FRONTIERS 2018/19
Emerging Issues of Environmental Concern
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In the first decade of the 20th century, two German chemists – Fritz Haber and Carl Bosch – developed a way to produce synthetic nitrogen cheaply and on a large scale. Their invention spurred the mass production of nitrogen-based fertilizers, and thus transformed farming around the globe. It also marked the beginning of our long-term interference with the Earth’s nitrogen balance. Every year, an estimated US$200 billion worth of reactive nitrogen is now lost into the environment, where it degrades our soils, pollutes our air and triggers the spread of “dead zones” and toxic algal blooms in our waterways.

It’s no wonder that many scientists are arguing that “the Anthropocene” should become the official name of the current geological era. In just a few decades, humankind has caused global temperatures to rise 170 times faster than the natural rate. We have also deliberately modified more than 75 per cent of the planet’s land surface, and permanently altered the flow of more than 93 per cent of the world’s rivers. We are not only causing drastic changes to the biosphere, we are also now capable of rewriting – and even creating from scratch – the very building blocks of life.

Every year a network of scientists, experts and institutions across the world work with UN Environment to identify and analyze emerging issues that will have profound effects on our society, economy and environment. Some of these issues are linked to new technologies that have astonishing applications and uncertain risks, while others are perennial issues, such as the fragmentation of wild landscapes and the thawing of long-frozen soil. Another issue, nitrogen pollution, represents an unintended consequence of decades of human activity in the biosphere. While the final issue analyzed here, maladaptation to climate change, highlights our failure to adequately and appropriately adjust to the shifting world around us.

There is some good news to report. As you can read in the pages that follow, a holistic approach to the global challenge of nitrogen management is beginning to emerge. In China, India and the European Union, we are seeing promising new efforts to reduce losses and improve the efficiency of nitrogen fertilizers. Ultimately, the recovery and recycling of nitrogen, as well as other valuable nutrients and materials, can help us to farm cleanly and sustainably, a hallmark of a truly circular economy.

The issues examined in Frontiers should serve as a reminder that, whenever we interfere with nature – whether at the global scale or the molecular level – we risk creating long-lasting impacts on our planetary home. But by acting with foresight and by working together, we can stay ahead of these issues and craft solutions that will serve us all, for generations to come.

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The Nitrogen Fix: From nitrogen cycle pollution to nitrogen circular economy

The global nitrogen challenge

The UNEP 2014 Year Book highlighted the importance of excess reactive nitrogen in the environment. Its conclusions are alarming. This is not just because of the magnitude and complexity of nitrogen pollution, but also because so little progress has been made in reducing it. Few of the solutions identified have been scaled up, while the world continues to pump out nitrogen pollution that contributes significantly to declines in air quality, deterioration of terrestrial and aquatic environments, exacerbation of climate change, and depletion of the ozone layer. These impacts hinder progress toward the Sustainable Development Goals as they affect human health, resource management, livelihoods and economies. Yet there are signs of hope. The past four years have seen a transformation in approaches to managing nitrogen pollution. These include new thinking for both consumption and production in order to seriously address the nitrogen problem.

Nitrogen is an extremely abundant element in the Earth’s atmosphere. In the form of the N₂ molecule, nitrogen is harmless, making up 78 per cent of every breath we take. The two nitrogen atoms are held together by a strong triple bond (N≡N), making it extremely stable and chemically unreactive. The planet benefits because N₂ allows a safe atmosphere in which life can flourish, while avoiding the flammable consequences of too much oxygen. The environmental interest in nitrogen focuses on the conversion of N₂ into other chemically reactive forms. For simplicity, scientists refer to all other nitrogen forms as “fixed” or “reactive nitrogen” (Nr). There are many types ofNr, with many different effects –
beneficial and harmful – and this is where the complications arise. Reactive nitrogen is essential for all life on earth. For example, ammonia (NH₃) is the foundation for amino acids, proteins, enzymes and DNA, and thus central to the metabolism of all life forms. Similarly, nitric oxide (NO) acts as a key biological signalling compound, while ammonium (NH₄⁺) and nitrate (NO₃⁻) are the major nutrient forms of nitrogen essential for plant growth. This points to a primary benefit of N₂ compounds in that they help to produce food and animal feed. Using the Haber-Bosch process of artificial nitrogen “fixation”, humans have massively scaled up the manufacture of fertilizers – ammonia, urea and nitrates – to sustain a growing world population. In parallel, humans benefit from the natural biological fixation of N₂ to N, by specialist bacteria found in soil and associated with the roots of legume crops.

Against these benefits must be set the numerous losses of ammonia, nitrate, nitric oxide (NO), nitrous oxide (N₂O) and many other forms of N₂ pollution that cause multiple impacts on the environment. These may occur directly following fertilizer use, while animal manure, human excreta and other organic wastes also cause huge losses of N₂ to the environment. Although the fraction of N₂ lost to the environment from biological nitrogen fixation is thought to be smaller than from many fertilizers, once excreted from animals and humans, both sources contribute to N₂ pollution. Reactive nitrogen is also yielded as a by-product of human activities. For instance, fossil fuel and biomass combustion processes release NO and NO₂, collectively called NOX. While major efforts have been made to reduce NOX from vehicles and energy generation, emissions are still escalating in rapidly developing parts of the world. Altogether, humans are producing a cocktail of reactive nitrogen that threatens health, climate and ecosystems, making nitrogen one of the most important pollution issues facing humanity. Yet the scale of the problem remains largely unknown and unacknowledged outside scientific circles.

Different forms of nitrogen in the environment

**Di-Nitrogen (N₂)**
- **Source**: N₂ makes up 78% of air we breathe
- **Benefits**: N₂ maintains stable atmosphere for life on Earth. It makes the sky appear blue.
- **Effects**: N₂ is harmless and chemically unreactive

**Ammonia (NH₃)**
- **Source**: Manure, urine, fertilizers and biomass burning
- **Benefits**: NH₃ is the foundation for amino acids, protein and enzymes. Ammonia is common used as fertilizer.
- **Effects**: NH₃ causes eutrophication and affects biodiversity. It forms particulate matter in air which affects health.

**Nitric Oxide (NO) and Nitrogen Dioxide (NO₂)**
- **Source**: Combustion from transport, industry and energy sector. NO and NO₂ are collectively known as NOX.
- **Benefits**: NO is essential in human physiology. NO₂ has no known benefit.
- **Effects**: NO and NO₂ (or NO₃) are major air pollutants, causing heart disease and respiratory illness.

**Nitrate (NO₃⁻)**
- **Source**: Wastewater, agriculture and oxidation of NOX
- **Benefits**: Widely used in fertilizers and explosives
- **Effects**: It forms particulate matter in air and affects health. In water, it causes eutrophication.

**Nitrous Oxide (N₂O)**
- **Source**: Agriculture, industry and combustion
- **Benefits**: Used in rocket propellants and in medical procedure as laughing gas
- **Effects**: N₂O is a greenhouse gas – 300 times more powerful than CO₂. It also causes depletion of stratospheric ozone.
The knowns and known-unknowns of nitrogen

Both the cycling of nitrogen compounds and the human impacts are well documented.\textsuperscript{4,12,27,28} Yet compared with the role of carbon in climate change, there has been little public debate about the need to take action on nitrogen. The increased levels of N$_r$ compounds in the air above cities and above agricultural areas are measurable, for example as NO$_x$, NH$_3$, and fine particulate matter, or PM$_{2.5}$. Elevated levels of NO$_3^-$ in groundwater under agricultural areas in several regions around the world and in rivers downstream of cities with little or no sewage treatment are equally quantifiable. Atmospheric concentrations of the greenhouse gas N$_2$O are accumulating at an accelerating rate. The clear message is that humans are massively altering the global nitrogen cycle, causing multiple forms of pollution and impacts, making N$_r$ a key pollutant to tackle, from local to global scales.\textsuperscript{22}

The European Nitrogen Assessment identified five key threats of nitrogen pollution: water quality, air quality, greenhouse-gas balance, ecosystems and biodiversity, and soil quality.\textsuperscript{4} It highlighted that nitrogen pollution itself is not a new problem, but that nitrogen management needs to be part of the solution to many existing environmental problems. Concerning food production, global nitrogen use is extremely inefficient.\textsuperscript{20,29} Considering the whole food chain, only around 20 per cent of the N$_r$ added in farming ends up in human food.\textsuperscript{11,17} This implies that a worrying 80 per cent is wasted as pollution and N$_2$ to the environment, demonstrating that N$_r$ pollution represents a massive loss of valuable resources.

While past efforts have focused on a fragmented approach between different N$_r$ forms, considering them all together has several advantages. First, it allows us to start looking at the synergies and trade-offs between N$_r$ benefits and different types of N$_r$ pollution. Secondly, and just as important, it encourages us to quantify the societal cost of all the impacts of nitrogen pollution in order to inform policy and the general public.\textsuperscript{13,30} Cost estimates can help guide mitigation policies, however, the true cost of N$_r$ pollution is really a known-unknown, since

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The average concentration of nitrogen dioxide (NO$_2$) in the troposphere in 2014

![Map of nitrogen dioxide concentration](image)

NO$_2$ is a gas emitted mainly from cars, power plants and industrial activity. NO$_2$ and other NO$_x$ react with other air pollutants to form harmful ground-level ozone, acid rain and particulate matter.

*Photo credit: NASA Goddard Space Flight Center*
impacts tend to be fundamentally “non-commensurable”, that is, it is hard to find a common measure. Comparing health, ecosystem and climate costs is like trying to compare apples and oranges. The available estimates, based on the willingness of people to reduce the risks of Nr pollution, or estimates of costs to ecosystems and healthcare services, are nevertheless informative and indicate a global cost of around US$340 billion to US$3,400 billion annually.11

A much simpler calculation, however, can be even more powerful. Globally, around 200 million tonnes of Nr resource is lost to the environment per year as Nr and N2.11,28 If we multiply this by a nominal fertilizer price of US$1 per kg N, then the total amounts to a cash loss of around US$200 billion per year. This represents a strong motivation for action. This message is also relevant for areas with too little Nr, such as sub-Saharan Africa, where reducing Nr pollution would help limited available Nr sources to go further in supporting food production.31 The conversion of Nr compounds back to N2 (termed “denitrification”) does not provide a safe way to avoid Nr pollution. Rather, it implies a need for fresh Nr inputs, tending to increase pollution. Indeed, all N2 and Nr losses need to be reduced if economy-wide nitrogen use efficiency (NUE) is to be increased.
Innovations and Risks

Sewage, wastewater, and food waste contain proteins.

About 16% of protein is nitrogen.

Fossil fuel combustions in the transport, energy and industrial sectors

High temperature combustion of coal, petroleum, and natural gas releases a large amount of N₂ in the form of NO and NO₂, collectively known as NOₓ.

The transport sector contributes to more than 65% of NOₓ emissions.

Fossil fuel combustion is responsible for 13% of the anthropogenic fixation of N₂ to N₂.

Fertilizer manufacture

The Haber-Bosch process was invented more than 100 years ago to meet the growing need for mass industrial production of N₂ fertilizers and nitrogen-based explosives. Like the natural nitrogen fixation by bacteria, it artificially fixes atmospheric N₂ into ammonia (NH₃).

Biological nitrogen fixation in crop cultivation

In nature, N₂ can be converted into N₂ through lightning and biological nitrogen fixation by nitrogen-fixing bacteria.

N₂ can also be biologically converted back to N₂ through the denitrification process by anaerobic bacteria. These natural processes keep a balanced cycle of nitrogen, but increased cultivation of nitrogen-fixing crops such as legumes has significantly added N₂ inputs and losses into the environment.

Waste

In addition to the food production and combustion of fossil fuels being key to mitigating N₂ emissions, the role of waste management is also significant in preventing more N₂ from cascading through the environment.

Unlike sewage and wastewater, a large amount of food waste is avoidable.

Cereals, fruits, vegetables, roots, and tubers make up the largest volumes of food losses and waste.

Every year about 1/3 of the food produced globally for human consumption is lost or wasted.
Nitrogen Oxides, NOx, affect urban air quality. Acute and chronic exposures to NO2 are linked to respiratory and cardiovascular diseases and mortality. Children, the elderly and persons with asthma are vulnerable to NO2.

80% of global Ammonia, NH3, emission comes from human activities, largely fertilizer applications and animal husbandry.

Nearly 80% of anthropogenic N2O emissions come from agriculture.

50% of nitrogen fertilizers added to farm fields ends up as pollution, or is wasted by denitrification back to N2.

80% of air is N2.

50% of nitrogen fertilizers added to farm fields ends up as pollution, or is wasted by denitrification back to N2.

In 2016 the world used 105 million metric tons of nitrogen fertilizers, or the equivalent to 4.2 million truckloads of fertilizers.

Long-term application of ammonium-based fertilizers causes soil to become acidic, negatively affecting crop production.

Ammonia pollution causes eutrophication, soil acidification and direct toxicity in organisms, reducing species richness and diversity.

Nitrous Oxide N2O is a greenhouse gas – 300 times more potent than CO2. It also damages the ozone layer.

Ammonia and nitric acid react to form ammonium nitrate in particulate matter, increasing risks of respiratory and heart disease.

Nitrogen is essential for every living organism. It is part of DNA, amino acids, proteins, chlorophylls, enzymes, vitamins and many other organic compounds.

N2 is abundant but metabolically unusable by living organisms except for some microbes. To make nitrogen usable, N2 must be converted into other forms of nitrogen or reactive nitrogen, Nr.

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80% of nitrogen fertilizers added to farm fields ends up as pollution, or is wasted by denitrification back to N2.
Policy fragmentation and circular economy solutions

Just as nitrogen science has become fragmented between environmental compartments and $N_r$ forms, the same is true of nitrogen policies. The impacts of $N_r$ cross multiple policy domains, such as air pollution, climate, freshwater and marine policy, biodiversity, health and food security. While this fragmentation is widely seen in the domestic policies of many countries, it is equally apparent in the Sustainable Development Goals (SDGs). Examination of the SDGs and the underlying indicators shows that nitrogen is relevant almost everywhere, but almost equally invisible. Only in the proposed indicator for SDG 14.1 on life below water is a nitrogen-related indicator currently being developed. Proposals to include NUE or nitrogen losses in the set of SDG indicators have not been adopted thus far.

The consequences of this policy fragmentation across the nitrogen cycle can easily be seen in policy trade-offs. For example, policies to reduce $NO_3^-$ pollution of water in the European Union led to the prohibition of manure application to land in winter “closed periods”. However, this led to an increase in spring-summer manure application, which in turn resulted in an increased peak in atmospheric ammonia concentrations. This temporal effect was only partly avoided in a few EU countries, by requiring low $NH_3^-$ emission application of manure. Another example concerns the recommendation to bring cattle indoors to reduce climate-relevant emissions of $N_2O$. However, even with the best technical measures to moderate emissions, this would generally lead to increased $NH_3$ emissions. Such trade-offs are also relevant for combustion sources. For example, the introduction of catalysts to reduce $NO_x$ emissions in the 1990s increased $N_2O$ and $NH_3$ emissions.

These examples illustrate the urgent need to bring nitrogen science and policies together across multiple threats. For example, the Chinese Government’s 2015 “Action Plan for the Zero Increase of Fertilizer Use” aimed to prevent the growth in synthetic fertilizer use by 2020 without reducing food production, which would limit all forms of $N_r$ pollution. It has been suggested that a next step should focus on socioeconomic barriers associated with farm size, innovation and information transfer.

Mobilization of the circular economy for nitrogen and other nutrients starts on farms, where reducing losses allows a more effective delivery of nutrients to support crop growth. A major need here is the provision of practical tools to guide farmers on reducing nitrogen inputs to account for reduced nitrogen pollution losses, achieved by implementing mitigation methods. These should be supported by appropriate soil testing to give farmers confidence in fine-tuning nutrient levels.

However, there is also massive potential for scaling up reuse of nitrogen and other nutrients for the production of value-added, marketable products. Just as major investment is transforming society for a “low-carbon economy” (e.g. through renewable energy sources), the value of nitrogen implies a major economic opportunity through investment toward a “nitrogen circular economy”.

Nitrogen, nutrients and the circular economy

The Circular Economy Package adopted by the European Union in 2015 aims to maximize the efficiency of resource use in all steps of the value chain – production, consumption, waste management and recycling of secondary raw materials. The plan recognizes the management and trade of organic and waste-based fertilizers as key in the recovery and recycling of bio-nutrients, such as nitrogen and phosphorus, back in the EU’s economy. The new regulation encourages the sustainable and innovative production of organic fertilizers using domestically available bio-waste, animal by-products such as dried or digested manure, and other agricultural residues. Currently, only 5 per cent of organic waste material is recycled and applied as fertilizer within the EU. Enabling free cross-border movement of the bio-based fertilizers would lead to the creation of a new market space and supply chain for secondary raw materials within the EU. It is estimated that around 120,000 jobs would be created as a result. The recovery of nitrogen from bio-waste is expected to reduce or substitute the need for synthetic or inorganic nitrogen fertilizers, the production of which has high carbon and energy footprints. At the same time, this will further help to reduce losses of reactive nitrogen into the environment.
It is also easy to envisage transforming the nitrogen cycle in agriculture into a model of the circular economy for nitrogen. Here improvements in efficiency and reduced losses from fertilizers, biological nitrogen fixation, urine and dung allow more of the fresh nitrogen to reach intended food and bioenergy products. At the same time, reprocessing of livestock and human excreta into new fertilizers offers the opportunity to market recycled fertilizer products.

The situation has been very different when it comes to combustion sources of NO$_x$, since all available technologies, for instance, catalytic and non-catalytic reduction, focus on denitrification of NO$_x$ back to N$_2$. Yet this represents a massive loss of resources. Multiplying global NO$_x$ emissions by the fertilizer price of N$_2$ would give an annual resource of US$50 billion globally, pointing to the need for technologies to recapture NO$_x$ as NO$_3^-$.\textsuperscript{11,39}

In India, a financial perspective also informs the government’s policy from 2016 requiring all urea fertilizer to be coated with neem oil, in order to reduce both environmental losses of N$_2$ and financial leakage of the subsidy to non-agricultural urea applications. The same principle underlies the Indian Prime Minister’s call in November 2017 for farmers to halve fertilizer use by 2020, as well as governmental backing for Zero Budget Natural Farming (ZBNF) in some Indian states. The ZBNF movement focuses on avoiding costly external inputs of fertilizers and pesticides, helping farmers avoid debt, while promoting organic opportunities to improve soil organic matter, soil biology and fertility. In Andra Pradesh, a rapid upscaling of ZBNF to thousands of enthusiastic farmers is being supported by partnership between BNP Paribas, United Nations Environment Programme (UNEP) and the World Agroforestry Centre ICRAF, through the Sustainable India Finance Facility (SIFF). This innovative approach is based on loans to support investment and expansion being paid back by the government, since much less fertilizer subsidy will be needed when the fertilizer use reduces.\textsuperscript{40,41}

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Regional consumptions of all types of nitrogen fertilizers in 1980 and 2016 (in million metric tonnes)

Year 1980
- Western and Central Europe: 1.8
- Africa: 3.6
- East Asia: 11.8
- Latin America and the Caribbean: 15

Year 2016
- Western and Central Europe: 4.7
- Africa: 9.4
- East Asia: 14.2
- Latin America and the Caribbean: 13

Data source: International Fertilizer Association (https://www.ifastat.org/databases/plant-nutrition)
Towards a holistic international approach for nitrogen

The encouraging news is that a few countries are piloting more integrated approaches to nitrogen management. For example, Germany quickly responded to the European Nitrogen Assessment by working on an integrated nitrogen strategy.\textsuperscript{23,44} The difficulty for many countries is that a response to address nitrogen threats is split across multiple ministries, making it difficult to coordinate action. For example, in Brazil, agriculture is still expanding over large areas and the need for better decoupling of crop and animal production with environmental impacts has not been expressly addressed.\textsuperscript{45} Internationally, the transboundary impacts of $\text{N}_2$ also require clear legislation and policy actions.

The members of the International Nitrogen Initiative (INI) have given considerable thought to these challenges. The first step has been to work with the United Nations Environment Programme to establish a coordinated approach to scientific support for international policy development, in the form of the “International Nitrogen Management System” (INMS).

With the support of the Global Environment Facility and 80 partner organisations, INMS is developing guidance on the management of nitrogen, the integration of flows and impacts, cost-benefit valuation, and future nitrogen scenarios. INMS is also developing regional multi-country demonstrations to show how holistic nitrogen management can help. A key outcome will be the first Global Nitrogen Assessment, due for publication in 2022.

The next challenge is to develop a more coherent policy framework for the nitrogen cycle. The need for this can clearly be seen in the multitude of the United Nations Environment Assembly resolutions relevant to nitrogen: 2/6 (Paris Agreement), 2/7 (Chemicals & Waste), 2/8 (Sustainable Consumption & Production), 2/9 (Food Waste), 2/10 (Oceans), 2/12 (Coral Reefs), 2/24 (Land Degradation), 3/4 (Environment & Health), 3/6 (Soil), 3/8 (Air Quality) and 3/10 (Water Pollution).\textsuperscript{46,47} The point is well made by Resolution 3/8, which encourages governments “to take advantage of synergistic effects of efficient nitrogen management on reducing air, marine and water pollution”.

Recent discussions in the scientific and policy communities have explored how to coordinate nitrogen policy engagement more effectively.\textsuperscript{48} Some possibilities include:
Option 1: Nitrogen fragmentation across policy frameworks – the status quo
Option 2: Nitrogen leadership under one existing policy framework. This provides a challenge to the mandate of each since existing Multilateral Environmental Agreements (MEAs) address only parts of the challenge.
Option 3: A new international convention to address the nitrogen challenge. There is currently little readiness for this approach.
Option 4: An “Inter-Convention Nitrogen Coordination Mechanism”, providing an intergovernmental forum for inter-institutional cooperation on nitrogen, perhaps under the mandate of the United Nations Environment Assembly.

At present the Coordination Mechanism is lacking, which limits the extent to which the existing MEAs learn from each other, while also being inefficient in requiring that INMS work individually with multiple MEAs. The Coordination Mechanism would serve to actively engage Member States and relevant MEAs. The Major Groups and Stakeholders to the United Nations Environment Programme already facilitate involvement of business and civil society. It should be noted that Option 4 remains just that – an option. It is for national governments to discuss which approach would be the most agile, efficient and cost-effective.

Nevertheless, this discussion points to another benefit. It is becoming increasingly obvious that global society needs a holistic approach for nitrogen science and policy. First, the multi-source, multi-sector perspective allows synergies and trade-offs to be considered. This would benefit agriculture and industry by providing a more coherent basis for business decision-making. Secondly, the holistic approach provides the foundation to develop the circular economy perspective that is vital to mobilizing change. In addition to these, such an approach for nitrogen becomes an illustration of how future environmental policy could coordinate more effectively between issues. As the United Nations Environment Programme works towards its strategy for a “Pollution-Free Planet”, the lessons are likely to be all the more important across the realms of interacting pollution issues.
References


