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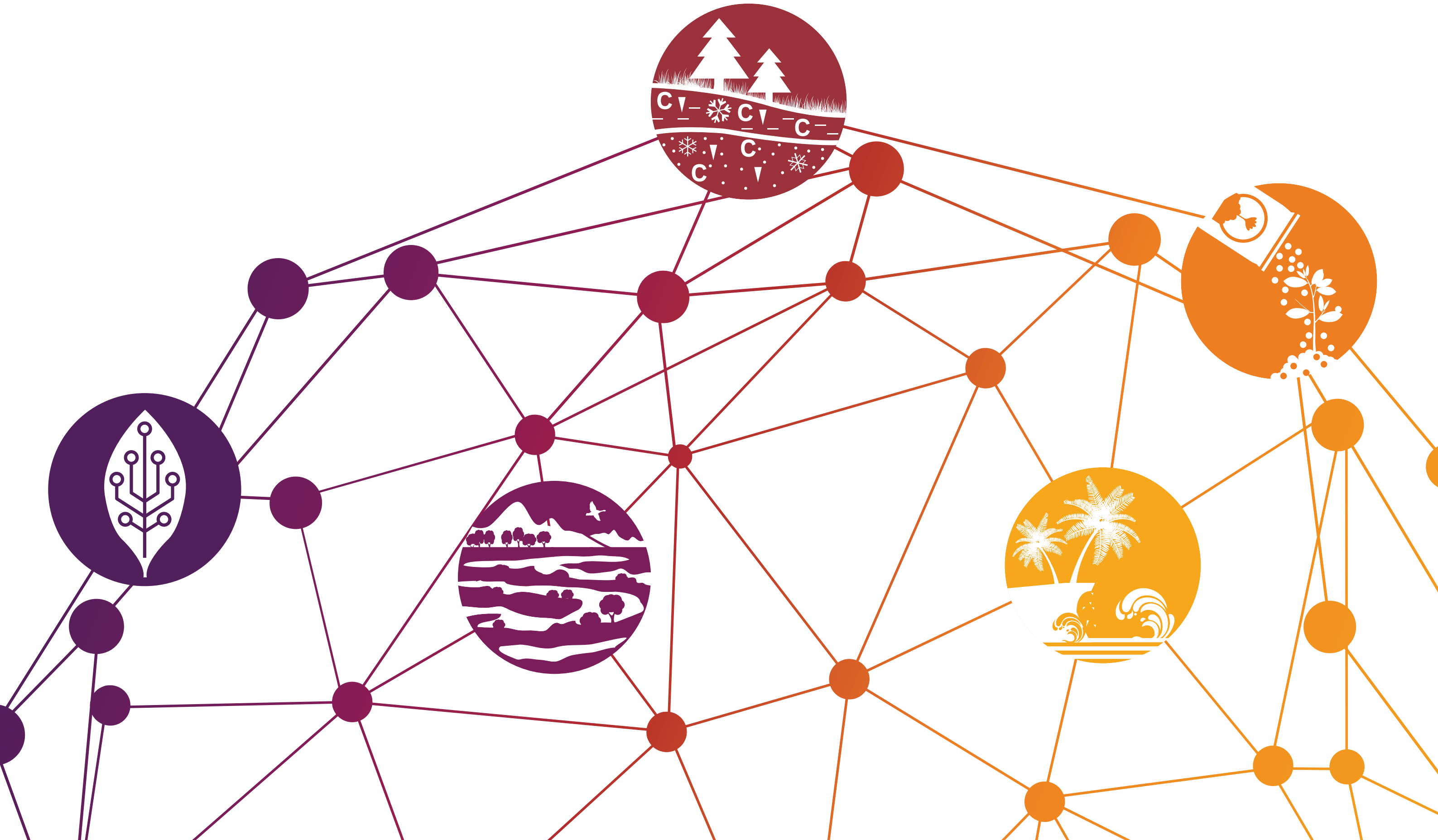
FRONTIERS 2018/19

Emerging Issues of Environmental Concern



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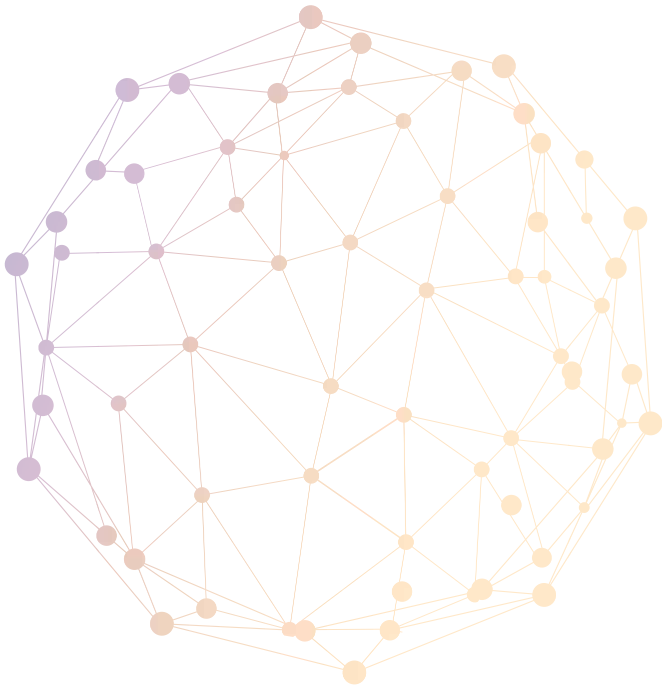
Emerging Issues of Environmental Concern



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Foreword

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.

Joyce Msuya
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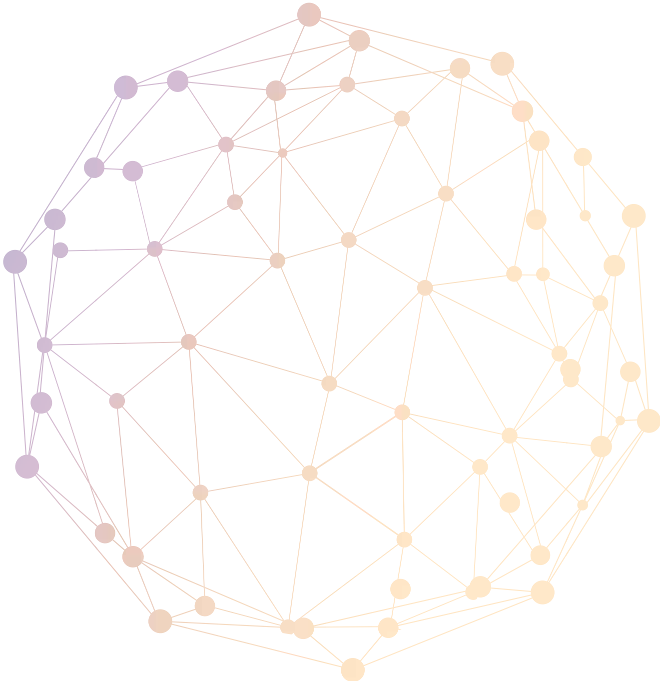


Photo credit: oticki / Shutterstock.com

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

The global nitrogen challenge

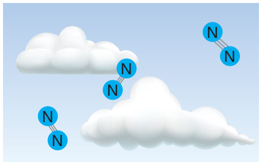
The *UNEP 2014 Year Book* highlighted the importance of excess reactive nitrogen in the environment.[1] Its conclusions are alarming. This is not just because of the magnitude and complexity of nitrogen pollution, but also because so little progress has been made in reducing it. Few of the solutions 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.[2-10] These impacts hinder progress toward the Sustainable Development Goals as they affect human health, resource management, livelihoods and economies.[11-15] 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.[16-24]

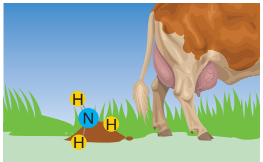
Nitrogen is an extremely abundant element in the Earth's atmosphere. In the form of the N_2 molecule, nitrogen is harmless, making up 78 per cent of every breath we take. The two nitrogen atoms are held together by a strong triple bond (N≡N), making it extremely stable and chemically unreactive. The planet benefits because N_2 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 N_2 into other chemically reactive forms. For simplicity, scientists refer to all other nitrogen forms as "fixed" or "reactive nitrogen" (N_r).[11,25] There are many types of N_r with many different effects –

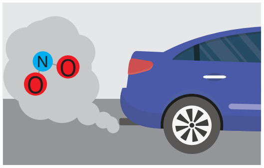
beneficial and harmful – and this is where the complications arise. Reactive nitrogen is essential for all life on earth. For example, ammonia (NH_3) is the foundation for amino acids, proteins, enzymes and DNA, and thus central to the metabolism of all life forms. Similarly, nitric oxide (NO) acts as a key biological signalling compound, while ammonium (NH_4^+) and nitrate (NO_3^-) are the major nutrient forms of nitrogen essential for plant growth. This points to a primary benefit of N_r 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.[26] In parallel, humans benefit from the natural biological fixation of N_2 to N_r by specialist bacteria found in soil and associated with the roots of legume crops.

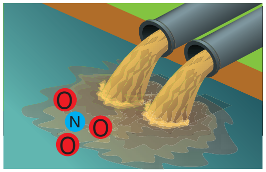
Against these benefits must be set the numerous losses of ammonia, nitrate, nitric oxide (NO), nitrous oxide (N_2O) and many other forms of N_r pollution that cause multiple impacts on the environment. These may occur directly following fertilizer use, while animal manure, human excreta and other organic wastes also cause huge losses of N_r to the environment. Although the fraction of N_r 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 N_r pollution. Reactive nitrogen is also yielded as a by-product of human activities. For instance, fossil fuel and biomass combustion processes release NO and NO_2, collectively called NO_x. While major efforts have been made to reduce NO_x from vehicles and energy generation, emissions are still escalating in rapidly developing parts of the world.[6,12] 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.

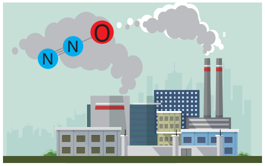
Different forms of nitrogen in the environment











	Di-Nitrogen (N_2)	**Ammonia (NH_3)**	**Nitric Oxide (NO) and Nitrogen Dioxide (NO_2)**	**Nitrate (NO_3^-)**	**Nitrous Oxide (N_2O)**
Source	N_2 makes up 78% of air we breathe	Manure, urine, fertilizers and biomass burning	Combustion from transport, industry and energy sector. NO and NO_2 are collectively known as NO_x.	Wastewater, agriculture and oxidation of NO_x	Agriculture, industry and combustion
Benefits	N_2 maintains stable atmosphere for life on Earth. It makes the sky appear blue.	NH_3 is the foundation for amino acids, protein and enzymes. Ammonia is common used as fertilizer.	NO is essential in human physiology. NO_2 has no known benefit.	Widely used in fertilizers and explosives	Used in rocket propellants and in medical procedure as laughing gas
Effects	N_2 is harmless and chemically unreactive	NH_3 causes eutrophication and affects biodiversity. It forms particulate matter in air which affects health.	NO and NO_2 (or NO_x) are major air pollutants, causing heart disease and respiratory illness.	It forms particulate matter in air and affects health. In water, it causes eutrophication.	N_2O is a greenhouse gas–300 times more powerful than CO_2. It also causes depletion of stratospheric ozone.

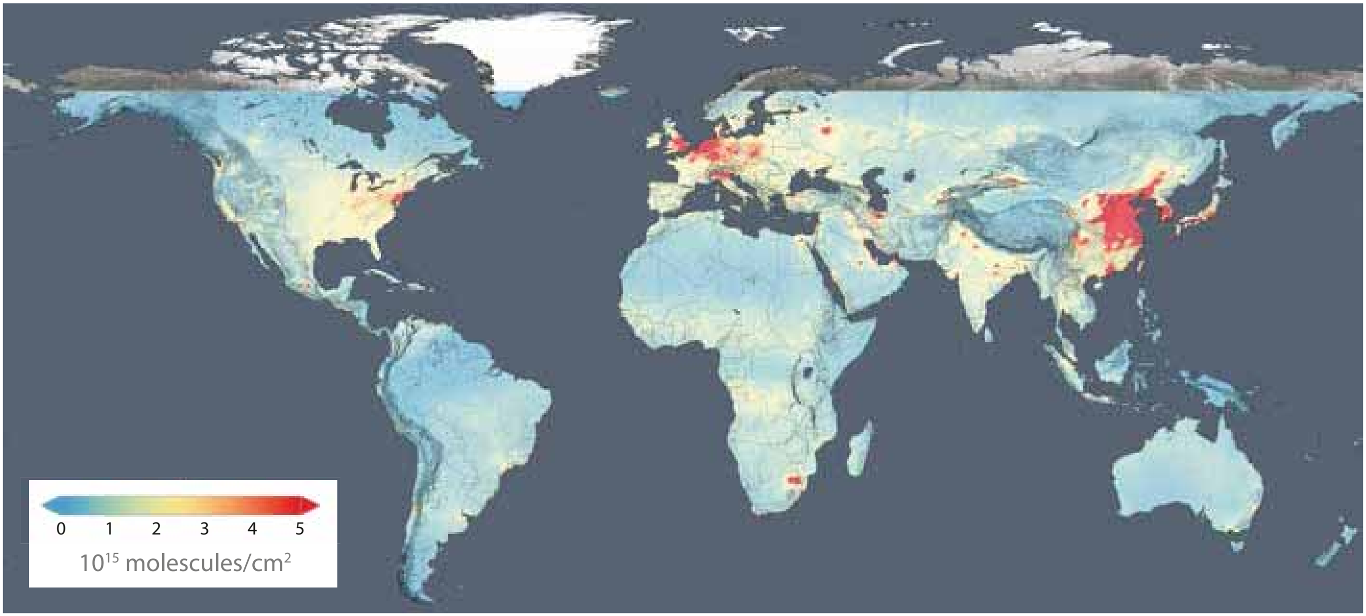
The knowns and known-unknowns of nitrogen

Both the cycling of nitrogen compounds and the human impacts are well documented.[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_2O 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.[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.[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.[20,29] Considering the whole food chain, only around 20 per cent of the N_r added in farming ends up in human food.[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.[13,30] Cost estimates can help guide mitigation policies, however, the true cost of N_r pollution is really a known-unknown, since

The average concentration of nitrogen dioxide (NO_2) in the troposphere in 2014



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

Video: Saving the Great Lakes from toxic algae

Video link: https://www.youtube.com/watch?v=b6JzL4NG26k © PBS NewsHour
Photo: Algal bloom in Pelee Island in the southeast of Lake Erie
Photo Credit: Tom Archer / Michigan Sea Grant (www.miseagrant.umich.edu)

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 N_r 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 N_r resource is lost to the environment per year as N_r and N_2.[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 N_r, such as sub-Saharan Africa, where reducing N_r pollution would help limited available N_r sources to go further in supporting food production.[31] The conversion of N_r compounds back to N_2 (termed "denitrification") does not provide a safe way to avoid N_r pollution. Rather, it implies a need for fresh N_r inputs, tending to increase pollution. Indeed, all N_2 and N_r losses need to be reduced if economy-wide nitrogen use efficiency (NUE) is to be increased.

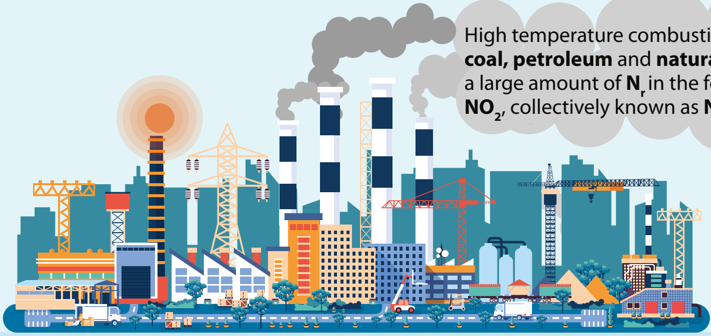
Algal bloom (shown in milky green) in the west of Lake Erie between Canada and the United States on 3 August 2014. Lake Erie's frequent algal blooms are caused by nitrogen and phosphorus loading from agricultural runoff of fertilizers and manure, municipal wastewater effluent and atmospheric deposition.

Photo credit: Jeff Schmaltz / NASA Goddard Space Flight Center

Video: Human fingerprint on global air quality

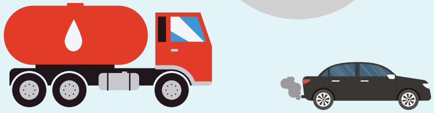
Video link: https://www.youtube.com/watch?time_continue=7&v=aMnDoXuTGS4 © NASA Goddard Space Flight Center
Photo credit: Doin / Shutterstock.com

Fossil fuel combustions in the transport, energy and industrial sectors



High temperature combustion of **coal, petroleum** and **natural gas** releases a large amount of **N_r** in the form of **NO** and **NO_2**, collectively known as **NO_x**

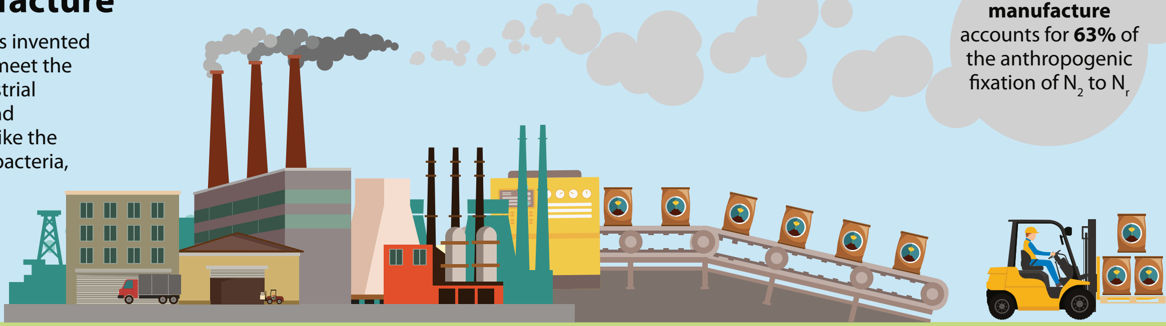
The **transport sector** contributes to more than **65% of NO_x** emissions



Fossil fuel combustion is responsible for **13%** of the **anthropogenic fixation of N_2 to N_r**

Fertilizer manufacture

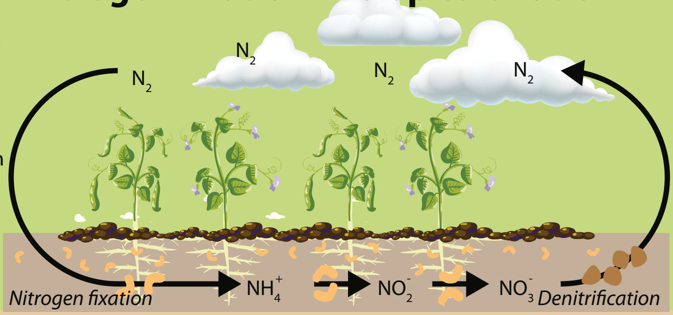
The Haber-Bosch process was invented more than 100 years ago to meet the growing need for mass industrial production of N_r fertilizers and nitrogen-based explosives. Like the natural nitrogen fixation by bacteria, **it artificially fixes atmospheric N_2 into ammonia (NH_3).**



Fertilizer manufacture accounts for **63%** of the anthropogenic fixation of N_2 to N_r

Biological nitrogen fixation in crop cultivation

In nature, N_2 can be converted into N_r through lightning and biological nitrogen fixation by nitrogen-fixing bacteria

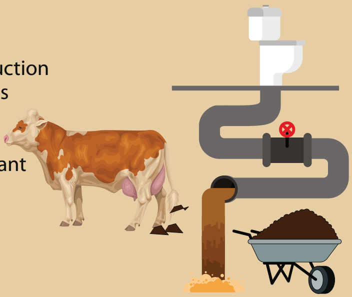


N_r can also be biologically converted back to N_2 through the **denitrification process** by anaerobic bacteria. These natural processes keep a balanced cycle of nitrogen, but increased **cultivation of nitrogen-fixing crops** such as legumes has significantly added N_r inputs and losses into the environment.

Biological nitrogen fixation in crop production is responsible for **24%** of the conversion of N_2 into N_r

Waste

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

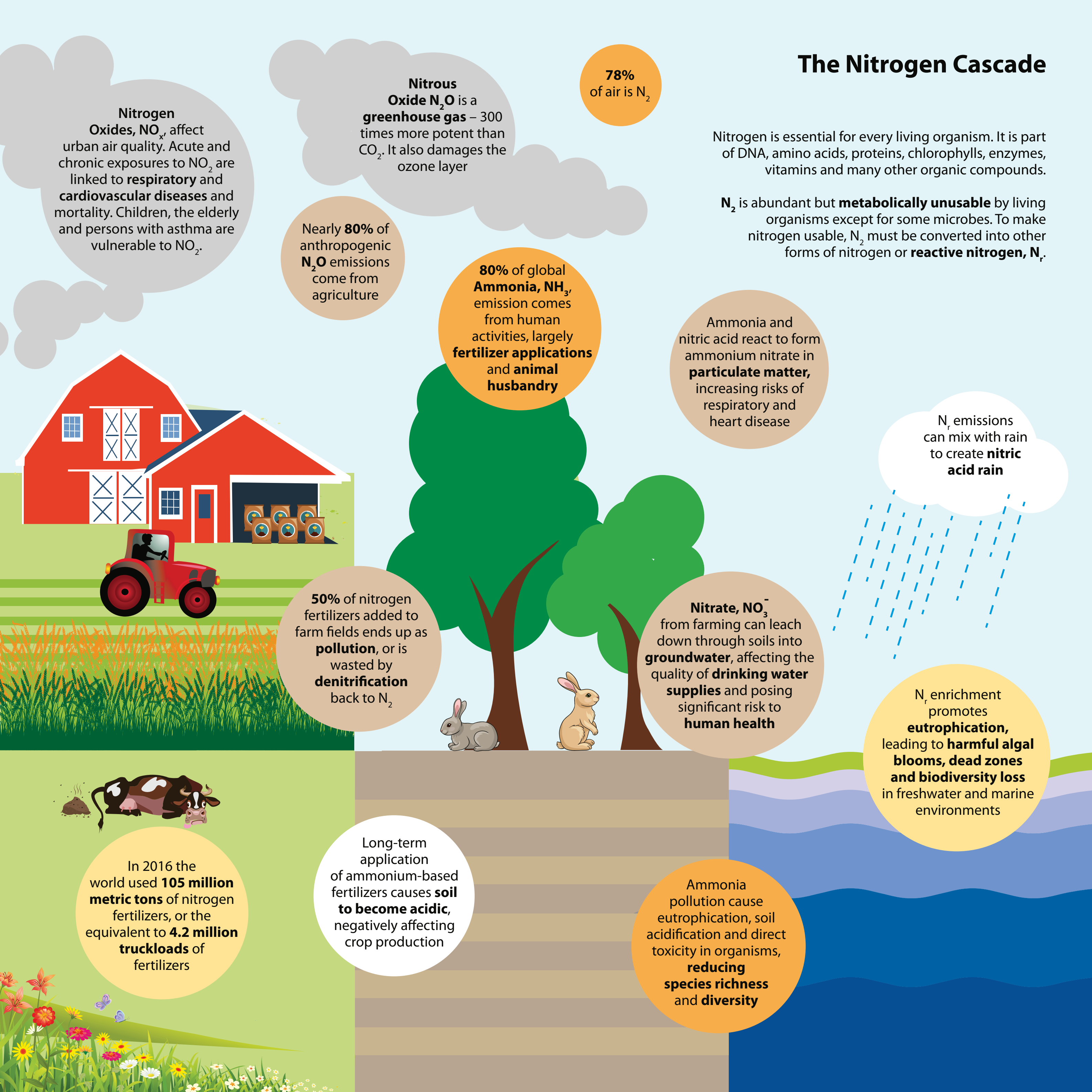


Sewage, wastewater and food waste contain proteins. About **16%** of **protein** is **nitrogen**

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

Cereals, fruits, vegetables, roots and **tuber**s 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**


The Nitrogen Cascade
Nitrogen is essential for every living organism. It is part of DNA, amino acids, proteins, chlorophylls, enzymes, vitamins and many other organic compounds.
N_2 is abundant but **metabolically unusable** by living organisms except for some microbes. To make nitrogen usable, N_2 must be converted into other forms of nitrogen or **reactive nitrogen, N_r**.
78% of air is N_2
Nitrogen Oxides, NO_x, affect urban air quality. Acute and chronic exposures to NO_2 are linked to **respiratory** and **cardiovascular diseases** and mortality. Children, the elderly and persons with asthma are vulnerable to NO_2.
Nitrous Oxide N_2O is a **greenhouse gas** – 300 times more potent than CO_2. It also damages the ozone layer
Nearly **80%** of anthropogenic **N_2O** emissions come from agriculture
80% of global **Ammonia, NH_3**, emission comes from human activities, largely **fertilizer applications** and **animal husbandry**
Ammonia and nitric acid react to form ammonium nitrate in **particulate matter**, increasing risks of respiratory and heart disease
N_r emissions can mix with rain to create **nitric acid rain**
50% of nitrogen fertilizers added to farm fields ends up as **pollution**, or is wasted by **denitrification** back to N_2
Nitrate, NO_3^- from farming can leach down through soils into **groundwater**, affecting the quality of **drinking water supplies** and posing significant risk to **human health**
N_r enrichment promotes **eutrophication**, leading to **harmful algal blooms, dead zones and biodiversity loss** in freshwater and marine environments
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 cause eutrophication, soil acidification and direct toxicity in organisms, **reducing species richness** and **diversity**

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.[32] Proposals to include NUE or nitrogen losses in the set of SDG indicators have not been adopted thus far.[20,33]

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.[34] This temporal effect was only partly avoided in a few EU countries, by requiring low NH_3^- emission application of manure.[35] 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.[36] 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.[11,30,37] 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.[38]

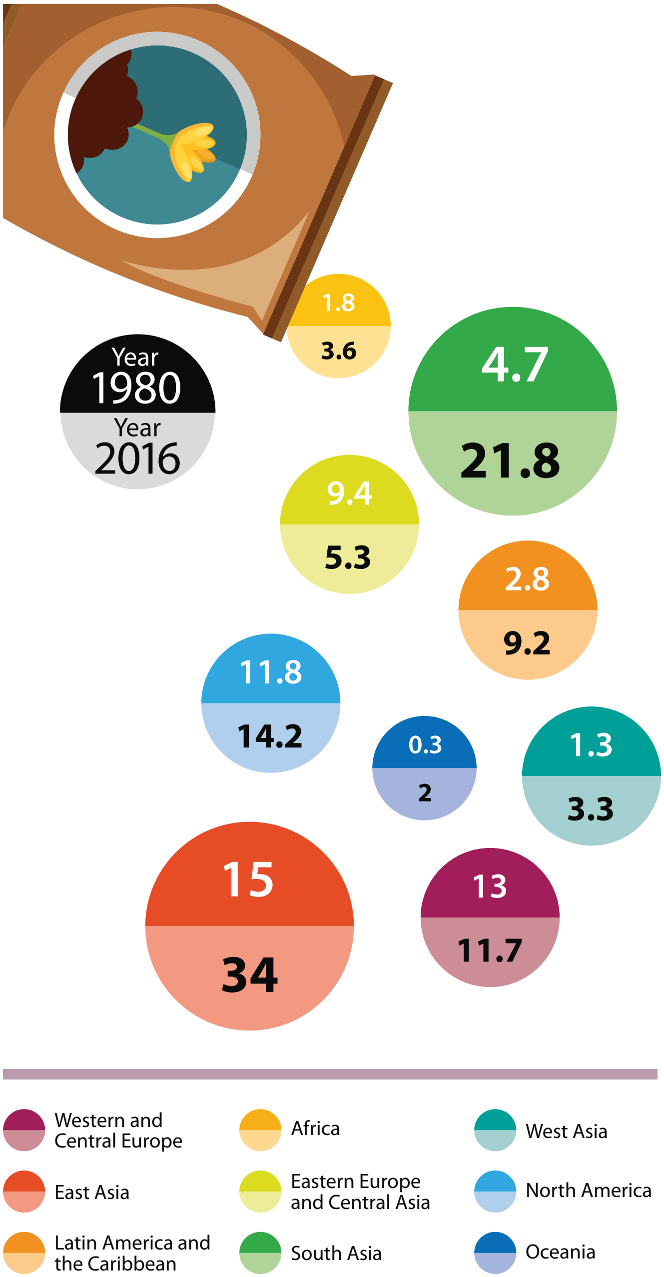
Nitrogen, nutrients and the circular economy

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.[42,43] 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.

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".

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



Data source: International Fertilizer Association (https://www.ifastat.org/databases/plant-nutrition)

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 bio-energy 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_r would give an annual resource of US$50 billion globally, pointing to the need for technologies to recapture NO_x as NO_3^-.[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_r 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.[40,41]

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.[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.[45] Internationally, the transboundary impacts of N_r 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).[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.[48] Some possibilities include:

Video: Why fertilizer matters to the environment and your bottom line

Video Link: https://www.youtube.com/watch?v=5TzzPOy1T3g *© Environmental Defense Fund*
Photo credit: Visual Generation / Shutterstock.com

Video: Air pollution from agriculture

Video Link: https://www.youtube.com/watch?v=07P_wXTTusI *© European Union*
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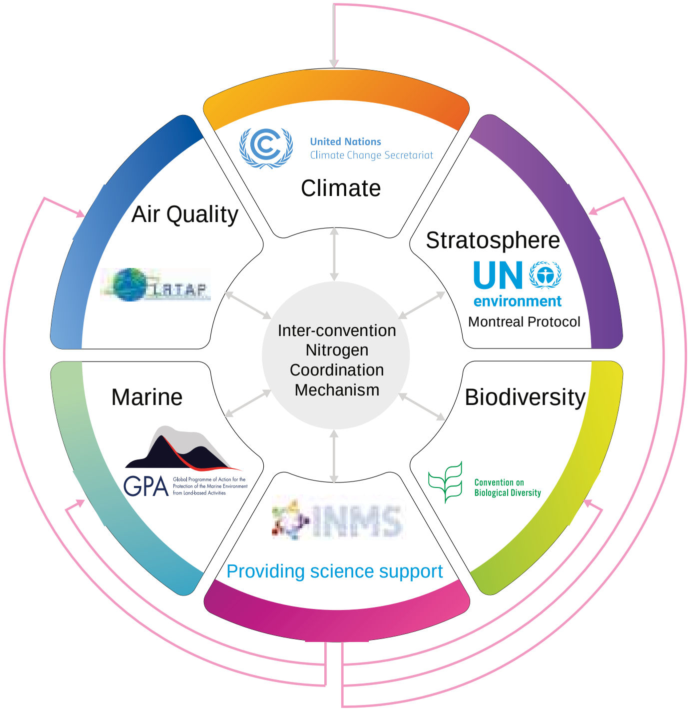
Option 1: Nitrogen fragmentation across policy frameworks – the status quo
Option 2: Nitrogen leadership under one existing policy framework. This provides a challenge to the mandate of each since existing Multilateral Environmental Agreements (MEAs) address only parts of the challenge.
Option 3: A new 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 goverments 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.

Inter-convention Nitrogen Coordination Mechanism



Video: The agricultural ammonia challenge

Video Link: https://www.youtube.com/watch?v=y0lG5mOWyAs *© CAFREtv*
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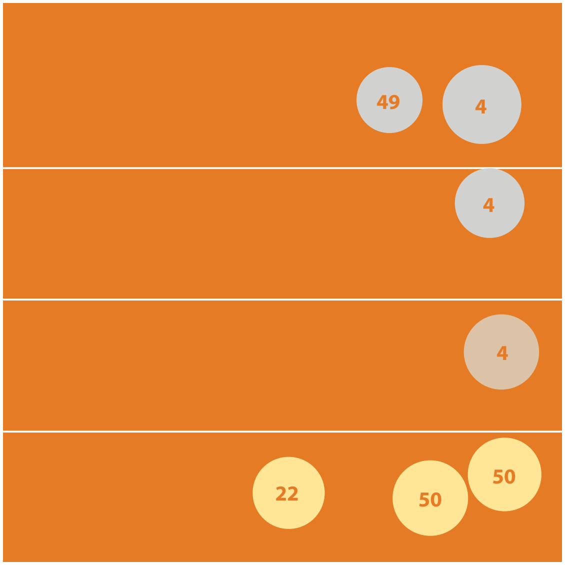
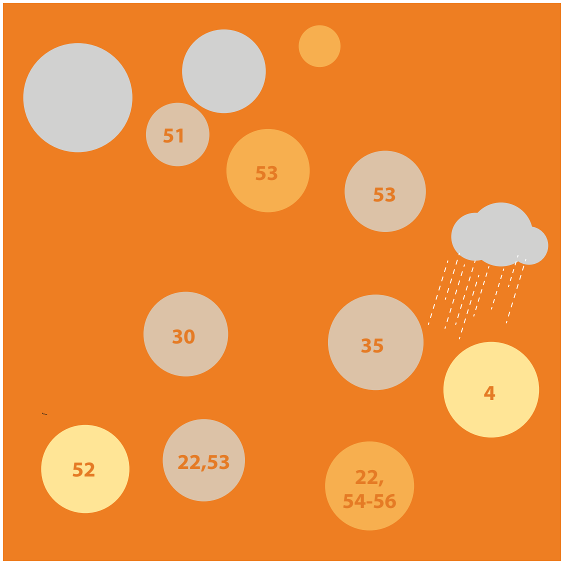
Graphic references





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