheat from France show an NUE increase from traditional breeding of about 29 percent over 35 years, and Mexico has improved wheat NUE by about 42 percent over 35 years.

Available information about the crops and genes in development for improved NUE suggests that these genes interact with plant genes in complex ways, such that a single engineered NUE gene may affect the function of many other genes. For example:

- In one of the most advanced GE NUE crops, the function of several unrelated genes that help protect the plant against disease has been reduced.

- Another NUE gene unexpectedly altered the output of tobacco genes that could change the plant's toxicological properties.

Many unexpected changes in the function of plant genes will not prove harmful, but some may make it difficult for the crops to gain regulatory approval due to potential harm to the environment or human health, or may present agricultural drawbacks even if they improve NUE. For the most advanced of the genes in the research pipeline, commercialization will probably not occur until at least 2012, and it will likely take longer for most of these genes to achieve commercialization—if they prove effective at improving NUE. At this point, the prospects for GE contributing substantially to improved NUE are uncertain.

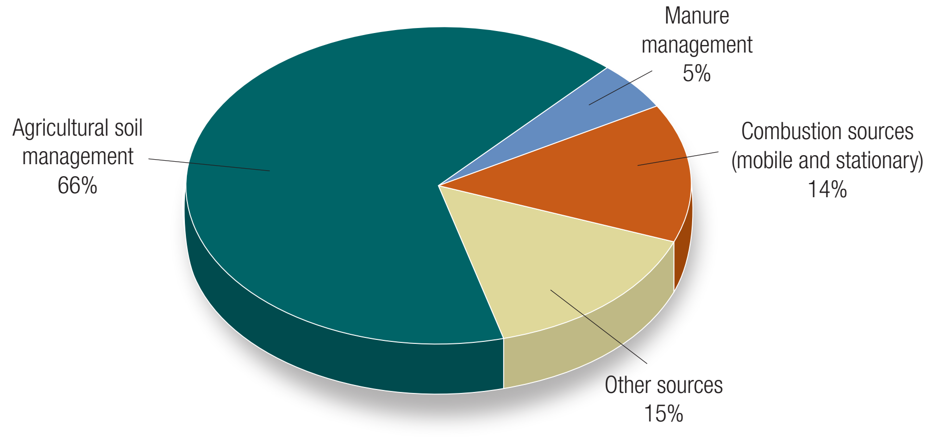
Other Methods for Reducing Nitrogen Pollution

Traditional or enhanced breeding techniques can use many of the same or similar genes that are being used in GE, and these methods are likely to be as quick, or quicker, than GE in many cases. Traditional breeding may have advantages in combining several NUE genes at once.

Precision farming—the careful matching of nitrogen supply to crop needs over the course of the growing season—has shown the ability to increase NUE in experimental trials. Some of these practices are already improving NUE, but adoption of some of the more technologically sophisticated and precise methods has been slow.

No genetically engineered NUE crop has been approved by regulatory agencies in any country or commercialized, although at least one gene has been in field trials for about eight years.

Sources of Human-Caused Nitrous Oxide Emissions in the United States (2007)



Agricultural soil management, which today is based on the addition of large quantities of nitrogen fertilizers, accounts for two-thirds of the United States' human-caused emissions of nitrous oxide—a potent heat-trapping gas.

Source: Adapted from U.S. Environmental Protection Agency data, online at *http://www.epa.gov/nitrousoxide/sources.html*.

Cover crops are planted to cover and protect the soil during those months when a cash crop such as corn is not growing, often as a component of an organic or similar farming system. Some can supply nitrogen to crops in lieu of synthetic fertilizers, and can remove excess nitrogen from the soil; in several studies, cover crops reduced nitrogen losses into groundwater by about 40 to 70 percent.

Cover crops and other "low-external-input" methods (i.e., those that limit use of synthetic fertilizers and pesticides) may also offer other benefits such as improving soil water retention (and drought tolerance) and increasing soil organic matter. An increase in organic matter that contains nitrogen can reduce the need for externally supplied nitrogen over time.

With the help of increased public investment, these methods should be developed and evaluated fully, using an ecosystem approach that is best suited to determine how reactive nitrogen is lost from the farm and how NUE can be improved in a comprehensive way. Crop breeding or GE alone is not sufficient because they do not fully address the nitrogen cycle on real farms, where nitrogen loss varies over time and space, such as those times when crops—conventional or GE—are not growing.

Conclusions

GE crops now being developed for NUE may eventually enter the marketplace, but such crops are not uniquely beneficial or easy to produce. There is already sufficient genetic variety for NUE traits in crops, and probably in close relatives of important crops, for traditional breeding to build on its successful track record and develop more efficient varieties.

Other methods such as the use of cover crops and precision farming can also improve NUE and reduce nitrogen pollution substantially.

Recommendations

The challenge of optimizing nitrogen use in a hungry world is far too important to rely on any one approach or technology as a solution. We therefore recommend that research on improving crop NUE continue. For traditional breeding to succeed, public research support is essential and should be increased in proportion to this method's substantial potential.

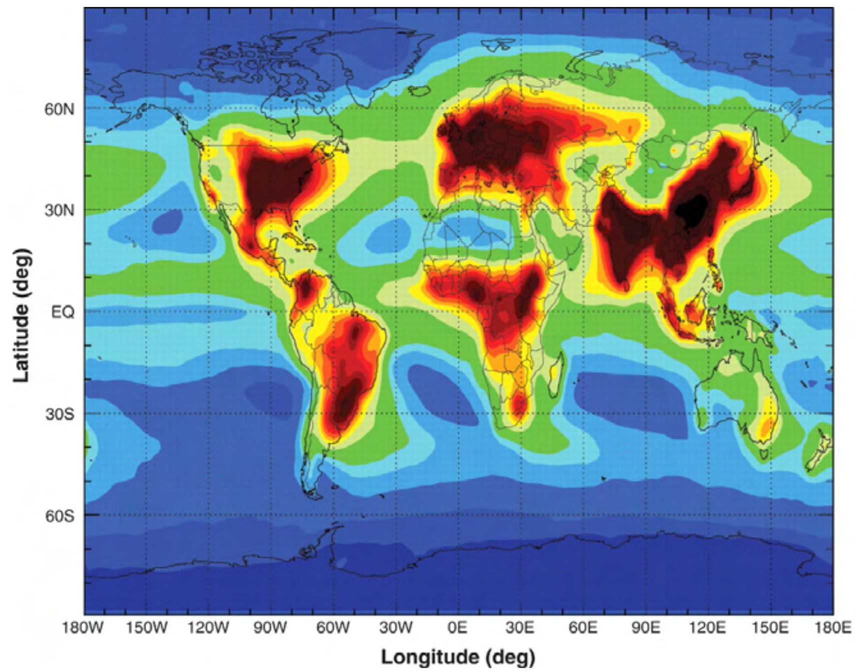
We also recommend that system-based approaches to increasing NUE—cover crops, precision application of fertilizer, and organic or similar farming methods—should be vigorously pursued and supported. These approaches are complementary to crop improvement because each addresses a different aspect of nitrogen use. For example, while breeding for NUE reduces the amount of nitrogen needed by crops, precision farming reduces the amount of nitrogen applied. Cover crops remove excess nitrogen and may supply nitrogen to cash crops in a more manageable form.

Along with adequate public funding, incentives that lead farmers to adopt these practices are also needed. Although the private sector does explore traditional breeding along with its heavy investment in the development of GE crops, it is not likely to provide adequate support for the development of non-GE varieties, crops that can better use nitrogen

Cover crops can supply nitrogen to crops in lieu of synthetic fertilizers, and can remove excess nitrogen from the soil; in several studies, cover crops reduced nitrogen losses into groundwater by about 40 to 70 percent.

Early-flowering hairy vetch is a leguminous cover crop commonly planted after a cash crop is harvested in the fall. Bacteria associated with hairy vetch convert unreactive nitrogen gas into reactive nitrogen, which is then returned to the soil the following spring (for use by the next cash crop).

Global Nitrogen Deposition



This map, which highlights those areas where the most nitrogen falls from the atmosphere to the earth, illustrates that nitrogen pollution is a global issue that must be addressed.

Source: Galloway, J.N., A.R. Townsend, J.W. Erisman, M. Bekunda, Z. Cai, J.R. Freney, L.A. Martinelli, S.P. Seitzinger, and M.A. Sutton. 2008. Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. *Science* 320(5878):889–892.

from organic sources, or improved cover crops that remove excess nitrogen from soil. We must ensure that broad societal goals are addressed and important options are pursued nevertheless.

In short, there are considerable opportunities to address the problems caused by our current overuse of synthetic nitrogen in agriculture if we are willing to make the necessary investments. The global impact of excess reactive nitrogen will worsen as our need to produce more food increases, so strong actions—including significant investments in technologies and methods now largely ignored by industrial agriculture—will be required to lessen the impact.

For more information and to read the full report, visit *www.ucsusa.org/NoSureFix*.

The Union of Concerned Scientists is the leading science-based nonprofit organization working for a healthy environment and a safer world.

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