Nitrogen

Grasping the Challenge

A Manifesto for Science-in-Action
through the International Nitrogen Management System

Summary Report

INMS UNEP gef INI NITROGEN FOR LIFE

Published by the Centre for Ecology & Hydrology (CEH), Edinburgh, UK on behalf of the International Nitrogen Management System (INMS).

Recommended Citation:

Sutton M.A., Howard C.M., Adhya T.K., Baker E., Baron J., Basir A., Brownlie W., Cordovil C., de Vries W., Eory V., Green R., Harmens H., Hicks K.W., Jeffery R., Kanter D., Lassaletta L., Leip A., Masso C., Misselbrook T.H., Nemitz E., Nissanka S.P., Oenema O., Patra S., Pradhan M., Ometto J., Purvaja R., Raghuram N., Ramesh R., Read N., Reay D.S., Rowe E., Sanz-Cobena A., Sharma S., Sharp K.R. Skiba U., Smith J.U., van der Beck I., Vieno M., and van Grinsven H.J.M. (2019) Nitrogen - Grasping the Challenge. A Manifesto for Science-in-Action through the International Nitrogen Management System. Summary Report. Centre for Ecology & Hydrology, Edinburgh, UK.

This summary report is available on-line at: www.inms.international

About INMS:

The International Nitrogen Management System (INMS) is a global science-support system for international nitrogen policy development established as a joint activity of the United Nations Environment Programme (UNEP) and the International Nitrogen Initiative (INI). It is supported with funding through the Global Environment Facility (GEF) and around 80 project partners through the 'Towards INMS' project (2016-2022).

INMS provides a cross-cutting contribution to multiple programmes and intergovernmental conventions relevant for the nitrogen challenge. These include the Global Partnership on Nutrient Management (GPNM) and the Global Waste Water Initiative (GWWI) under the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA), the UNECE Convention on Long-Range Transboundary Air Pollution (Air Convention), through its Task Force on Reactive Nitrogen (TFRN), the UN Convention on Biological Diversity (CBD), the UN Framework Convention on Climate Change (UNFCCC), the Vienna Convention for the Protection of the Ozone Layer, and many regional agreements, such as the Black Sea Commission, the Lake Victoria Basin Commission, the Partnership for Environmental Management for the Seas of East Asia (PEMSEA) and the South Asian Cooperative Environment Programme (SACEP).

INMS receives major additional funding through the work of the GCRF South Asian Nitrogen Hub supported by the UK Research & Innovation (UKRI) Global Challenges Research Fund (GCRF).

Nitrogen for Life is the motif of UN Nitrogen Campaign launch, held in Colombo, Sri Lanka on 23-24 October 2019

Cover Photo: *Juxtaposition of high- and low-tech. International inter-comparison of ammonia flux measurement methods held at the Indian National Rice Research Institute (NRRI), Cuttack, during September 2017 under the NEWS India-UK Virtual Joint Centre on Agricultural Nitrogen. Photo Credit: Mark Sutton.*

Nitrogen

Grasping the Challenge

A Manifesto for Science-in-Action
through the International Nitrogen Management System

Summary Report

Sutton M.A., Howard C.M., Adhya T.K., Baker E., Baron J., Basir A., Brownlie W., Cordovil C., de Vries W., Eory V., Green R., Harmens H., Hicks K.W., Jeffery R., Kanter D., Lassaletta L., Leip A., Masso C., Misselbrook T.H., Nemitz E., Nissanka S.P., Oenema O., Patra S., Pradhan M., Ometto J., Purvaja R., Raghuram N., Ramesh R., Read N., Reay D.S., Rowe E., Sanz-Cobena A., Sharma S., Sharp K.R. Skiba U., Smith J.U., van der Beck I., Vieno M., and van Grinsven H.J.M.

Contents

Executive Summary

The Nitrogen Challenge

- Nitrogen is fundamental for life on Earth, being critical to sustain **global food** and **bio-energy** production. However, its inefficient use contributes to multiple pollution problems globally:
    - **Water Quality** Nutrient pollution of coastal seas leads to oxygen depletion (hypoxia) representing a loss of ecosystems services worth ~US$ 170 billion annually. Nitrate continues to threaten drinking-water quality, mainly from wastewater and agricultural sources.
    - **Air Quality** Nitrogen compounds threaten health, contributing about 10-50% of fine particulate matter ($PM_{2.5}$), 100% of the NO_x and 60% to the increase in tropospheric ozone (O_3) pollution, mainly from transport, industry, energy and agricultural sources.
    - **Greenhouse Gases & Climate** Nitrous oxide (N_2O) has a warming potential 300 times that of carbon dioxide with an atmospheric lifetime of 200 years. Around 70% arises from agricultural sources (fertilizers, manures), in addition to wastewater, industry and traffic.
    - **Ecosystems & Biodiversity** Atmospheric nitrogen deposition, resulting from nitrogen oxides (NO_x) and ammonia (NH_3) emissions from industrial, transport and agricultural sources, is threatening biodiversity in many biodiversity hotspots globally.
    - **Stratospheric Ozone** Following controls in manufactured ozone-depleting-substances, nitrous oxide is now the dominant cause of ozone depletion for 2020 and beyond.
- Nitrogen can be considered as 'everywhere and invisible': relevant across almost all of the UN Sustainable Development Goals, but not mentioned by any them.

Way Forward

- Past fragmentation across nitrogen science and policies is now being addressed through the International Nitrogen Management System (INMS), as a science-support process for global and regional policy development, working with countries through the United Nations.
- A key milestone has been the adoption by UN member states of a first-ever Resolution on Sustainable Nitrogen Management, agreed at the fourth session of the United Nations Environment Assembly in March 2019 (UNEP/EA.4/Res.14).
- Having explored options for policy frameworks, INMS is working with countries via the Committee of Permanent Representatives to the UN Environment Programme, to support development of a 'UN Roadmap for Sustainable Nitrogen Management, 2020-2022' and the establishment of an Inter-convention Nitrogen Co-ordination Mechanism (INCOM).
- A goal to Halve Nitrogen Waste would offer a resource saving worth US$100 billion annually, providing a key stimulus for the nitrogen circular economy, in addition to the environment, climate and health benefits. Pathways to achieving this goal would foster innovation in farming, wastewater, energy and transport, food choices and landscape integration.

Public Awareness

- Lack of citizens' awareness has provided a barrier to the development of actions to address the global nitrogen challenge, highlighting the importance of developing clear public messages.
- This report contributes to the launch of a first UN Nitrogen Campaign, which will promote public awareness about the nitrogen challenge. The launch event on 23-24 October, under the leadership of the President of Sri Lanka, highlights nitrogen as the next step for global environmental cooperation linked to United Nations Day 2019. The event includes adoption of the Colombo Declaration on Sustainable Nitrogen Management, a multi-actor dialogue, a first Nitro-Innovation Exhibition and the world premiere of a specially commissioned nitrogen song.

Why Nitrogen?

> "If new plant varieties were the engine of the Green Revolution, then nitrogen fertilizers were its fuel."
>
> *This report (Section 1.1)*

1. **Nitrogen for Life:** Without nitrogen there would be no life on Earth: no chlorophyll, no haemoglobin, no plants or animals. While carbon gives the basic skeleton of organic matter, nitrogen is fundamental to life's functioning and diversity. From amines and amino acids to proteins and DNA, all of them are nitrogen compounds.
2. **A nitrogen-rich atmosphere:** As di-nitrogen (N_2), nitrogen is extremely abundant. It makes up 78% of every breath we take. It makes the sky blue, and it provides a unique atmosphere in the Solar System, which allows life on Earth to flourish with safe levels of oxygen.
3. **Dead or Alive:** N_2 may be thought of as 'dead nitrogen', an inert medium that allows life to flourish and to which 'live nitrogen' reverts upon its decay. In order to form the building-blocks of life, N_2 must first be converted into reactive nitrogen (N_r) compounds, such as ammonia (NH_3), ammonium (NH_4^+) and amino acids, from which proteins, DNA and other nitrogen molecules are made. Decay of organic matter releases these reactive nitrogen compounds, which are eventually converted (or 'denitrified') back to N_2.
4. **Nitrogen Civilization:** The very existence of humanity depends on inputs of nitrogen compounds into agriculture. New sources of fresh N_r production include synthetic nitrogen fertilizers, biological nitrogen fixation and a small amount of nitrate (NO_3^-) from lightning. These nitrogen compounds are needed to raise crops and livestock, where increased N_r production by humans has allowed an approximate doubling of world's human population, together with even larger increases in livestock populations. In soils, nitrogen is also made available by mobilization of existing nitrogen pools, e.g., by decomposition of plant material and manure.

Figure ES1: Major threats associated with unstainable nitrogen management.

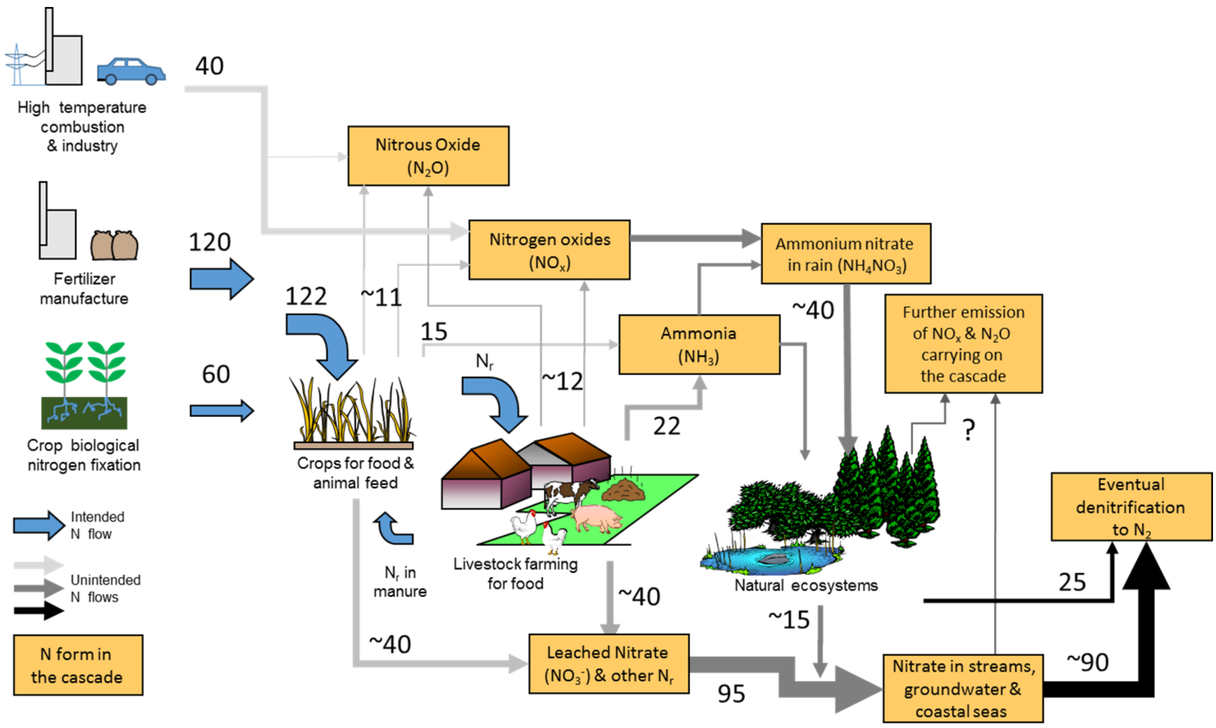

Figure ES2: Global nitrogen flows expressed in the form of the nitrogen cascade. Intended flows are shown with blue arrows, while unintended flows are shown in grey-black arrows. The diagram emphasizes the magnitude of nitrogen wasted through losses of different nitrogen forms, with the overall global system efficiency is around 20% with 80% of nitrogen inputs wasted (from Indian Nitrogen Assessment based on estimates from Our Nutrient World).

5. **Nitrogen waste causes multiple pollution problems:** Globally, only around 20% of nitrogen compounds reach useful products, with 80% lost to the environment, through a multiplicity of nitrogen sources and forms. Wasted nitrogen includes losses as ammonia (NH_3), ammonium (NH_4^+), nitrous oxide (N_2O), nitrogen oxides (NO_x, including nitric oxide, NO, and nitrogen dioxide, NO_2), nitrate (NO_3^-) and di-nitrogen (N_2). Together the different forms of wasted nitrogen threatens air quality, water quality, climate change, soil quality and biodiversity and leads to the depletion of stratospheric ozone. All these losses reduce economy-wide Nitrogen Use Efficiency (NUE), exacerbating the threats of nitrogen pollution (**Figure ES1**). The global flow of nitrogen can be envisaged as a cascade, where 1-2% of world energy is used to make synthetic fertilizers, and further energy used in biological nitrogen fixation and inadvertent oxidation of N_2 to NO_x and N_2O in high temperature combustion processes. Energy is dissipated as nitrogen cascades through multiple forms with multiple impacts until it is eventually denitrified back to N_2 (**Figure ES2**).
6. **Everywhere and Invisible.** Nitrogen pollution arises from multiple sectors: from agriculture, livestock, wastewater, industry, energy and transport systems. Nitrogen affects all aspects of our lives. It is all around us as N_2, within our blood and part of our DNA. It feeds our crops and livestock. Nitrogen contributes simultaneously to air, soil and water pollution, threatening human health, environment and the economy. The result is that nitrogen is relevant almost everywhere across the 17 UN Sustainable Development Goals (SDGs) (**Figure ES3**). Remarkably, however, nitrogen is almost entirely invisible in the SDG process and SDG indicators. This reflects the fragmentation of nitrogen science and policies, leading to this major global issue being largely ignored by the SDGs. Figure ES3 illustrates how a coherent approach to Sustainable Nitrogen Management would contribute to meeting multiple SDGs, where a goal to Halve Nitrogen Waste from all sources would mobilize shared global action.

Figure ES3: Nitrogen is almost everywhere relevant, but currently invisible in the UN Sustainable Development Goals (SDGs). The figure illustrates the multiple ways in which Sustainable Nitrogen Management can contribute to meeting the SDGs, highlighting the potential of an ambitious aspiration to Halve Nitrogen Waste globally from all sources of nitrogen pollution.

BNF is 'biological nitrogen fixation', a process through which bacteria associated with plant roots and in the soil convert di-nitrogen into reactive nitrogen compounds.

A Manifesto for Science-in-Action

7. This report summarizes the state-of-the-art in global nitrogen science and policy development. It outlines the global nitrogen challenge and highlights the limits of what is being done about it. It then identifies options for consideration in moving forward if the nitrogen challenge is to be grasped. It identifies key areas of what is currently known or not known, especially in the light of the importance of nitrogen action for achieving the United Nations Sustainable Development Goals for 2030 and beyond.
8. The report is framed as a manifesto for 'Science-in-Action'. By this we mean applying the evidence from science and the experience of researchers engaged in policy development to

develop a vision of how Sustainable Nitrogen Management must be a core theme for sustainable development. The report is aimed at stimulating discussion, raising awareness and catalysing action by governments, business, civil society, scientists and citizens for a more sustainable Nitrogen Earth. We present options as opportunities for environment, health and economy. In identifying these opportunities, we point to benefits and limitations of particular actions, while avoiding recommendations for specific policies. These must be for governments to agree, locally, regionally, nationally and internationally, in the light of the emerging evidence.

Multiple Co-benefits through Nitrogen Management

9. Sustainable nitrogen management recognizes that nitrogen is not just another problem; rather it must be part of the solution to so many of the challenges we know so well. For example:
   - **Water Quality, Clean Rivers and Seas:** The problems of algal blooms, hypoxia and fish kills, as well as nitrate (NO_3^-) in drinking water quality, cannot be achieved without sustainable nitrogen management.
   - **Air Quality and Health:** Clean air with low levels of particulate matter, nitrogen dioxide (NO_2) and tropospheric ozone cannot be achieved without sustainable nitrogen management to reduce nitrogen oxides (NO_x) and ammonia (NH_3) emissions and deposition.
   - **Greenhouse Gases and Climate**: Substantial reductions in the greenhouse gas nitrous oxide (N_2O) cannot be achieved without sustainable nitrogen management. If countries wish to keep global temperatures within 1 or 2 °C, then this cannot be done without action on nitrogen.
   - **Ecosystems & Biodiversity Protection**: Levels of atmospheric nitrogen deposition are well-above safe thresholds, pointing to the need for sustainable nitrogen management to reduce ammonia NH_3 and NO_x emissions.
   - **Stratospheric ozone**: N_2O is now the major ozone depleting substance, pointing to the need for actions to reduce emissions.
   - **Soil quality & Food Production**: Excess atmospheric nitrogen pollution can lead to the acidification of natural soils, while maintenance of nitrogen in soil organic matter is essential for the health and resilience of agricultural soils, while promoting carbon sequestration.
10. Sustainable nitrogen management provides a framework to add-up the multiple co-benefits of taking action, for water, air, climate, biodiversity and stratospheric ozone. ***The core hypothesis is that fragmentation between science and policies across these issues has contributed substantially to the barriers-to-change.*** By bringing these issues together through a clearly visible and coherent approach, we hypothesize a win-win-win situation for environment, health and economy that will help to overcome the barriers-to-change.
11. **Too much and too little**: In many parts of the world excess use and waste of nitrogen is a core cause of many pollution problems. Simultaneously, in other parts of the world, especially in Sub-Saharan Africa and parts of Latin America, inputs of reactive nitrogen and other nutrients are insufficient to meet crop needs, risking 'soil mining' of nitrogen that is also associated with depletion of soil organic matter, further reducing soil fertility. Nitrogen pollution can still be an issue in such regions where low nitrogen use efficiency continues to waste the limited amounts of available reactive nitrogen to air

> "Nitrogen is not just another problem; rather it must be part of the solution to many of the challenges we know so well."
>
> *This report (Section 1.2)*

and water pollution. This means that a focus on reducing wasted nitrogen can be of benefit to all, whether in regions of nitrogen surplus or nitrogen shortage.

12. If all pathways of nitrogen losses are added-up globally, the total nitrogen wasted amounts to around 200 million tonnes of nitrogen per year. Multiplied by a nominal fertilizer price of US$1 per kg, this is equivalent to a waste of US$200 billion annually. This cash value is in addition to even larger estimated societal costs for health, ecosystems and climate, estimated at 400 to US$4000 billion, but is much easier to value.

Halving Nitrogen Waste

13. A goal to Halve Nitrogen Waste would save US$100 billion annually, stimulating innovation in an emerging Nitrogen Circular Economy, where Nitro-Finance could become a key theme in mobilizing change, with multiple economic and environmental benefits. Such a global goal would broadly halve the overall contribution of nitrous oxide to climate change and stratospheric ozone depletion, halve the contribution of nitrogen to air and water pollution and halve the nitrogen threat to human health, ecosystems and biodiversity. In this way, it would make a major contribution to meeting multiple Sustainable Development Goals.
14. In the *Our Nutrient World* report previously prepared for the UN Environment Programme, a less ambitious goal was identified to improved Nitrogen Use Efficiency (NUE) by 20%, offering cash savings of US$23 billion and net economic benefits (considering implementation costs and societal benefits to environment, climate and health) worth US$170 billion, annually.
15. Using the shared goal from *Our Nutrient World* to increase efficiency by 20% had a disadvantage for equitability, in that those countries with the highest efficiency were assigned the largest improvement requirements. For example, a country with a present NUE of 20% would have a goal of 24% (i.e., a relative increase of 20% requires an absolute improvement of only 4%), whereas a country with a present NUE of 50% would have a goal of 60% (representing an absolute improvement of 10%) (see **Table ES1**).

	Current Situation		Future goal		Change needed to meet future goal	
	Economy-wide NUE	Nitrogen waste from all sources	Economy-wide NUE	Nitrogen waste from all sources	Economy-wide NUE	Nitrogen waste from all sources
'Our Nutrient World' goal to increase Nitrogen Use Efficiency (NUE) relatively by 20%						
Country A	20%	80%	**24%**	(76%)	+4%	-4%
Country B	50%	50%	**60%**	(40%)	+10%	-10%
Future goal to halve nitrogen waste from all sources globally						
Country A	20%	80%	(60%)	**40%**	+40%	-40%
Country B	50%	50%	(75%)	**25%**	+25%	-25%

Table ES1: Illustration of how a shared goal to halve nitrogen waste from all sources would be more equitable than a shared goal to improve nitrogen use efficiency (NUE), since less is required of countries having the highest current nitrogen use efficiency and lowest total nitrogen waste. Numbers in bold are the targets, with numbers in brackets calculated by difference. The same principle applies for other percentage goals.

16. By contrast, a goal to reduce nitrogen waste by a standard amount (here set at half), offers a more equitable approach, since those countries currently wasting more nitrogen would need to take more ambitious steps. For example, in a country wasting 80%, halving nitrogen waste across the economy would need to reduce total nitrogen losses from all sources to 40% of inputs (absolute reduction of 40%). By contrast, in a country wasting only 50%, halving nitrogen waste would reduce total losses to 25% (requiring an absolute reduction of 25%) (**Table ES1**).

17. **The goal to *halve* nitrogen waste is taken as an aspirational focus to raise awareness:** a) in getting serious about grasping the Nitrogen Challenge, b) in examining the multiplicity and scale of benefits and c) in focusing attention on the feasibility and barriers to progress. Its purpose is not to indicate whether this represents a suitable level of ambition, which must be a matter for global society and governments to decide, based on the outcomes of the assessment.
18. A first examination of the global goal to halve nitrogen waste indicates that it represents an extremely ambitious target that is only likely to be achievable by multiple actions across multiple source sectors, including production and consumption oriented measures across food, energy, wastewater and transport systems. The following key areas need to be considered:
    i. **Improving the performance of nitrogen fertilizers** through a combination of technical measures including more widespread adoption of improved products, including application of precision agriculture, fertigation and conservation to target placement and timing.
    ii. **Improving the management of biological nitrogen fixation** as a natural 'slow release' source of nitrogen, including use of legume and other nitrogen fixing intercropping, and exploration of methods to avoid 'hot-moments' of nitrogen losses following ploughing-in of green manures such as legumes.
    iii. **Improving the performance of livestock production**, including all measures relevant to increase feed conversion efficiency and reduce livestock excretion per kg of food product, including optimization of livestock diets and actions to improve animal health and welfare.
    iv. **Ensuring that all available organic nitrogen resources are used**, including animal manures, urine, human wastes and plant residues, avoiding discharges to air and water, while ensuring links to carbon, phosphorus and other nutrient management to restore and improve resilience of degraded soils.
    v. **Improving the methods by which organic nitrogen are utilized**, reducing the need for fertilizer manufacture from new nitrogen fixation, including reprocessing of available organic resources. Marketing opportunities should be considered for companies committing that their fertilizers are made from a minimum (e.g. 20%) of recycled nutrients.
    vi. **Developing new technologies to recapture nitrogen oxides** from combustion sources as a resource that could ultimately produce value added nitrogen products. Such innovation would complement existing technologies that focus on reducing nitrogen oxides emissions from combustion sources (by destruction of NO_x to N_2).
    vii. **Avoiding excessive meat and dairy consumption**, especially where above the recommended mean daily intake (RMDI), including a mix of demitarian, vegetarian and other dietary approaches while meeting dietary requirements, since this reduced the total nitrogen inputs required to sustain the food systems, thereby reducing nitrogen pollution.
    viii. **Applying measures to avoid food waste** across the agri-food chain, including post-harvest waste and consumer food waste, which otherwise multiply nitrogen requirements for food production and the associated nitrogen pollution.
    ix. **Applying measures to avoid waste-water pollution** from nitrogen and phosphorus, including increased adoption of sewage collection and treatment, and implementation of measures to safely process and recycle the nutrients in agriculture and value-added agricultural products.
    x. **Applying measures to improve landscape resilience to nitrogen pollution**, including adoption of spatially targeted planning requirements to avoid pollution in the most sensitive locations, use of buffer approaches to protect nearby nature features (e.g. natural land and rivers) and use of regional planning to reduce unsustainable regional nitrogen surpluses and sinks, including promoting the connection between crop and livestock systems.

19. *Achievement of an ambitious goal to halve nitrogen waste would be expected to give major profit opportunities for innovative business models* (e.g. financial savings for farms with less nitrogen pollution; new fertilizer manufacture from recycled manure, wastewater and NO_x resources; low-cost improved products with improved NUE). Through the development of Nitro-finance to catalyse change, major business realignment of could be expected.
20. Next steps in the INMS research will focus on relating different pathways to halve nitrogen waste to a wide range of future nitrogen scenarios drawing on experience from international climate and land use assessments.
21. These activities form part of the ongoing programme of INMS to develop a first comprehensive International Nitrogen Assessment (for 2022) together with detailed guidance on assessment methodologies and measures for improved nitrogen management.

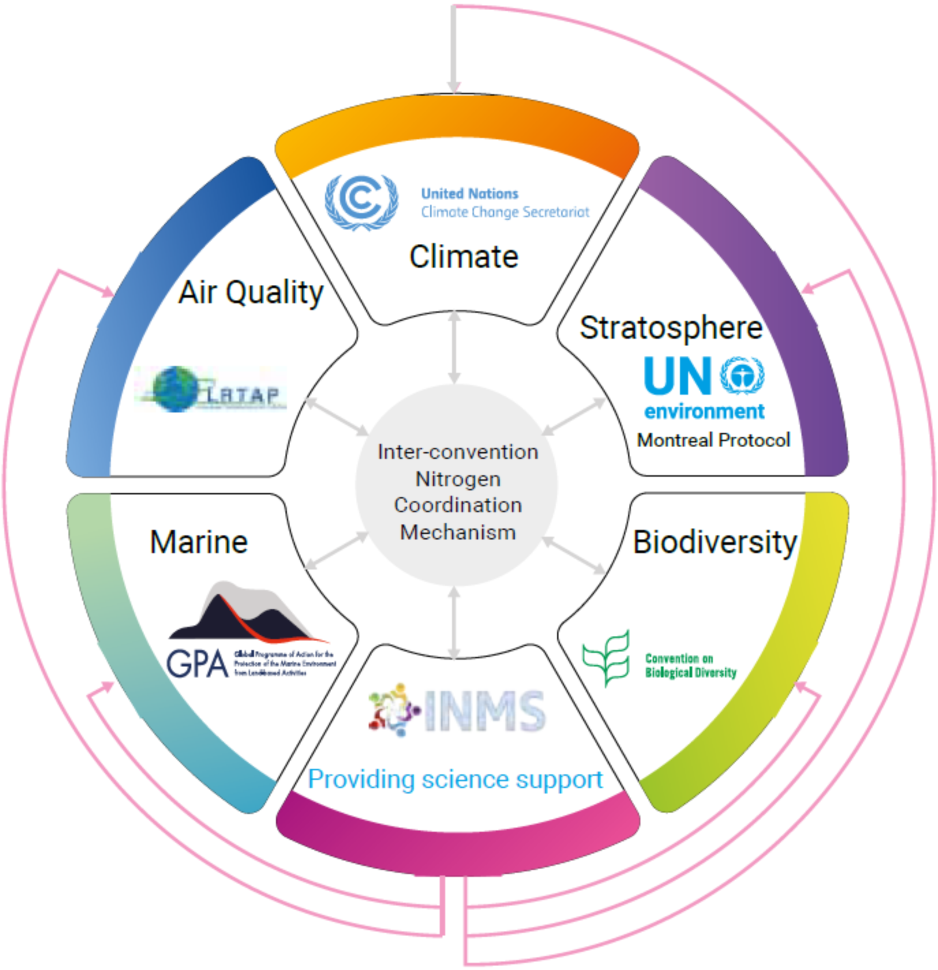

Figure ES4: Illustration of the Nitrogen Policy Arena, showing the role of the International Nitrogen Management System (INMS) in providing science support to the proposed Inter-convention Nitrogen Coordination Mechanism, bringing together Inter-governmental Conventions and Programmes through through the UN Environment Programme.

Public Awareness and Global Cooperation

22. Despite its critical importance for civilization and the future of the world environment, there is still little public awareness of the global nitrogen challenge. This lack of awareness can be directly linked to lack of coherency and limited progress among existing environmental policies related to nitrogen.

23. To address this concern, INMS is providing support to the UN Environment Programme as it prepares to launch a global awareness campaign on the nitrogen challenge. The launch is scheduled for 23-24 October in Colombo, under the leadership of His Excellency the President of Sri Lanka.
24. The UN Nitrogen Campaign is being launched under the theme of 'Nitrogen for Life', raising awareness that nitrogen is 'Everywhere And Invisible' and stimulating discussion on the question of what it would mean to 'Halve Nitrogen Waste'.
25. The proposed aspiration to Halve Nitrogen Waste should be seen as a starting point to raise public awareness and to support negotiations among countries of the United Nations about how fast they wish to act in harvesting the multiple environmental and economic benefits of sustainable nitrogen management.
26. The present Manifesto for Science-in-Action illustrates how the international scientific community may contribute in the years ahead. In particular, we outline how the efforts of INMS contribute to the development of a proposed 'UN Roadmap for Sustainable Nitrogen Management 2020-2022'.
27. A key element in developing the Roadmap for Sustainable Nitrogen Management is the proposal to establish an Inter-convention Nitrogen Coordination Mechanism (INCOM). Four options to develop a more coherent approach to international nitrogen policy were examined over the period 2016 to 2019 including:
    a. **Option 1:** Nitrogen fragmentation across policy frameworks. This represents the status quo.
    b. **Option 2:** Nitrogen leadership under one existing policy framework. This option proves difficult due to the limited mandate of each existing policy framework.
    c. **Option 3:** A new international convention to address the nitrogen challenge. Feedback shows that this option is unattractive for most policy makers, who are already saturated with policy processes, and typically recommend to work with existing processes (Option 2).
    d. **Option 4:** A nitrogen coordination mechanism, e.g., under the mandate of UNEA. This option aims to take the best of Options 2 and 3, working with existing policy processes, while focusing on bringing them together to share experiences and develop more coordinated approaches to harvest synergies and avoid trade-offs.
28. The conclusion of the fourth INMS plenary meeting points to Option 4 as the favoured approach, for which a Nitrogen Working Group under the Committee of Permanent Representatives is now being established to develop terms of reference.
29. It is evident that nitrogen requires a new level of working together, where solutions for water pollution, air pollution, climate change, biodiversity, soil degradation and stratospheric ozone depletion, and sustainable systems for food, transport and energy go hand-in-hand with development of the nitrogen circular economy. In order to increase public awareness as a precursor for substantive action, the opportunity is now being taken to launch a UN Nitrogen Campaign on United Nations Day 2019. It represents a new step for the global science community to work together with countries across the UN, crossing the boundaries for innovation in Sustainable Nitrogen Management.

Grasping the Nitrogen Challenge

Why Nitrogen?

Alteration of the global nitrogen cycle is without doubt one of great intractable development challenges facing humanity. Humans have more than doubled annual terrestrial cycling of reactive nitrogen (N_r) compounds, with fertilizer permitting almost half of humanity to be fed based on current diets.[1] If new plant varieties were the engine of the Green Revolution, then N_r fertilizers were its fuel.

Yet the fraction of human produced N_r that reaches final products is extremely low. Globally, full-chain nitrogen use efficiency (NUE_{fc}, e.g. from fertilizer to fork) is only around 20%, with 80% wasted and lost to the environment.[2] This is not only an economic loss, because N_r contributes to a plethora of problems: pollution of freshwater and marine systems affecting drinking water and livelihoods; air pollution shortening human lives; greenhouse gas emissions that also deplete stratospheric ozone; and all of this while threatening soil quality and ecosystem services.[3]

It makes for an intractable 'wicked problem' that cuts across the Sustainable Development Goals (SDGs). As humans, we need nitrogen to live, but our present use of it is driving a web of pollution that threatens health, climate, ecosystems and livelihoods.

Everywhere & invisible!

The text box, right, illustrates why this is an intractable challenge. There are multiple nitrogen forms, with multiple impacts (see **Figure 1**). The high-energy state of NH_3 and NO_x also means that there is a 'nitrogen cascade', through a complex sequence as N_r compounds gradually revert back to low-energy, unreactive N_2, whilst on the way multiplying the impacts of newly fixed N_r.[4,5] (**Figure 2**).

This multiplicity of N_r forms and effects also points to *the critical problem of fragmentation*, across academic disciplines, across traditional policy domains and across the challenges faced by practitioners, be they industrialists, farmers, water companies, vehicle drivers or conservation managers. *It is for this reason that the nitrogen challenge is relevant across almost all 17 SDGs, and yet unless you look carefully, it is nearly invisible in the SDG indicators.*[6] The fragmentation of issues across the nitrogen cycle appears to be one of the key barriers-to-change, with the result that essential synergies are missed that might otherwise make the difference between action and no action.

These opening comments help point the way towards a future strategy: *nitrogen is not just another problem; rather it must be part of the solution to many of the challenges we know so well.* The nitrogen case shows how integration of linked issues may build "*the gravity of common cause*"[2] that helps overcome the barriers to better food security and climate resilience, cleaner air and water, healthier people, seas and forests.

The language of nitrogen

N_2	Unreactive di-nitrogen. 78% of the air we breathe.
N_r	Reactive nitrogen – all other forms, with many impacts.
NH_3	Ammonia, the primary form of reduced nitrogen. Used for fertilizers & emitted to the air.
NH_4^+	Ammonium ion, contributes to PM & water pollution.
N_2O	Nitrous oxide, a greenhouse gas. It also depletes the stratospheric 'ozone layer'.
NO	Nitric oxide, the primary form of oxidized nitrogen, emitted to the air from burning & soils.
NO_2	Nitrogen dioxide, rapidly formed in air from NO.
NO_x	Mixture of NO and NO_2, affecting human health.
NO_3^-	Nitrate ion, contributes to PM & water pollution.
OrgN	Organic nitrogen, a plethora of forms with many impacts.
PM	Particulate Matter, especially as air pollution, adversely affecting health & visibility.

Nitrogen Form	Structure	Typical concentrations	Main Sources	Main Effects	
Di-nitrogen (N_2)		78% of air	Conversion from NO_3^- & NH_4^+ in soil & waters	Natural chemical inertness in the world's atmosphere	
Ammonia (NH_3)		0.1 to 100 ppb of air	Manure, urine, fertilizers, biomass burning, cars	Forms ammonium (NH_4^+) containing Particulate Matter (PM) in air affecting health (heart disease, respiratory illness); Causes eutrophication of ecosystems, affecting biodiversity	
Nitric oxide (NO)		0.1 to 100 ppb of air	Combustion from transport & energy sources	Direct health risks, and forms NO_2 in air affecting health (heart disease, respiratory illness).	**Sum = NO_x**
Nitrogen dioxide (NO_2)		0.1 to 100 ppb of air	Formed by rapid oxidation of NO	Direct health risks; Forms Particulate Matter (NH_4NO_3) in air contributing to heart disease, respiratory illness. Also causes ground-level ozone air pollution (O_3)	
Nitrates (NO_3^-)		Air: 0.1-10 µg m^{-3} Water: 1-500 mg per litre	Air: Oxidation of NO_x Water: Agriculture, waste water. Formed by oxidation of NH_4^+	As Particulate Matter (e.g. NH_4NO_3) in air it affects health (heart disease, respiratory illness) As a water contaminant, it affects health (e.g. bowel cancer) & causes eutrophication of ecosystems threatening biodiversity	
Nitrous Oxide (N_2O)		330 ppb in air	Agriculture, industry, combustion; Formed by conversion from NH_4^+ & NO_3^- in soil and waters	A powerful greenhouse gas contributing to climate change. Now the main cause of stratospheric ozone depletion	

Figure 1: Summary of major nitrogen forms of environmental importance. Ppb is parts per billion by volume.

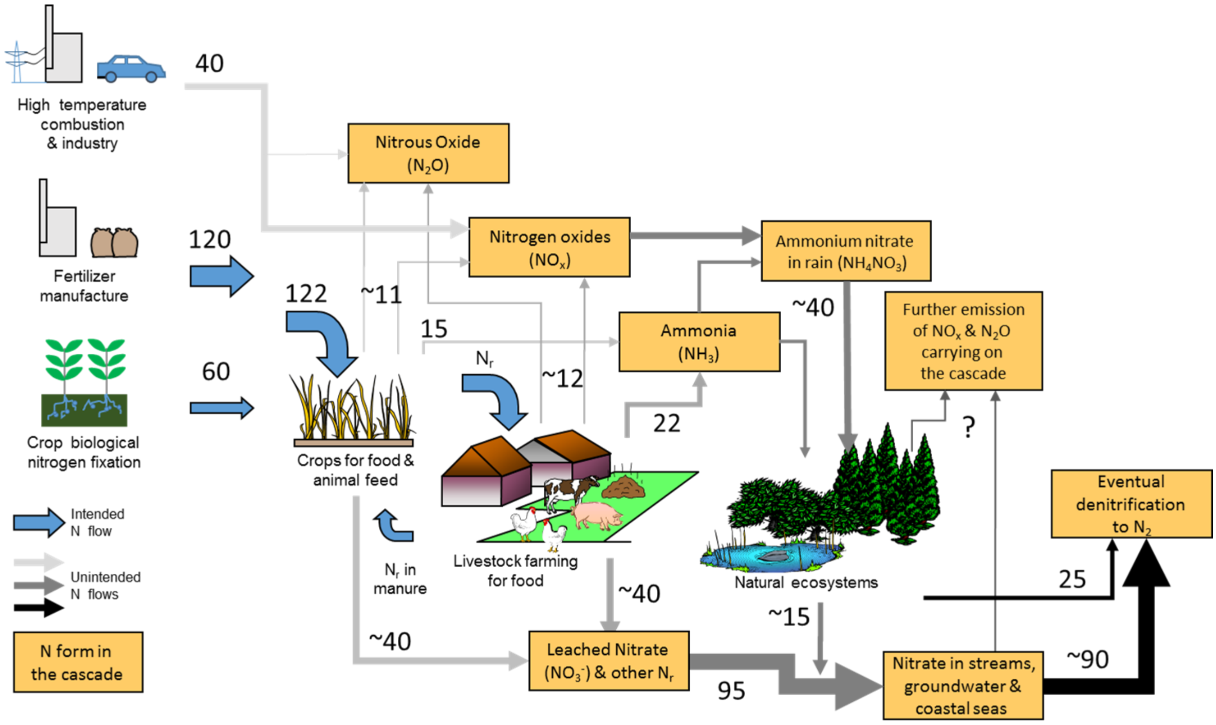

Figure 2: Global nitrogen flows expressed in the form of the nitrogen cascade. Intended flows are shown with blue arrows, while unintended flows are shown in grey-black arrows. The diagram emphasizes the magnitude of nitrogen wasted through losses of different nitrogen forms, with the overall global system efficiency is around 20% with 80% of nitrogen inputs wasted.

As di-nitrogen (N_2), nitrogen is extremely abundant. It makes up 78% of every breath we take. It makes the sky blue, and it provides a unique atmosphere in the Solar System, which allows life on Earth to flourish with safe levels of oxygen. N_2 may be thought of as 'dead nitrogen', an inert medium that allows life to flourish and to which 'live nitrogen' reverts upon its decay. In order to form the building-blocks of life, N_2 must first be converted into reactive nitrogen (N_r) compounds, such as ammonia (NH_3), ammonium (NH_4^+) and amino acids, from which proteins, DNA and other nitrogen molecules are made. Decay of organic matter releases these reactive nitrogen compounds, which are eventually converted (or 'de-nitrified') back to N_2.

It is no exaggeration to say that without nitrogen there would be no life on Earth. This can be easily illustrated by the molecular structure of both chlorophyll and haemoglobin, where the central functioning part links four nitrogen atoms with a metal ion (Magnesium in the case of chlorophyll and Iron in the case of haemoglobin) (**Figure 3**). Similarly, amino acids are at the heart of all proteins, enzymes and DNA. In this way, while it is carbon that gives the basic skeleton of organic matter, nitrogen is fundamental to both life's functioning and its diversity.

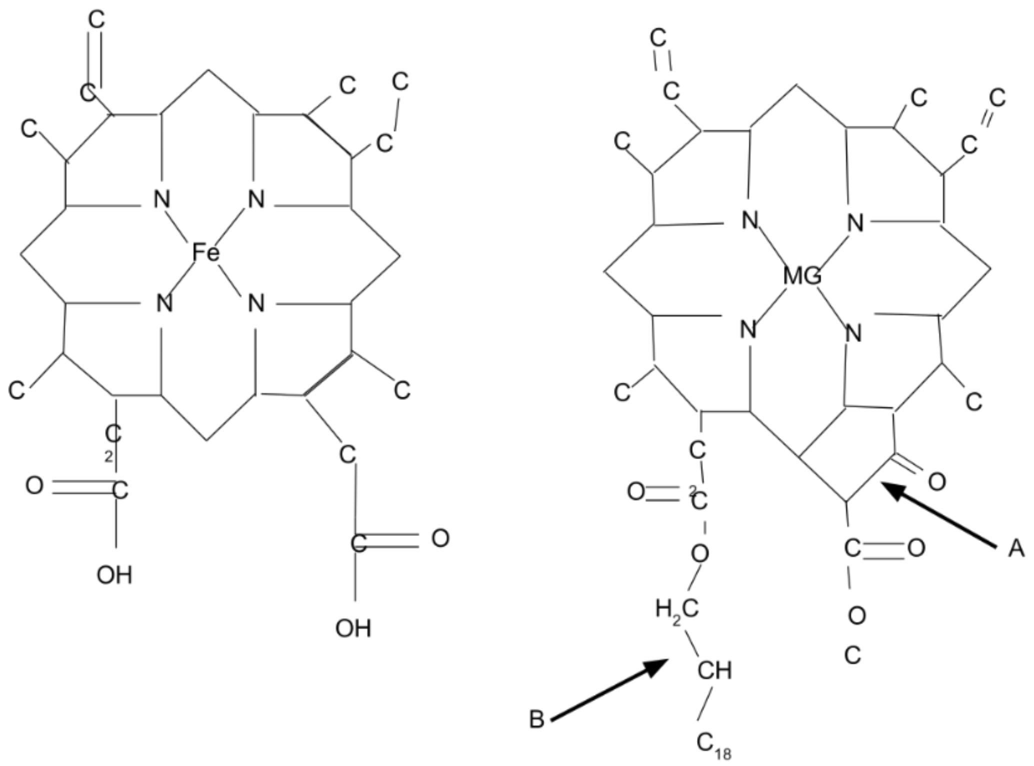

Figure 3: Chemical structure of haem (left) and chlorophyll (right). Haem forms the active structure of the blood protein haemoglobin, while the action of chlorophyll is at the heart of photosynthesis in plants. Both molecules include four nitrogen atoms, which hold a metal ion at the centre: iron (in haem) and magnesium (in chlorophyll). The arrows indicate the position of variants for Chlorophyll A and B.

Summary of Major Nitrogen Impacts

The following table provides an overview of key nitrogen impacts for different parts of the world. The threats listed cover each of the major issues, water pollution, air pollution, climate, biodiversity loss and threats to natural soils. The risks for large marine ecosystems are shown in future detail for 2000 and future projections for 2030 and 2050 in **Figure 4**.

In the case of the human health estimates, minimum figures are based on contribution of nitrogen share to small particulate matter (PM2.5) and tropospheric ozone. The additional effect on life shortening from nitrate in drinking water and stratospheric ozone depletion has not been included. Global figures and country-level figures for Brazil, China, India and USA are from 2015 (Cohen et al, 2017, The Lancet 389, 10082). Figures for the UK are from the COMEAP report The Mortality Effects of Long-Term Exposure to Particulate Air Pollution in the United Kingdom (2018), and figures for Europe are from the EEA 2018 Air Quality in Europe report. Separate ozone figures could not be obtained for the UK, so it was assumed that the proportion of total risk from ozone was the same for the UK as for Europe as a whole (4% of the risk from PM2.5). To estimate the proportion of health impacts due to nitrogen pollution, it was conservatively assumed that 30% of PM2.5 and ozone is nitrogen-related. All estimates were rounded down.

Table 1: Summary of major impacts of nitrogen pollution example parts of the world

Key Nitrogen Indicator (date)	World	Europe (EU28)	Brazil	China	India	UK	USA
Water: % of area at risk of nitrate pollution of of failing nitrogen/ nutrient water quality standards	NN	62% of agricultural area at risk of nitrate pollution	12% (total) & 22% (urban) of monitoring stations in bad/very bad condition (2017)	NN	NN	58% of agricultural area at risk of nitrate pollution	34% lakes 41% rivers failing standards
Water: % of large marine ecosystems (LMEs) with medium to highest nitrogen threat.	Of 63 LMEs: 36% (2000) 41% (2030) 46% (2050)	Of 7 LMEs: 70% (2000) 70% (2030) 70% (2050)	Of 3 LMEs: 33% (2000) 33% (2030) 67% (2050)	Of 4 LMEs: 100% (2000) 100% (2030) 100% (2050)	Of 2 LMEs: 100% (2000) 100% (2030) 100% (2050)	Of 2 LMEs: 100% (2000) 100% (2030) 100% (2050)	Of 10 LMEs: 20% (2000) 20% (2030) 20% (2050)
Air: % contribution of N compounds to $PM_{1.0}$ by mass	10-50% (2000-2010)	20-50% (2000-2010)	NN	20-40% (2000-2010)	NN	30-50% (2000-2015)	10-40% (2000-2010)
Air: % annual yield losses for major crops due to N contribution to ground level ozone	Soybean 6% Wheat 4% Maize 3% Rice 2% (2010-2012)	Soybean 8% Wheat 3% Maize 4% Rice 3% (2010-2012)	Soybean 5% Wheat 4% Maize 3% Rice 2% (2010-2012)	Soybean 10% Wheat 5% Maize 5% Rice 4% (2010-2012)	Soybean 8% Wheat 6% Maize 4% Rice 3% (2010-2012)	Soybean ND Wheat 1% Rice ND Maize ND (2010-2012)	Soybean 8% Wheat 4% Maize 4% Rice 3% (2010-2012)
Greenhouse Gas: % contribution of N_2O to emissions as CO_2 equivalent	6% (2016)	6% (2015)	19% (2005) 14% (2015)	5% (2005)	5% (2000)	5% (2015)	6% (2017)
Greenhouse Gas: % share of agriculture to total N_2O emissions.	70% (2008)	60% (2000) 74% (2015)	82% (2008)	75% (2008)	74% (2008)	57% (2000) 69% (2015)	69% (2000) 77% (2015)
Ecosystems: % area of Natural Habitats under threat from atmospheric N deposition	11% (2010) (40% of protected areas globally)	72% (2015)	NN	NN	NN	58% (2016)	56% (1995) 51% (2006)
Ecosystems: % area exceeding NH_3 critical level (protection threshold) for ecosystems with lichens & bryophytes	NN	NN	NN	NN	NN	60% (2016)	NN
Soils: % area of natural habitats under threat of soil acidification	NN	6% (2015)	NN	NN	NN	38% (2016)	50% (1995) 42% (2006)
Human Health: estimated N-related life shortening (disability adjusted life years).	30,000,000 per year	1,000,000 per year	300,000 per year	6,000,000 per year	8,000,000 per year	100,000 per year	400,000 per year
Total Nitrogen Losses: all N_r + N_2 emissions (1000 tonnes per yr)	200,000 (2000-2010)	23,500 (2000-2010)	9,600 (2014)	-	16,600 (2000) 22,200 (2015)	1,440 (2000-2010)	23,300 (2007)
Annual economic loss of total nitrogen waste (cash resource at @US$1 per kg N).	$200 billion	$23.5 billion (€21 billion)	$9.6 billion (BRL 40 billion)	-	$16-22 billion (INR Crore 7126)	$1.4 billion (£1.1 billion)	$23.3 billion

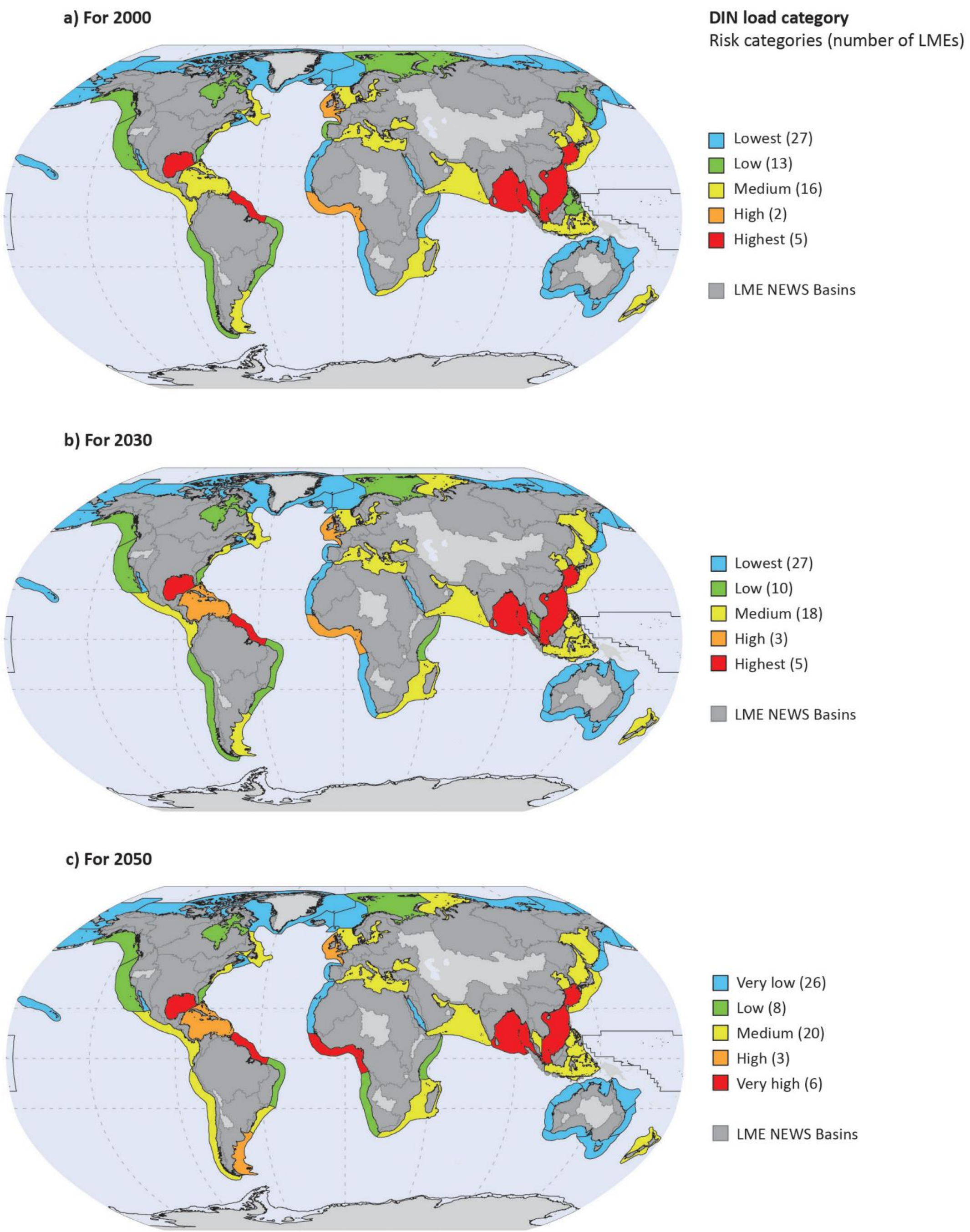

Figure 4: Risks of riverine nitrogen loads to Large Marine Ecosystems (LMEs) including from food and energy production, based on loads of Dissolved Inorganic Nitrogen (DIN). From Seitzinger and Mayorga (2016).