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Excess Nitrogen in the U.S. Environment: Trends, Risks, and Solutions

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SUMMARY

It is not surprising that humans have profoundly altered the global nitrogen (N) cycle in an effort to feed 7 billion people, because nitrogen is an essential plant and animal nutrient. Food and energy production from agriculture, combined with industrial and energy sources, have more than doubled the amount of reactive nitrogen circulating annually on land. Humanity has disrupted the nitrogen cycle even more than the carbon (C) cycle. We present new research results showing widespread effects on ecosystems, biodiversity, human health, and climate, suggesting that in spite of decades of research quantifying the negative consequences of too much available nitrogen in the biosphere, solutions remain elusive. There have been important successes in reducing nitrogen emissions to the atmosphere and this has improved air quality. Effective solutions for reducing nitrogen losses from agriculture have also been identified, although political and economic impediments to their adoption remain. Here, we focus on the major sources of reactive nitrogen for the United States (U.S.), their impacts, and potential mitigation options:

Sources:

- Intensive development of agriculture, industry, and transportation has profoundly altered the U.S. nitrogen cycle.
- Nitrogen emissions from the energy and transportation sectors are declining, but agricultural emissions are increasing.
- Approximately half of all nitrogen applied to boost agricultural production escapes its intended use and is lost to the environment.

Impacts:

- Two-thirds of U.S. coastal systems are moderately to severely impaired due to nutrient loading; there are now approximately 300 hypoxic (low oxygen) zones along the U.S. coastline and the number is growing. One third of U.S. streams and two fifths of U.S. lakes are impaired by high nitrogen concentrations.
- Air pollution continues to reduce biodiversity. A nation-wide assessment has documented losses of nitrogen-sensitive native species in favor of exotic, invasive species.
- More than 1.5 million Americans drink well water contaminated with too much (or close to too much) nitrate (a regulated drinking water pollutant), potentially placing them at increased risk of birth defects and cancer. More research is needed to deepen understanding of these health risks.
- Several pathogenic infections, including coral diseases, bird die-offs, fish diseases, and human diarrheal diseases and vector-borne infections are associated with nutrient losses from agriculture and from sewage entering ecosystems.
- Nitrogen is intimately linked with the carbon cycle and has both warming and cooling effects on the climate.

Mitigation Options:

- Regulation of nitrogen oxide (NO_X) emissions from energy and transportation sectors has greatly improved air quality, especially in the eastern U.S. Nitrogen oxide is expected to decline further as stronger regulations take effect, but ammonia remains mostly unregulated and is expected to increase unless better controls on ammonia emissions from livestock operations are implemented.
- Nitrogen loss from farm and livestock operations can be reduced 30-50% using current practices and technologies and up to 70-90% with innovative applications of existing methods. Current U.S. agricultural policies and support systems, as well as declining investments in agricultural extension, impede the adoption of these practices.

Society faces profound challenges to meet demands for food, fiber, and fuel while minimizing unintended environmental and human health impacts. While our ability to quantify transfers of nitrogen across land, water, and air has improved since the first publication of this series in 1997, an even bigger challenge remains: using the science for effective management policies that reduce climate change, improve water quality, and protect human and environmental health.

Cover photo credit: *Nitrogen deposition at the Joshua Tree National Park in California has increased the abundance of exotic grasses, which are more prone to fire than native vegetation. The upper photo shows a site dominated by exotic annual grasses five years after a burn, and the lower shows a site immediately post-burn. Photos courtesy of Edith Allen.*

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Introduction

Thanks largely to the early 20th century invention of synthetically manufactured nitrogen (N) fertilizers, the growing human population is, on average, better nourished now than ever before in human history. About 40 to 60% of the current human population depends upon crops grown with synthetic nitrogen fertilizer. Unfortunately, this impressive advance in agricultural productivity and human nutrition has come at a high price of environmental degradation and human health risks from pollution. A large fraction of nitrogen fertilizer applied to cropland – often over half – is not used by the crops and is lost to air, water, and downstream and downwind habitats, polluting landscapes and waterscapes. At the same time, energy, transportation, and industrial sectors also emit nitrogen pollution into the air through increasing use of fossil fuels. In 1997, the first *Issue in Ecology* described the magnitude, causes, and consequences of these human alterations of the nitrogen cycle, documenting how humans have more than doubled the amount of reactive nitrogen (see Glossary for definitions) annually in circulation in the terrestrial biosphere. Several of these trends have continued along with increasing numbers of people, including improving human diets in the developing world, increasing global use of fertilizers, increasing atmospheric concentrations of the potent greenhouse gas nitrous oxide, and increasing eutrophication of aquatic and terrestrial habitats. Fifteen years later, we now ask: "Has scientific awareness of the growing problems of nitrogen pollution fostered progress in finding solutions?"

In some respects, the answer is a disappointing "no." Atmospheric nitrous oxide is still increasing, the number of aquatic ecosystems experiencing eutrophication and hypoxia (low oxygen waters) has grown, and biodiversity losses due to air pollution have continued. Indeed, these problems have been exacerbated by unanticipated new demands for biofuel crops, which created further demand for agricultural expansion and fertilizer inputs. Yet there have been important success stories. Significant air quality improvements are the result of regulations and technological innovations that have reduced nitrogen emissions from industry and automobiles in many developed countries. The amount of nitrogen in air pollution that some ecosystems can sustain (the "critical load") without significant loss in diversity or ecosystem function has been estimated. Progress has also been made on improving the efficiency of fertilizer use and on identifying effective management options to reduce nitrogen losses from agricultural lands. Evidence of the links between excess reactive nitrogen in the environment and specific human health outcomes is growing, providing compelling motivation for pollution abatement. Perhaps the most encouraging aspect of progress in reducing nitrogen pollution is that technological solutions do exist. Research is needed to reduce costs of these solutions, and better communication is needed to foster the cultural and political will to apply them.

While the nitrogen cycle disruption is global, the impacts are often felt locally, and the solutions are region-specific. Here, we focus on the major sources of reactive nitrogen for the U.S., their impacts on ecosystems, climate, and human health, and options to minimize nitrogen losses and impacts.

The Major Anthropogenic Sources Of Reactive Nitrogen In The U.S.

For the U.S., the combined anthropogenic sources of reactive nitrogen are about four times larger than natural sources of inputs from biological nitrogen fixation (see Glossary for definitions) in native ecosystems and from lightning (Table 1). Because of intensive agricultural and industrial development, the alteration of the U.S. nitrogen cycle is greater than the global average. While nitrogen fertilizer use is growing in emerging-market regions such as Asia, it has nearly leveled off in the U.S. Soybean production has been increasing, which increases biological nitrogen fixation in croplands. Nitrogen oxide (NO_X) emissions have declined and are expected to decline further.

In addition to the annual inputs of newly fixed reactive nitrogen shown in Table 1, the redistributions and transfers of nitrogen across landscape components are also important (Figure 1). These include ammonia, nitrogen oxides and nitrous oxide emissions from soils to the atmosphere, leaching of nitrate and dissolved organic nitrogen from land to water, food harvests, and sewage disposal. This movement of reactive nitrogen into air, water, and non-agricultural land leads to unintended, mostly undesirable consequences for ecosystem and human health. A 2011 EPA report (see suggestions for further reading) describes these estimates in more detail. Our emphasis here will be in describing and quantifying impacts on human and ecosystem health and potential solutions.

IMPACTS ON ECOSYSTEMS

Research during the last few decades has led to an improved understanding of the relationship between nitrogen inputs and nitrogen demand by plant communities. Nitrogen generally enhances the growth of plants, but plant species differ in their ability to respond to increased nitrogen, due to variation in their inherent growth rates and their responses to other associated changes, such as acidification and nutrient imbalances. Many native hardwood tree species in the eastern U.S., such as red and sugar maple, white ash, black cherry, tulip poplar, and red oak, respond positively to nitrogen deposition from air pollution, whereas beech and several birch and oak species show no growth response. Conifer responses are mixed, with several species, particularly red pine, showing reduced growth with increasing nitrogen deposition (Figure 2). In addition to effects on trees, the understory vegetation is often particularly susceptible to changes in species composition due to increasing nitrogen deposition.

Trees grow slowly where soils are thin and the growing season is short, for example in the Rocky Mountains. Field research has shown that much less nitrogen deposition is needed to satu-

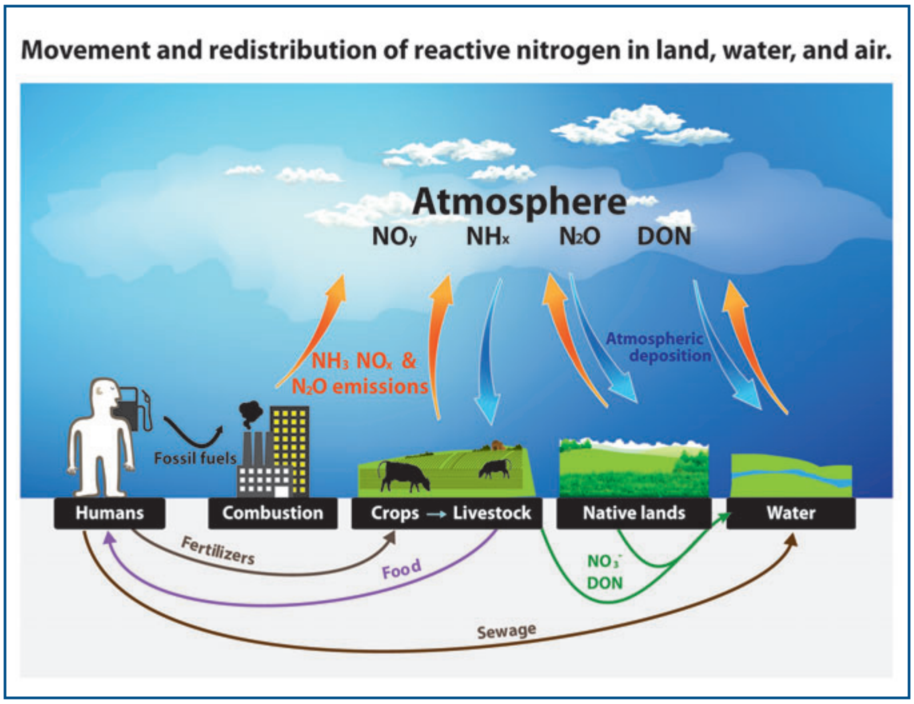


Figure 1. The most important transfers and redistributions of reactive nitrogen among landscapes and waterscapes (see Glossary for abbreviations). Biological nitrogen fixation, denitrification, and a few minor transfers are omitted for visual simplicity.

Table 1. Estimates of the major sources of natural and anthropogenic N inputs to the United States in 1990 and 2008 and projections for 2014.

U.S. Nitrogen Sources	1990	2008	2014 Projection
	Millions of metric tons N per year		
Natural sources			
Lightning	0.1	0.1	0.1
Biological N fixation	6.4	6.4	6.4
Agriculture			
Synthetic N fertilizer	9.7	11.4	11.9
Crop biological N fixation	5.4	8.3	9.1
Food imports	0.2	0.2	0.2
Combustion			
Industrial NO_X	1.5	1.1	1.1
Transportation NO_X	3.7	2.6	2.0
Electric generation NO_X	1.8	0.8	0.6
Industrial uses*	4.2	4.2	4.2
TOTAL	34.0	35.2	35.8

*Industrial uses of synthetic reactive N include nylon production and munitions. The only estimate available is for 2002, which we assume is constant for this time period for lack of better data. Sources include EPA reports and datasets (EPA-SAB-11-013, EPA-HQ-OAR-2009-0491, http://www.epa.gov/ttnchie1/trends/) and the International Fertilizer Industry Association.

Figure 2. *Nitrogen deposition from air pollution increases the growth of many hardwood tree species, such as the red maple (left). Some conifers, such as red pine (right), show a decreased growth rate. Responses of the 24 most common species in the eastern U.S. can be found in Thomas* et al*. 2010.* Nature Geoscience*, 3:13-17.*

rate the plant demand in high elevation forests compared to low elevation forests. Much of the nitrogen that is not taken up by the plants then enters streams, groundwater, and lakes, where it affects algal productivity and aquatic food webs. This type of research throughout the country is leading to estimates of "critical loads" of nitrogen deposition calculated for each ecosystem type and location (see Box 1).

In addition to supplying an essential plant nutrient, nitrogen deposition also affects soil properties. Both nitrogen and sulfur from air pollution contribute to the acidification of soils, which leads to the loss of essential plant nutrients, such as calcium and magnesium, and alters the availability of phosphorus. Soil acidification mobilizes elements like aluminum, which is toxic to many plants on land and to many fish and other fauna in streams and lakes. Acidification of soils can increase forest susceptibility to disease and drought by stressing plants. Air polluted with nitrogen is often accompanied by ozone pollution, which suppresses plant photosynthesis.

Species vary in their ability to tolerate these stresses from air pollution. Species-specific responses to elevated nitrogen deposition have reduced the diversity of terrestrial and aquatic ecosystems. In general, fast growing, "weedy" species, many of which are non-native, respond quickly and positively to increased nitrogen deposition, whereas slow-growing native species that are adapted to naturally low levels of nitrogen are less able to use the additional nitrogen. The differing responses can drive local populations of rare, slow-growing, native plant species

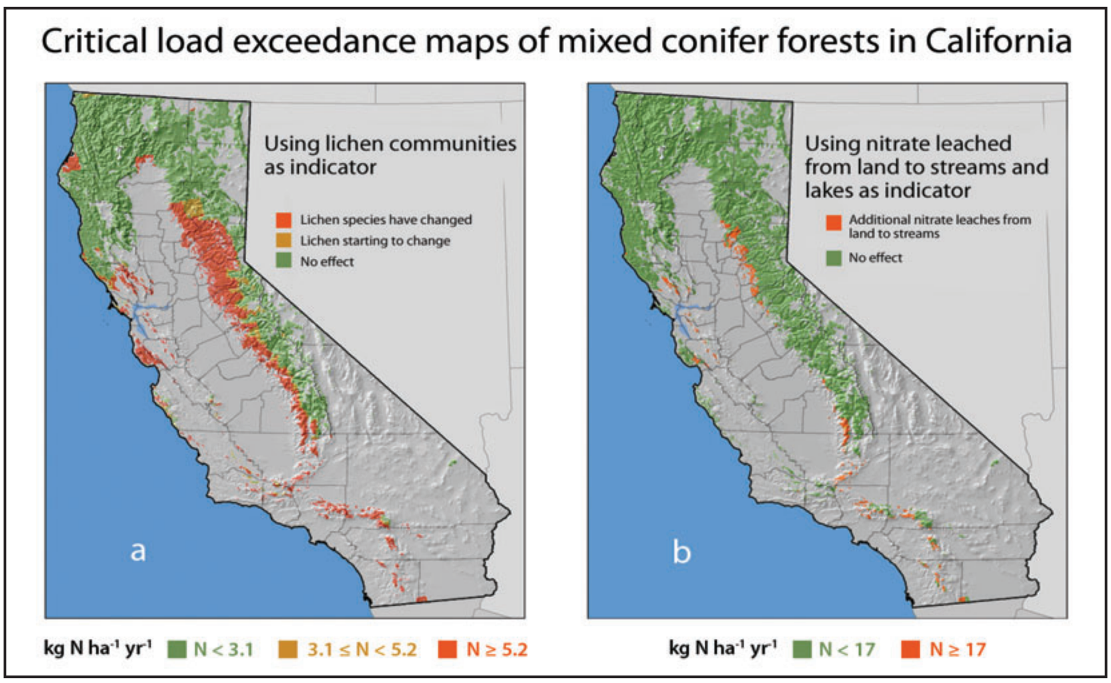


Figure 3. *In California, airborne nitrogen is impacting one third of the state's natural land areas. Lichens and stream nitrate concentrations have been used as effective indicators of undesirable changes in ecosystems. Areas shaded in red indicate conifer forests at risk because inputs from nitrogen in air pollution are exceeding the estimated critical load, either because (a) the species of lichen is expected to change or (b) nitrate in stream water is expected to exceed an established threshold value. Green shading indicates areas where pollution inputs are less than the critical loads. Redrawn from Fenn* et al. *(2010.* Journal of Environmental Management *91:2404-2423), where critical load exceedance maps for additional California ecosystems can be found.*

Box 1. CRITICAL LOADS: HOW MUCH NITROGEN IS TOO MUCH?

Excess nitrogen can disrupt natural ecosystems, causing acidification, nutrient imbalances, and loss of biodiversity. To manage nitrogen effectively, it is important to know how much nitrogen can be added to an ecosystem without provoking harmful effects. The term "critical load" describes how much nitrogen is too much. Critical loads usually refer to nitrogen deposited from air pollution and are expressed as loading rates of nitrogen in a given area over time, usually as kilograms of nitrogen per hectare per year. They are widely used in Europe and Canada to evaluate how nitrogen, sulfur, and other air pollutants affect streams, lakes, and forests, and are now being developed for ecosystems in the U.S. Maps of critical loads are combined with maps of air pollution to show where pollution loads exceed the estimated local critical load, putting ecosystems at risk. For example, in California, maps of critical loads combined with actual nitrogen loads highlight areas where nitrogen is likely affecting forests (Figure 3), grasslands, coastal sage, desert, and streams. This information helps air quality managers determine where and how much air quality needs to be improved, in order to reduce excess nitrogen loadings and to restore harmed areas.

to extinction. The herbivores that feed on these plants are also affected. For example, checkerspot butterfly populations in serpentine grasslands of California have declined following replacement of native with invasive nitrogen-loving grasses. In other cases, herbivore populations expand when the plants they feed upon become enriched with higher tissue concentrations of nitrogen, and lower concentrations of defensive chemicals. The expansion of nitrogen-loving, non-native, highly flammable grasses in the western U.S. has increased fire risk. (e.g., see cover photos)

Much of the reactive nitrogen in terrestrial ecosystems that is not taken up by plants or retained in soils ends up in aquatic ecosystems. Roughly two-thirds of U.S. coastal systems have recently been classified as moderately to severely impaired due to nutrient loading. Over-enrichment with nitrogen is associated with increased frequency, severity, and extent of hypoxic (low oxygen) and anoxic (no oxygen) events, harmful and nuisance algae blooms, and species shifts leading to biodiversity loss. An increase in occurrence of coastal hypoxic and anoxic zones has been reported every decade since the early 1900s, with nearly 300 hypoxic zones along the U.S. coastline. In New England estuaries, phytoplankton (microscopic algae) now dominate over native sea grasses, resulting in aquatic ecosystems with much less structural complexity and lower water clarity.

Enrichment of nitrogen in freshwaters often has negative impacts similar to those seen in coastal waters, and also affects drinking water quality (see human health impacts section). Although plant and algal growth in freshwater systems is strongly constrained by phosphorus (P), there is considerable evidence for co-constraints by both nitrogen and phosphorus. Recent surveys carried out by the EPA indicate that roughly one-third of the total stream length in the U.S. is considered "most disturbed" with respect to total nitrogen concentrations, and roughly one-fifth of all U.S. lakes are ranked poor with respect to total nitrogen concentrations.

IMPACTS ON CLIMATE

The importance of the nitrogen cycle in regulating climate is gaining increasing attention. Early global climate models focused solely on the physics of greenhouse gas effects; later models incorporated biological sources and sinks of carbon dioxide, but did not include carbon-nitrogen interactions. In recent years, a few earth system models have added some representation of the nitrogen cycle as a crucial regulator of the carbon (C) cycle, climate, and atmospheric chemistry, but the representation of nitrogen cycling processes in climate models remains far from complete.

Deposition of airborne reactive nitrogen onto land affects terrestrial carbon sinks through two key processes. First, inputs of nitrogen often increase the growth of trees, which store high amounts of carbon in their wood. The magnitude of growth stimulation is of some debate, but is likely greatest in regions of moderate nitrogen deposition. Increasing atmospheric carbon dioxide concentrations also stimulate plant growth, but this stimulation is constrained by the availability of nitrogen to plants. Second, inputs of reactive nitrogen slow breakdown of dead plant material and soil organic matter in many, but not all forest soils. Why nitrogen deposition slows these breakdown processes is an area of active research into changes in soil microbial communities, microbial biomass, and enzyme production needed to break down complex organic matter.

The most direct effect of nitrogen on climate is through nitrous oxide, the third most important anthropogenic greenhouse gas, contribut-

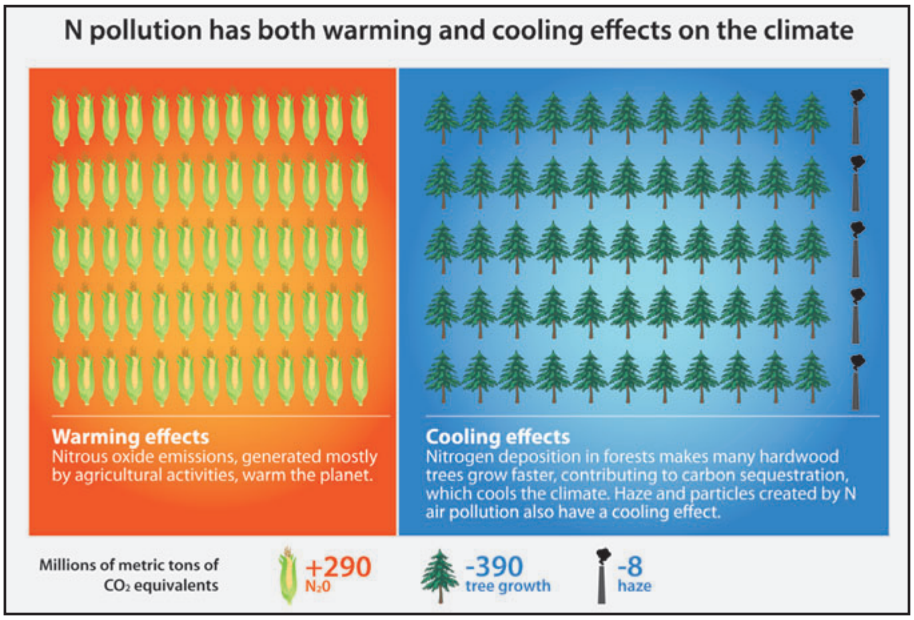


Figure 4. The cooling effects resulting from U.S. nitrogen deposition (which allows trees to remove carbon from the atmosphere and causes reflection of the sun by nitrogen-containing haze and particles in the air) slightly outweigh the warming effect of U.S. nitrous oxide emissions. However, uncertainties in these calculations are large, yielding the following ranges of estimates: +180 to +400 for N_2O; -240 to -540 for tree growth; and -2 to -16 for haze, where positive numbers indicate warming and negative numbers cooling. Because various different greenhouse gases and aerosols are included in this analysis, all are converted to the common currency of "CO_2-equivalents" on a 100-year global warming potential time frame, using the methodologies of the Intergovernmental Panel on Climate Change.

ing 6% of total human-induced global warming. It has about 300 times the per-molecule warming potential of carbon dioxide and is long-lived in the atmosphere (a "mean residence time" of more than 110 years). Atmospheric concentrations of nitrous oxide have increased rapidly since 1860, as livestock herds increased globally and as use of synthetic-nitrogen fertilizers increased after World War II. The EPA estimates that agricultural activities are directly or indirectly responsible for emissions of 0.48 million tons of nitrogen as nitrous oxide per year, which is about 80% of total U.S. nitrous oxide production (the remainder is from energy and industrial sources) and about 10% of the global nitrous oxide emissions from agriculture.

Reactive nitrogen also affects methane, another important greenhouse gas, through chemical reactions that destroy atmospheric methane and through inhibition of methane production and consumption by microbes in soils and wetlands. However, the overall climate impacts of reactive nitrogen via methane are small compared to those of nitrous oxide and carbon sequestration.

While not greenhouse gases directly, nitrogen oxides often affect the production of ozone in the troposphere (the lower atmosphere). Ozone affects climate directly as a greenhouse gas, and it is also toxic to plants, decreasing photosynthesis and plant uptake of atmospheric carbon dioxide by as much as 20%.

Both nitrogen oxides and ammonia affect the formation of tiny airborne particles, also known as aerosols, and their chemical properties. The abundance and properties of these particles influence the formation of cloud droplets. In some cases this causes clouds to be brighter and longer-lived, which has important effects on precipitation and temperature patterns. Overall, aerosols have a short-term cooling effect, but the long-term effect is small because the aerosols are frequently washed out of the air by rain.

The above discussion of the impacts of reactive nitrogen on climate is global in scope, not U.S.-specific. Efforts are underway to create a U.S.-specific nitrogen assessment, with preliminary findings shown in Figure 4. It compares the long-term warming potentials of nitrogen gases and particulates and carbon sequestration attributable to U.S. emissions of reactive nitrogen. The cooling effects of nitrogen deposition through carbon sequestration roughly cancel the warming effect of nitrous oxide (Figure 4). Putting these estimates into a broader perspective, these contrasting warming and cooling effects of nitrogen are equivalent to less than 10% of the warming effect of U.S. emissions of carbon dioxide from fossil fuel combustion.

IMPACTS ON HUMAN HEALTH

Drinking water and human health

Nitrate concentrations in groundwater are increasing in many parts of the U.S., raising concerns for human health, particularly in rural agricultural areas where shallow groundwater is often used for domestic water supplies. The EPA's maximum contaminant level (MCL) for public drinking water supplies is 10 milligrams per liter as nitrate-nitrogen (or about 45 milligrams per liter as nitrate). Nitrate concentrations above the MCL are relatively uncommon in streams and deep aquifers used for drinking water supplies. However, the MCL was exceeded in 22% of shallow (less than 100 feet below the water table) domestic wells in agricultural areas, an increase from a decade earlier, according to a 2010 U.S. Geological Survey (USGS) report. Taking into account the regional sources of nitrate and regional differences in geology that affect its movement to groundwater, the USGS study shows large areas in agricultural and urban regions with shallow groundwater nitrate exceeding 10 milligrams nitrogen per liter (Figure 5). Based on a USGS model of drinking water quality, it is estimated that about 1.2 million Americans use private drinking wells with nitrate concentrations between 5 and 10 milligrams nitrogen per liter, and about a half million Americans use wells that exceed the MCL of 10 milligrams nitrogen per liter. Future contamination of deeper groundwater pumped from public supply wells is a growing concern due to increasing nitrate concentrations of deep aquifers resulting from downward transit of shallow groundwater.

The EPA and World Health Organization drinking water standards were set to prevent methemoglobinemia in infants, also known as "blue baby syndrome." Methemoglobinemia is uncommon in the U.S. due, in part, to adherence to the standards in most areas. However, other health conditions have been linked to nitrate ingestion. About 5% of ingested nitrate is converted by bacteria in the mouth to nitrite, which then forms several compounds with different effects in the body. In the acidic stomach, nitrite forms nitric oxide, which lowers blood pressure, providing a beneficial effect. Nitrite also reacts with amines and amides, present in proteins from the diet or from medications, to form N-nitrosamines and N-nitrosamides (collectively N-nitroso compounds; see Figure 6). These compounds damage DNA and have been shown to cause birth defects and cancer in animals.

Because all animal species tested so far have been susceptible to cancer induced by N-nitroso-compounds, it is likely that humans are also affected. However, well-designed human studies that include factors affecting N-nitroso-compound formation in the body are few, limiting the ability to draw definitive conclusions about cancer risk at this time. Nevertheless, the UN World Health Organization International Agency for Research on Cancer expert working group concluded: "Ingested nitrate or nitrite under conditions that result in endogenous nitrosation is probably carcinogenic to humans" (endogenous nitrosation refers to the formation of N-nitroso-compounds in the stomach, as described above). Increased risks for stomach, esophageal, colon, and kidney cancer have been found in the few studies that have evaluated people with high intake of nitrate from drinking water or diet and low intake of vitamin C. The production of N-nitroso-compounds is decreased by vitamin C and other compounds in fruits and vegetables and increased by heme iron in red meats, so the risk could be minimized by a diet rich in fruits and vegetables and worsened by a diet rich in red meat.

In addition to cancer risks, high nitrate concentrations in drinking water supplies have been linked to increased risk of spontaneous abortions, premature births, and intrauterine growth retardation, although not all studies found these associations. In four studies to date, central nervous system malformation has been linked to the nitrate in drinking water of pregnant women, including some evidence at nitrate concentrations below the EPA standard. High levels of nitrate ingestion via drinking water were associated with increased rates of thyroid enlargement (hypertrophy) and thyroid underfunction (hypothyroidism). Given these findings, more research is needed to evaluate the range of health effects due to nitrate ingestion.

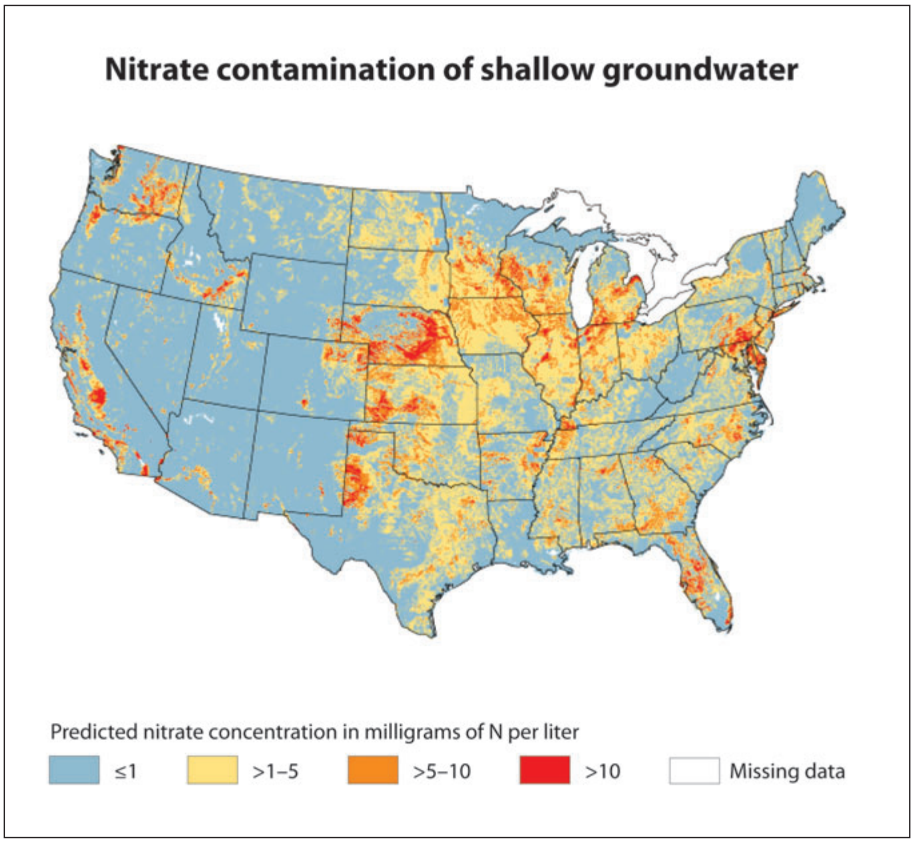


Figure 5. A U.S. Geological Survey model for shallow groundwater predicts moderate (yellow and orange) to severe (red) nitrate contamination in areas with large nitrogen sources and where the geologic features allow the nitrate to reach the groundwater. Redrawn from USGS Circular 1350 by Dubrovsky et al. (2010).

Air pollution and human health

A growing body of evidence demonstrates that some nitrogen-related air pollutants are hazardous for human health (Table 2). Nitrogen oxide is an important component of outdoor and indoor air pollution. Nitrogen oxide is emitted by automobiles, electrical power plants, and construction machinery. Tailpipe emissions make up the majority of urban sources; minor natural sources include lightning, soil emissions, and wildland fires. Nitrogen oxide reacts with other components of air pollution to form ozone and several constituents of fine particulate matter. Particulate matter is a mixture of solid and liquid particles that

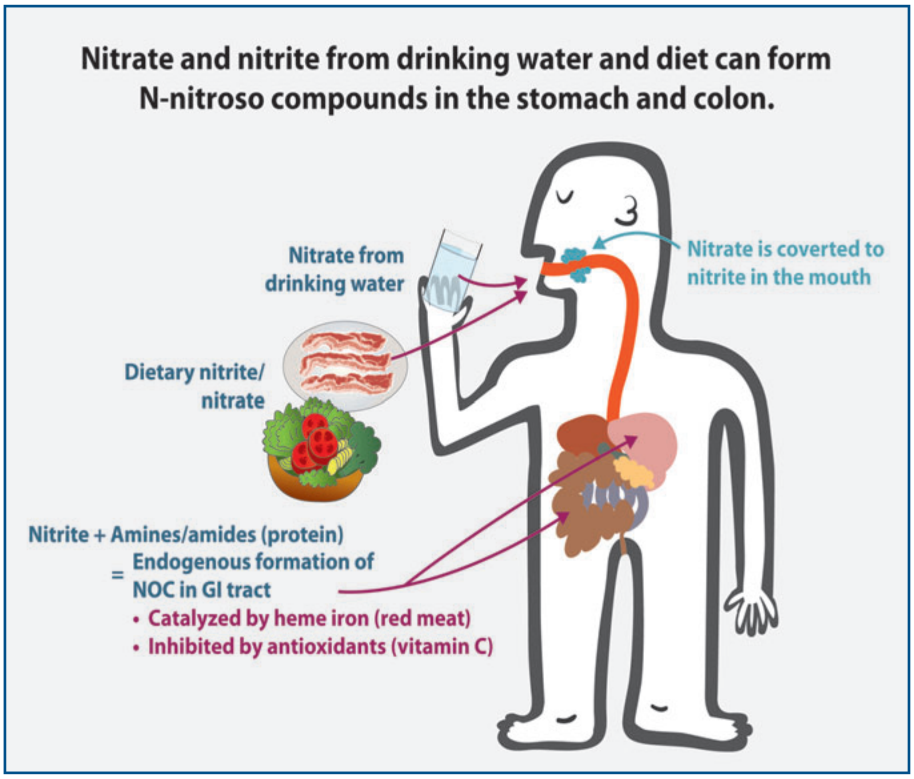


Figure 6. N-nitroso-compounds (NOCs) damage DNA and cause birth defects and cancer in animals. There is a need for more well-designed human studies to draw stronger conclusions about cancer risk from nitrate and nitrite ingestion.

vary in size and chemical composition, often containing ammonium and/or nitrate. Particulate matter that is less than 2.5 microns in diameter, $PM_{2.5}$, penetrates and deposits in the lungs, causing the most harm. Using 2005 air pollution data, EPA analysts estimated that $PM_{2.5}$ exposure caused 130,000 annual premature deaths in the U.S. and ozone exposure caused another 4,700. It is estimated that these pollutants spur hundreds of thousands of hospital visits and millions of additional respiratory symptoms each year in the U.S.

For the regulated pollutants shown in Table 2, populations at increased risk include those with pre-existing cardiovascular and respiratory conditions, developing fetuses, infants, children, and the elderly. Outdoor work or physical exertion, lifestyle (e.g., poor nutrition), low socio-economic status, and genetic predisposition also increase risks. It is possible that these pollutants could interact with each other or with other pollutants to produce health effects, but current regulatory and research frameworks do not address the effects of multi-pollutant atmospheres.

Table 2. Summary of evidence for links between N-related air pollutants and human health.

Pollutant and Scientific Assessment	Evidence Suggests A Clear Link	Probable Link (More Evidence Needed)
NO_x (typically measured as NO_2) 2008 EPA Integrated Science Assessment (ISA)	Short-term* respiratory disease, including: • increased lung inflammation and sensitivity, particularly among asthmatics • increased wheezing, coughing, and asthma symptoms • increased hospital visits for asthma and other respiratory ailments	Short-term increased risk of death from respiratory and heart disease Long-term* respiratory disease, including: • decreased lung function • decreased lung growth and function in children
Ozone 2006 EPA Air Quality Criteria Document (AQCD)	Short-term respiratory disease, including: • increased hospital visits • increased lung inflammation and sensitivity, particularly among asthmatics • increased wheezing, coughing, and asthma symptoms Short-term increased risk of death from respiratory and heart disease	Short-term heart disease, including: • increased hospital visits • decreased heart function
$PM_{2.5}$ 2009 EPA Integrated Science Assessment (ISA) for PM	Short-term and long-term heart and respiratory disease, including: • increased hospital visits • decreased heart and lung function Short-term and long-term increased risk of death from respiratory and heart disease	Adverse reproductive outcomes, such as: • increased risk of preterm birth • decreased birth weight • increased risk of infant mortality Long-term increased risk of cancer

* Short-term refers to days or weeks between exposure of the pollutant and onset of health symptoms. Long-term refers to months or years.

Effects on human health through wildlife

In contrast to toxicological diseases such as blue-baby syndrome, most emerging human infectious diseases are zoonotic, meaning they depend on wildlife as hosts, vectors, or reservoirs. As a result, understanding the factors that contribute to zoonotic diseases requires an ecological approach that recognizes the linkages among environmental change, pathogen transmission, and human and non-human hosts. Nutrient runoff and the concentrations of nitrogen, phosphorus, and organic matter have frequently been associated with a wide range of pathogenic infections, including coral diseases, bird die-offs, diarrheal diseases, vector-borne infections, and fish diseases.

Experimental studies have helped to identify the ways that nitrogen exacerbates disease, including changes in host or vector density, host distribution, infection resistance, pathogen virulence or toxicity, and the increases in resources to the pathogen. For example, West Nile virus was first introduced to the U.S. in 1999 and has since spread across North America through bird hosts and mosquitoes. The mosquito vectors of West Nile virus, including wetland-breeding species such as *Culex tarsalis*, increase egg laying and larval growth rates in response to nutrient enrichment. Several plausible but undocumented effects of nitrogen enrichment of ecosystems merit further study, including greater toxicity of harmful algal blooms, increases in allergy-provoking pollen from weedy plants like ragweed, and more favorable conditions for snails that harbor the fluke parasite that causes swimmer's itch.

MITIGATION OPPORTUNITIES IN AGRICULTURE

The challenge of supplying sufficient nitrogen to crops has figured prominently in the development of agriculture. Since the time of Aristotle, farmers valued legumes for their ability to restore and maintain soil fertility, although the role of legumes in fixing nitrogen was not known until the 19th century. At that time, supplemental nitrogen sources such as Chilean saltpeter (sodium nitrate) and bat guano also came into use. Nevertheless, the lack of nitrogen often kept crop yields low. It was not until development of the Haber-Bosch synthesis process that nitrogen limitation was finally overcome for most of the world's agriculture, although fertilizers are still often not available or affordable in sub-Saharan Africa. Synthetic nitrogen fertilizer use began in the U.S. following World War II, and rapidly increased during the 1960s and 1970s. Since then, nitrogen fertilizer consumption has increased only slightly each year, now approaching 12 million metric tons of nitrogen per year (Figure 7).

Increased nitrogen fertilizer application has increased crop harvests, although improved soil conservation, nutrient, pest and water management, and crop varieties have also contributed to yield increases. These practices have contributed to overall improved fertilizer use efficiency. For example, corn yields have steadily increased at an average of 1.9% per year since 1960 (Figure 7), while nitrogen fertilizer average application rates to corn have remained relatively constant during the last 30 years at about 145 kg nitrogen per hectare.

Despite improvements in crop production and nitrogen fertilizer efficiency, large losses of reactive nitrogen to the environment are still common from agricultural systems through transport of nitrate to groundwater or surface waters and through emissions of nitrogen gases to the air. Such nitrogen losses are especially common in regions where artificial subsurface drainage systems remove excess soil water from farms established on natural wetland areas. This loss is partly due to a timing problem. Large amounts of nitrate are present in the soil in the spring, but the crop either has not yet been planted or is still too small to take up much of the nitrogen, so that snow melt and spring rains often wash much of the nitrate away into groundwater and streams. Additional losses occur by release of ammonia, nitric oxide, and nitrous oxide gases to the atmosphere.

Much of the U.S. crop production is fed to animals for meat and dairy production. Most livestock only utilize about 30% of the nitro-

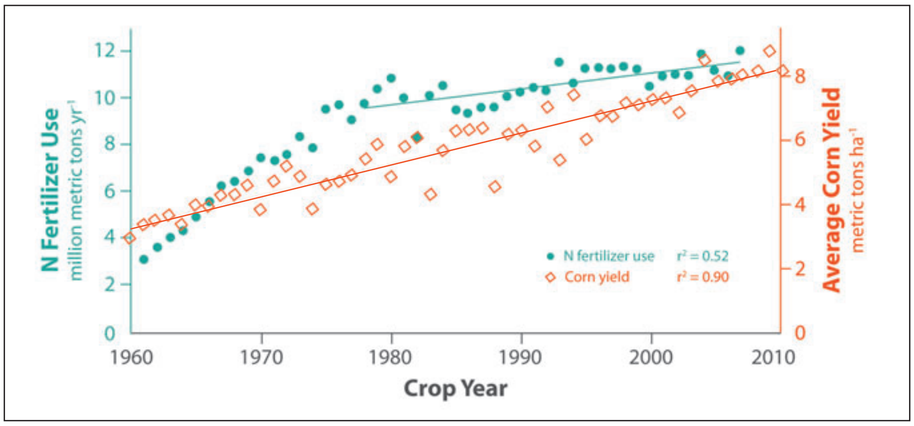


Figure 7. U.S. fertilizer-N consumption rate increased rapidly in the 1960s and 1970s, but has since slowed to 0.6% per year since 1978 (blue circles and blue regression line). In contrast, average corn yield continues to increase at a rate of 1.9% per year (red diamonds and red regression line), indicating improved nitrogen use efficiency. Data from Association of American Plant Food Control Officials, The Fertilizer Institute, and the USDA National Agricultural Statistics Service (NASS).

gen in their feed; the rest is excreted in manure (feces and urine). Prior to modern agriculture, most farms had animals and diversified crop rotations, where nitrogen fixed by legumes would be used by the next year's grain crops to feed people and animals, and the manure was applied back to the land to fertilize crops. In contrast, modern animal production is often located hundreds to thousands of miles away from primary crop producing regions. For example, intensive hog production in North Carolina requires grain imports from the Midwest, but it is not economically viable to ship the hog manure back to the Midwest for recycling as fertilizer. About 50% of the manure nitrogen is lost during collection, handling, and land application, mostly as ammonia and nitrous oxide gases. As animal production systems continue to expand and intensify, improved manure handling and distribution will be key to reducing nitrogen losses.

Our current food production system poses a dilemma. We have constructed an economically efficient system that produces relatively cheap food, which people want, but at a high cost to the environment, particularly with respect to nitrogen. How can we reduce nitrogen losses from agriculture to maintain clean air and water, which people also want? Many existing mitigation strategies have been demonstrated to reduce nitrogen losses to the environment from both farms and livestock production systems (Table 3), potentially reducing nitrogen losses within the current

Table 3. Agricultural practices that reduce reactive N outputs. Some would require changes in current farm systems, some might create other environmental problems, and some also yield co-benefits of other improved ecosystem services.

Mitigation strategy	Feasible under current system?[1]	Could substitute one environmental loss for another?[2]	Additional ecosystem services
Fertilizer management			
Timing (fall versus spring; small, frequent applications; use of urease and nitrification inhibitors)	Yes	Yes	No
Rate	Yes	Yes	No
Form of N (slow or controlled release)	Yes	Yes	No
Placement	Yes	Yes	No
Manure management			
Timing, rate, & placement	Yes	Yes	No
Manure treatment (chemical & physical)	Yes	Yes	No
Alternative use (bioenergy)	Yes	Yes	Yes
Ecological			
Complex rotations	No	No	Yes
Cover crops	No	No	Yes
Legumes	No	No	Yes
Perennials	No	No	Yes
Integration of animal agriculture	No	No	Yes
Edge-of-field			
Controlled drainage	Yes	Yes	No
Tile bioreactors	No	Yes, but not likely	No
Denitrification walls	No	Yes	No
Tile-fed wetlands	Yes	Yes, but not likely	Yes
Landscape			
Buffer strips	Yes	Yes	Yes
Forested riparian zones	Yes	Yes	Yes
Herbaceous riparian zones	Yes	Yes	Yes
Wetlands	Yes	Yes, but not likely	Yes
Meandering stream channels	No	Yes	Yes
Two-stage ditches	No	Yes	Yes

[1] "Feasible" means that this practice could be accomplished without changing the current agricultural subsidy system.
[2] This strategy may decrease N loss in one form or pathway but inadvertently increase loss in another form or pathway.

agricultural system by 30 to 50% or more. However, improved infrastructure for fertilizer application and manure handling, better education and training of crop advisers, and willingness by farmers to adopt these practices are needed. An ecologically intensive approach that integrates complex crop rotations, cover crops, perennials, and improved animal operations, could also reduce nitrogen losses by as much as 70-90%.

Another approach is to treat nitrogen as it leaves agricultural systems at "edge-of-field" operations, such as bioreactors or constructed treatment wetlands. Similarly, landscape approaches could better utilize sinks for nitrogen that escapes farms, such as streamside buffer strips (planted with grasses or trees), natural wetlands, and more complex stream habitats. These approaches allow current agricultural production practices to continue, but remove reactive nitrogen by plant and microbial uptake and denitrification before environmental and health impacts occur. In addition, these strategies often provide other ecological services, such as flood control, carbon sequestration, wildlife habitat, and recreational access (Table 3).

Nitrogen use in most row crop agriculture is currently designed to ensure that yields and profits are not reduced due to lack of nitrogen. Another approach would be to optimize for nitrogen use efficiency – i.e., getting the greatest crop yield for the amount of nitrogen fertilizer applied – which would result in less nitrogen loss to air and water. All of the practices in Table 3 could optimize agricultural production based on nitrogen use efficiency, are currently available to U.S. farmers and ranchers, and could be implemented now (see Iowa and Nebraska case studies in Box 2), but most are not used under the current voluntary, incentive-based system. Nearly all of these practices involve additional costs or risks to farmers, who are unlikely to adopt them without some form of support, incentive, or regulation.

The Conservation Effects Assessment Program report for the Upper Mississippi River Basin indicated that progress on con-

Box 2. Case Studies of Potentials for Reduced Nitrogen Loss from US Agriculture

Nebraska regulation and education example: Groundwater contamination with nitrate has been a problem in Nebraska (Figure 5), where irrigated corn is grown. Beginning in 1987, a phased regulation and education program was carried out in the Central Platte Natural Resources District, demonstrating that increases in groundwater nitrate concentrations could be stopped, and in some areas reversed. Regulations focused on nitrogen fertilization amounts and timing (banning fall or winter applications, requiring spring split applications or use of a nitrification inhibitor), as well as accounting for all sources of nitrogen when calculating fertilizer amounts needed. Fertilizer nitrogen rates were unchanged, even as yields increased. Improved application timing accounted for an approximate 20% decline in groundwater nitrate, because more nitrogen was removed in the crop harvest. Conversion of furrow to sprinkler irrigation permitted water to be applied uniformly with better control over the nutrient levels. Cost-sharing was available to help producers buy the equipment. Changes in water application were responsible for about half the observed decline in groundwater nitrate concentrations. However, based on the rates of decline in groundwater nitrate, it may be decades before concentrations fall below the 10 milligram nitrate-nitrogen per liter drinking water standard. More information on this case study can be found in Exner *et al*. (2010. *The Scientific World Journal* 10:286-297).

Iowa case study: This is a hypothetical example of how several practices might be used to reduce nitrogen loads. The Cedar River watershed in eastern Iowa is cropped in mostly corn and soybeans, with tile drainage on about half the watershed. In 2006, the Iowa Department of Natural Resources called for a 35% reduction in the 25,910 metric tons of nitrogen per year load coming from the watershed. Figure 8 shows how this reduction could be achieved by adopting several currently available management practices, implemented over a 20-year period. The 20-year estimated cost for achieving the reduction is $71 million per year, or $7.78 per kg nitrogen removed per year. For comparison, total spending of USDA's Environmental Quality Incentives Program in Iowa in 2009 was $25 million; the cost for removing a kilogram of nitrogen at the Des Moines water works was about $10; and the price of nitrogen fertilizer was $0.72 per kilogram in 2010.

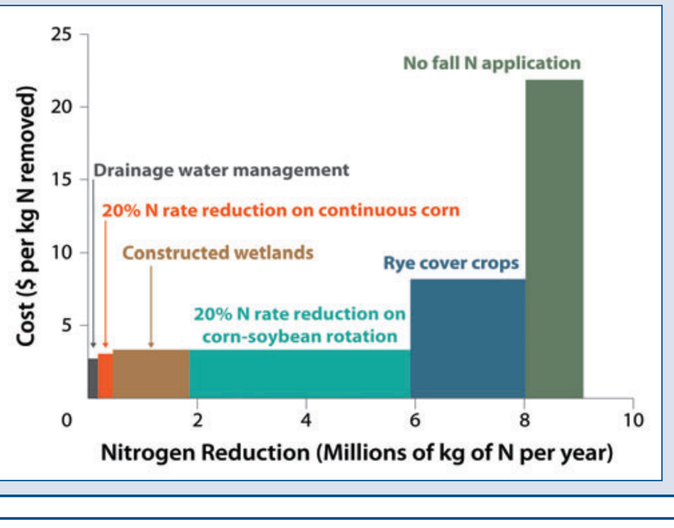


Figure 8. Several practices taken together could lead to a 35% reduction in nitrogen loads from the Cedar River watershed. In this analysis of costs, the width of each bar indicates the amount of nitrogen reduction that could be achieved by each mitigation practice and the height of the each bar indicates its cost per kilogram of nitrogen removed. The most cost-effective interventions are on the left and the most expensive ones on the right. This figure is drawn from data published in Helmers and Baker (2010). Proceedings of the 22nd Annual Integrated Crop Management Conference. p.195.

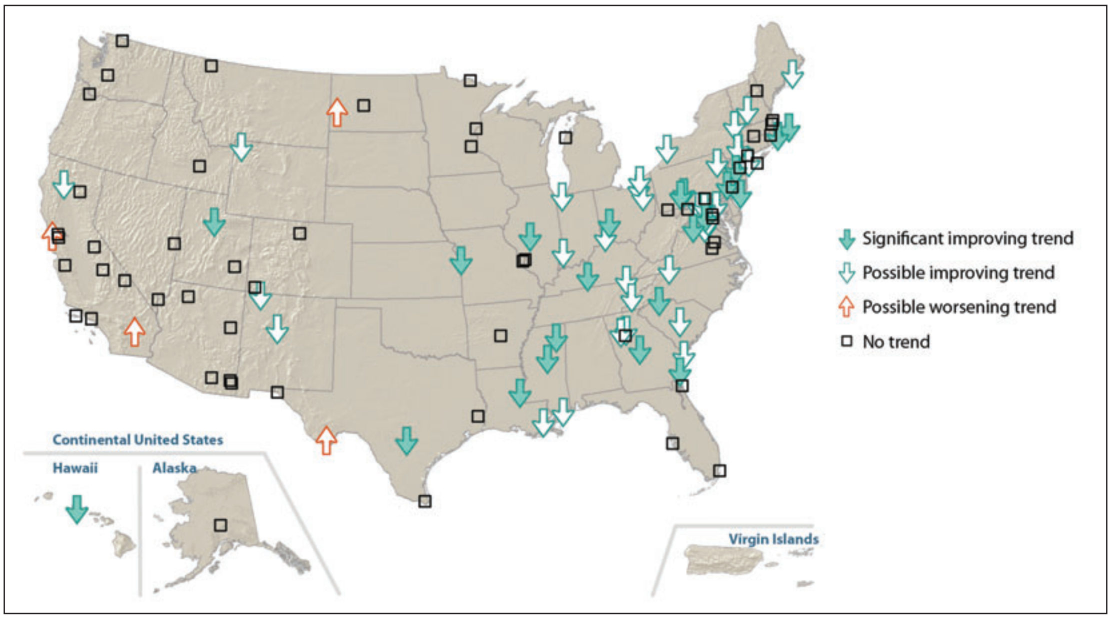
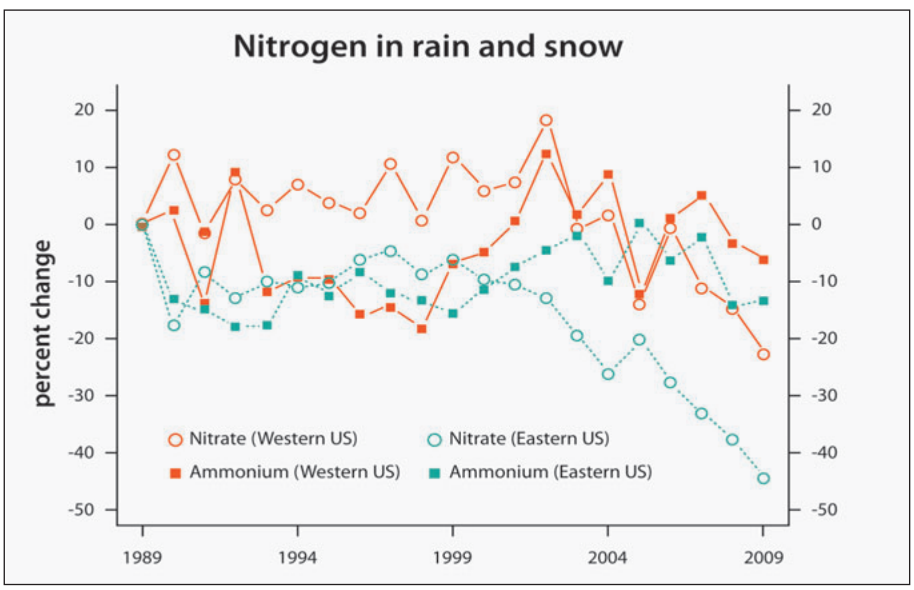


Figure 9. Trends in ozone concentrations from 1999-2008 in national parks show that regional nitrogen oxide control programs have resulted in significant ozone decreases in many areas of the East. The West has seen less improvement. This figure is based on a National Park Service Natural Resource Report, Air Quality in National Parks (NPS/NRPC/ARD/NRR2010/266).

trolling surface runoff and erosion has been much more widespread than progress on reducing nitrogen losses from this region. Practices implemented in USDA programs are estimated to have reduced erosion and phosphorus and pesticide losses by 69, 49, and 51%, respectively, but have only reduced subsurface nitrate loss by 5%. If conservation practices were focused on the nitrate reduction techniques could similar progress be achieved? Model results showed that if all 14.6 million hectares of the region's agricultural land were treated with both erosion control and nutrient management conservation practices, total nitrogen losses could be reduced by 43%. Although the specific numbers are subject to the limitations of the modeling approach, the survey clearly showed that major gains are possible by applying current nutrient management techniques.

Figure 10. Nitrate concentration in rain and snow in the eastern U.S. (blue circles) has decreased due to air pollution regulations on automobiles, electrical generation plants, and industry and due to technological innovation. Less progress has been made in the western U.S. (red circles). Ammonium, which comes mostly from agriculture, is unregulated, and no consistent changes have been measured (red and blue squares).



MITIGATION OPPORTUNITIES IN TRANSPORTATION, ENERGY, AND INDUSTRIAL SECTORS

The most progress made on reducing releases of reactive nitrogen to the environment in the U.S. has stemmed from implementation of the Clean Air Act. Between 1990 and 2008, national nitrogen oxide emissions decreased 36% (Table 1), with the largest decreases from mobile sources (e.g., cars, trucks, buses, construction equipment) and electrical generation.

These sources contribute differently to nitrogen oxide emissions depending upon the region of the country. The preponderance of coal-fired power plants in the eastern U.S. create more nitrogen oxide emissions than in the West. The Cross-State Air Pollution Rule is expected to decrease nitrogen oxide emissions from electrical generation in the East by over 50% from 2005 levels by 2014 as states work to meet the National Ambient Air Quality Standards for fine particulates and ozone. Mobile source nitrogen oxide emissions will continue to decline everywhere as new vehicles hit the road with tighter emission standards under current federal regulations (California, the exception, has stricter requirements). Automobile emissions are predicted to decrease about 70% and off-road machinery emissions by 40% from 2002-2018.

Due to the overall decreasing trend in nitrogen oxide emissions, related air pollution has changed, with substantial improvements seen in ozone and fine particle concentrations and deposition of oxidized nitrogen in many regions:

- Nitrogen dioxide concentrations – The average annual concentration of nitrogen dioxide decreased approximately 40% between 1980 and 2006, and is currently about 20 parts per billion (ppb). Measurements near busy roadways and inside vehicles, however, show substantially higher concentrations (40 ppb to greater than 100 ppb).

- Ozone concentrations – Nationally, ground-level ozone concentrations were 10% lower in 2008 than in 2001. However, as shown in Figure 9, this progress is predominantly located in the East, with little or no consistent trend in the West. More than 100 million Americans live in areas with ozone levels still above the current EPA standards.

- Fine particulates – Nationally, annual fine particulate ($PM_{2.5}$) concentrations declined by 17% between 2001 and 2008. Most areas of the U.S. have concentrations below the current EPA regulatory levels, although more than 70 million live where $PM_{2.5}$ levels are still above the current EPA standards.

- Deposition of nitrogen – Nitrate and ammonium concentrations in rain and snow decreased by 10-20% between 1989-1991 and 2006-2008. Nitrate concentrations reflect the significant decreases in nitrogen oxide emissions in the East, with smaller decreases in the West (Figure 10). No consistent change in ammonium concentrations is apparent.

Ammonia emissions result primarily from agricultural practices, including the use of fertilizers and confined livestock operations. Agriculture contributed over 80% of the national ammonia emissions in 2008. Less than 10% of the nation's ammonia is emitted as a byproduct of technologies used to control nitrogen oxide emissions from electric utilities and automobiles. In contrast to expected decreases in nitrogen oxide emissions, ammonia emissions are expected to increase significantly in the central and eastern U.S. and remain stable in the West from 2002-2018. The growing contribution of ammonia emissions to nitrogen deposition and to fine particle formation is an issue of particular concern. As nitrogen oxide emissions decrease, the fraction of nitrogen deposition attributable to ammonia will increase, becoming 60% by 2020. Whereas the majority of nitrogen oxide emissions fall under EPA air pollution regulations, the ammonia emissions from agriculture are mostly unregulated. Achieving stricter fine particulate standards for human health and reductions in nitrogen deposition to ecosystems will be difficult without ammonia emission regulation.

CONCLUSIONS

Increasing demands for food, fiber, and fuel virtually assure that society will face growing challenges for how to meet those demands while minimizing unintended environmental and human health impacts. Air pollution regulations in the U.S. have demonstrated that reductions of nitrogen oxide emissions have been technologically, socially, and economically viable, followed by measurable improvements in air quality and environmental and human health. Overall, the saga of nitrogen in air pollution is at least a partial environmental policy success story for the U.S., and more reductions and improvement are expected. However, the story has not ended, and there remain areas of poor air quality and high deposition due to nitrogen oxide and ammonia emissions. Though technologies exist to significantly reduce agricultural releases of reactive nitrogen, numerous cultural and economic barriers stand in the way. Growing evidence of human health impacts of nitrate ingestion, inhalation of nitrogen dioxide, ozone, and fine particles, and effects of reactive nitrogen on human disease carriers is likely to bring more attention to the trade-offs between the positive benefits of good human nutrition and the negative consequences of inefficient use of nitrogen to produce food. Because nitrogen is a key element in virtually all biological processes, evidence for environmental impacts is accumulating, such as climate change, biodiversity, spread of invasive species, fire risk, fisheries management, and ecosystem health.

While our ability to quantify transfers of nitrogen across land, water, and air has improved since the first publication of this series, perhaps a more important development is a growing recognition of the need for integration of natural and social sciences to address the consequences of increasing reactive nitrogen in the environment. Agronomists, soil scientists, engineers, atmospheric chemists, meteorologists, terrestrial and aquatic ecologists, biogeochemists, economists, and epidemiologists are now working together in efforts such as this publication and planned nitrogen assessments to evaluate consequences and mitigation options from multiple perspectives. In many cases, we already have sufficient scientific understanding and appropriate technologies available to reduce undesirable nitrogen releases into the environment. However, socio-economic and political considerations pose serious impediments, partly due to lack of clarity of the complex trade-offs among human health, ecosystem health, and economic costs and benefits. Because these issues of reactive nitrogen do not fit neatly under the rubric of a single governmental agency or discipline, such as environment, agriculture, energy, or health, these cross-sector and cross-discipline collaborations will be needed to build effective solutions.

GLOSSARY. KNOW YOUR NITROGEN

N_2	Atmospheric nitrogen, also called dinitrogen, formed from two nitrogen atoms. An inert, harmless gas not usable by most life forms. Makes up 78% of the atmosphere.
Nr	Reactive nitrogen. All forms of N other than N_2. An essential nutrient for all life and also reactive in the atmosphere. Produced naturally by biological N fixation (see definition below) and lightning. Also produced by humans through fertilizer and munitions manufacturing and burning of fossil fuels.
N_2O	Nitrous oxide. A potent greenhouse gas and a reactant that destroys stratospheric ozone. Produced mostly by bacteria in soils, sediments, and water bodies, also by fire and industrial processes such as nylon production.
NH_x	Reduced-N. Any of the forms of N that have a reduced oxidation state relative to N_2 (e.g., NH_3, NH_4^+, urea, amino acids).
NH_3	Ammonia. A gas emitted from soil and manure and as a minor component of automobile exhaust. Also used as fertilizer. Contributes to smog and haze and inadvertent nutrient additions to downwind ecosystems.
NH_4^+	Ammonium. A soluble form of ammonia found in fertilizers, soils, water bodies, and in the atmosphere. Can contribute to creation of algal blooms and soil acidification.
NO	Nitric oxide. A precursor to ozone formation. A gas created mostly from fire and fossil fuel burning, but also emitted from soil.
NO_2	Nitrogen dioxide. A gas that reacts in complex photochemical reactions involving ozone formation and destruction. Produced when NO is oxidized in the atmosphere and from fire and fossil fuel burning. A regulated pollutant linked to human respiratory disease.
NO_X	Nitrogen oxides. Shorthand for NO + NO_2. Created mostly by fossil fuel burning but also emitted from soils.
NO_y	Oxidized-N. Any of the oxides of N (e.g., NO, NO_2, NO_2^-, NO_3^-).
NO_2^-	Nitrite. A soluble form usually found in low concentrations in soils and water bodies and within the human body. Generally toxic to most organisms when present at high concentrations.
NO_3^-	Nitrate. A soluble form found in fertilizers, soils, water bodies, and in the atmosphere. A regulated pollutant in drinking water; can cause algal blooms.
NOCs	N-nitroso compounds such as N-nitrosamines and N-nitrosamides that are produced within the animal (and human) gut from NO_2^- and are potentially carcinogenic.
N deposition	Reactive nitrogen, mostly as NH_4^+, NO_3^-, and DON, that falls onto water and land from the atmosphere, either carried by rain, snow or aerosol particles.
BNF	Biological N fixation. The process of converting atmospheric nitrogen (N_2) by bacteria, fungi, and bluegreen algae into reactive forms, that are usable by plants and animals, including humans.
Nitrification	An important two step process, carried out mostly by microorganisms in soils and water bodies, involving the oxidation of NH_4^+ to NO_2^- which is then further oxidized to NO_3^-.
Denitrification	The multi-step conversion of reactive NO_3^- to NO_2^-, NO, N_2O, and ultimately to unreactive N_2, carried out by bacteria in soils, sediments, and water bodies. Typically occurs in low oxygen situations.
DON	Dissolved organic nitrogen. Soluble organic forms of N that occur in soils, groundwater, and water bodies; can cause algal blooms.
Inorganic N	Generally refers to NH_4^+ and NO_3^- but also includes any form of Nr that is not bound to carbon in an organic molecule.
PM	Particulate matter – fine particles, including aerosols, found in the atmosphere, often containing NH_4^+ and/or NO_3^-. Very fine particulate matter of only 2.5 microns in diameter, called $PM_{2.5}$, is a regulated pollutant because it can lodge in the lungs and cause respiratory disease.
Synthetic N	Reactive N created by the industrial Haber-Bosch process of reducing N_2 to NH_3 under high temperature and pressure. Includes fertilizer N, explosives, and some other industrial uses.
Urea	A commonly used form of synthetic N fertilizer, which usually quickly breaks down in the soil to ammonia or ammonium. Animal-urine (including human urine) contains a similar compound called uric acid. Can contribute to creation of algal blooms.

Suggestions for Further Reading

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