Human Acceleration of the Nitrogen Cycle

Managing Risks and Uncertainty

POLICY HIGHLIGHTS

OECD

BETTER POLICIES FOR BETTER LIVES


NITROGEN

Three ways to tackle nitrogen pollution

Despite immense benefits in terms of food and energy security, the use of fertilisers and the burning of fossil fuels release excess reactive nitrogen that poses serious threats to health and the environment.

The use of chemically-reactive nitrogen in fertilisers has brought immense benefits in terms of agriculture productivity and food security. Nitrogen also has many industrial uses and the combustion of fossil fuels releases reactive nitrogen to the atmosphere as a by-product. Since the start of the 20th century, humans have doubled the inputs of reactive nitrogen to the environment (Fowler et al., 2013) and this now poses serious threats to health and the environment.

Did you know?

Until one century ago, Chilean saltpetre (and before it Peruvian guano) was the main source of nitrogen for world agriculture and industry.

Excess nitrogen pollutes air, soil and water; increases greenhouse gas emissions; and impacts biodiversity and ecosystem functioning. Reactive nitrogen stimulates the formation of ground-level ozone and particles in the atmosphere; increases soil acidification; and, the transfer of nitrogen from terrestrial to coastal systems is leading to algal blooms and a decline in the quality of aquatic ecosystems. Not only is nitrogen a greenhouse gas (GHG) itself (in the form of nitrous oxide), but it also contributes to depletion of the stratospheric ozone.

Countering nitrogen pollution in a cost-effective way requires a threefold approach:

- **Implement impact-pathway analysis (IPA) to better managing the risks of air, soil, water and ecosystem pollution.**
- **Manage nitrous oxide as part of GHG mitigation policies.**
- **Monitor and manage any residual nitrogen excess by measuring the effect of the above measures on the national nitrogen budget.**

Measures to counter nitrogen pollution should be based on their impact and applied as close as possible to the point of emission to maximise effectiveness and cost-efficiency. Often, the best environmental outcome and greater political acceptability will require a combination of measures: "polluter pays" and "beneficiary pays" policies, alongside direct environmental regulation.

1 How excess nitrogen threatens health and the environment

AIR

Human activity – especially the burning of fossil fuels – is a major source of nitrogen oxides (NO_x) in the troposphere, the lowest region of Earth's atmosphere. In such combustion processes, under high temperature and pressure conditions, atmospheric nitrogen (N_2) combines with oxygen atoms to create NO_x. Human activity – especially agricultural practices – is also a major source of ammonia (NH_3).

In the atmosphere, nitrogen dioxide (NO_2) and, to a lesser extent, NH_3, are directly harmful to human health, increasing likelihood of respiratory problems. NH_3 and NO_x can react with each other or with atmospheric components, contributing to the most serious air pollution problems for human health – airborne particulate matter (PM). The effects of PM can range from eye and respiratory irritation to cardiovascular disease, lung cancer and consequent premature death. Exposure to high levels of ground-level ozone, caused by NO_x and volatile organic compounds that react under the influence of heat and the sun, increases the risk of premature death from lung disease and also affects vegetation by damaging leaves and reducing growth. NH_3 can also be harmful to vegetation, especially lower plants, through direct damage to leaves.

Air motions play a key role in the distribution of reactive nitrogen in the atmosphere and in its transport distance before "deposition" on the ground. In the United States, the National Atmospheric Deposition Program (NADP) has mapped the risk of nitrogen aerosol deposition. As evidenced by the risk assessment, it can be expected that ammonium (NH_4^+) wet deposition occurs near or downwind of major agricultural centres, and that nitrate (NO_3^-) levels in wet deposition are consistent with NO_x emissions (USEPA-SAB, 2011).

The health impact of air pollution by nitrogen incurs social costs that are already in the hundreds of billions of USD. This is because nitrogen compounds represent a significant part of urban pollution with fine particles ($PM_{2.5}$) whose health cost in terms of premature deaths is estimated at USD 1.8 trillion in OECD countries and USD 3.0 trillion in the BRIICS countries (Brazil, Russia, India, Indonesia, China and South Africa) (Roy and Braathen, 2017). For example, nitrogen-containing aerosols accounted for an estimated 30% of $PM_{2.5}$ emissions measured in Beijing from June 2014 to April 2015 (Huang et al., 2017).

Did you know?

The atmosphere we breathe is 78% dinitrogen (N_2). However, if we had to rely on dinitrogen only, it would be like floating on the sea, dying of thirst.

When adding ground-level ozone pollution, of which nitrogen is also a precursor, health costs amount to USD 1.9 trillion in OECD countries and USD 3.2 trillion in BRIICS countries (Roy and Braathen, 2017).

Despite a steady decline in NO_x emissions since 2000, most EU countries have at least one city where the annual average concentration of NO_2 exceeds (sometimes considerably) the EU's legal limit values, which are set equal to the World Health Organisation (WHO) Air Quality Guideline (OECD, 2017).

GREENHOUSE BALANCE AND THE STRATOSPHERIC OZONE LAYER

Microbial "denitrification" is a key pathway in the nitrogen cycle of soils and oceans, but a pathway that is still poorly understood. Denitrification returns nitrogen from the biosphere to the atmosphere as N_2, thereby closing the nitrogen cycle; this may involve the production of nitrous oxide (N_2O) as an intermediate product. Human activity – especially agriculture – is a major source of N_2O production. N_2O emissions of crops depend on the type of fertiliser (with emissions typically being higher for urea than for ammonium nitrate) and soil type, with emissions generally high for clay soils with poor drainage.

N_2O is the third most common long-lived GHG after carbon dioxide (CO_2) and methane. The N_2O greenhouse effect is partially offset by increased CO_2 by ecosystems uptake due to nitrogen deposition. N_2O contributes not only to climate change but also to the depletion of the stratospheric ozone layer, which protects life on Earth by absorbing some of the ultraviolet rays from the sun. With the phasing-out of chlorofluorocarbons (CFCs), N_2O has become a major depleting threat for ozone in the stratosphere (Ravishankara et al., 2009) and is currently unregulated by the Montreal Protocol on Substances that Deplete the Ozone Layer.

SOIL

Many of the natural transformations involved in the biogeochemical nitrogen cycle are carried out by microorganisms in soil. Conversion of N_2 to biologically available ("reactive") nitrogen, a process called "fixation", involves several processes, as part of the nitrogen cycle.

Nitrogen-fixing bacteria convert N_2 to NH_3, which tends to converts into NH_4^+ in non-alkaline soils. Under aerobic conditions (in the presence of oxygen), nitrifying bacteria can oxidise NH_4^+ to NO_3^- as an energy-yielding process. Because it releases hydrogen, nitrification contributes to the acidification of soils.

Under anaerobic conditions (in the absence of oxygen), denitrifying bacteria can use NO_3^- in place of oxygen, reducing it to N_2. In the process, denitrification may generate N_2O.

Microbial activity in soils is also driven by "rhizodeposition" – the release of organic carbon and

Did you know?

Microbial denitrification is a key pathway in the nitrogen cycle of soils and oceans, but a pathway that is still poorly understood.

organic nitrogen (e.g. amino acids) by plant roots into their surrounding environment – and microbial mineralisation of soil organic matter. While the available organic carbon and oxygen have a major impact on total denitrification, the soil pH mainly influences the N_2O/N_2 ratio (the ratio tends to increase with decreasing pH).

The major nitrogen threats to soil quality, for both agricultural soils and natural soils, are related to acidification and loss of soil biodiversity. Soil acidification may lead to a decrease in crop and forest growth and leaching of components negatively affecting water quality, including heavy metals. Nitrogen may also be lost from soils as NO_3^-, via leaching, or in gaseous forms such as NH_3, by volatilisation, or else N_2O and N_2, via denitrification.

The effect of nitrogen on diversity of soil micro-organisms and the effects of changes of soil biodiversity on soil fertility, crop production and nitrogen emissions towards the environment are not fully understood. Very few studies have examined the links between the nitrogen cycle, plant activity, and associated changes in microbial diversity. Despite the significance of soil organic matter in agricultural ecosystems, current knowledge of the soil organic matter dynamics is still limited. New nitrogen source discovered in Earth's bedrock challenges estimates of carbon sequestration by natural ecosystems (Houlton et al., 2018).

WATER

Water pollution by nitrogen has high costs for human health as well as for ecosystems. High concentrations of NO_3^- in drinking water can cause blood disorder in infants and may also increase risk of colorectal cancer (Schullehner et al., 2018). NO_3^- contributes to eutrophication of coastal waters, which is responsible for algal blooms (including toxic algal blooms) on the surface and can lead to the reduction or even the disappearance of oxygen ("hypoxia") and thus of fish in the deep waters that become "dead zones". There is compelling evidence of a rapid increase in the number of ocean dead zones for about 50 years, since the term was first applied to the hypoxic area of the northern Gulf of Mexico, which receives large amounts of nutrients from the Mississippi and Atchafalaya river basins. Robert Diaz, of the Virginia Institute of Marine Sciences, has so far identified no less than 884 ocean dead zones in the world.

Nitrogen finds its way into fresh water via pathways that are mainly fed by agriculture, such as groundwater, drainage water and runoff, as well as direct discharges of wastewater from firms and sewage treatment plants, and atmospheric deposition. Nitrogen pathways in marine water include nitrogen imports by river discharge and precipitation; microbial fixation of N_2; and bacterial remineralisation of dead particulate biomass in sediments.

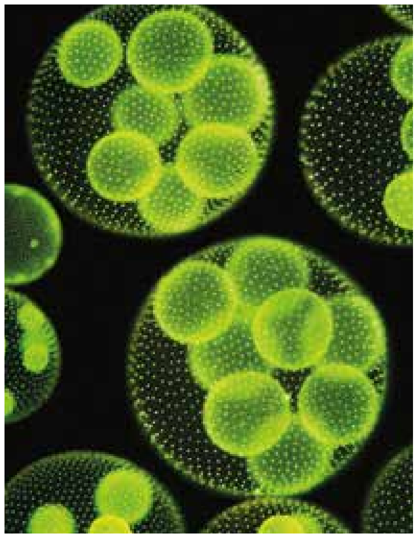
Oceanic currents may shift the impact of excess nitrogen over long distances. For example, nitrogen from the Amazonian Basin, where soils are washed away by the rains as a result of deforestation and intensive agriculture, has largely contributed to the proliferation of algae in coastal areas of the Caribbean.

Climate change could aggravate fresh water pollution by nitrogen. For example, climate change-induced precipitation changes alone are projected by one recent study to increase runoff nitrogen in U.S. waterways by 19% on average over the remainder of the century under a business-as-usual climate scenario (Sinha et al., 2017). Ocean dead zones are particularly vulnerable to climate change, which exacerbates hypoxic conditions by increasing sea temperature, ocean acidification, sea level, precipitation, and, in some regions, wind and storms (Altieri and Gedan, 2015).

Did you know?

70% of protected ecosystems across Europe exceed critical loads for eutrophication due to nitrogen deposition.

(Posch et al., 2018)



ECOSYSTEMS AND BIODIVERSITY

Nitrogen reduces the diversity of vegetation primarily through eutrophication and acidification. The accumulation of extra nutrients (eutrophication) is harming habitats whose biodiversity developed in direct response to low nutrient levels. Acidification is a cumulative problem for non-alkaline soils; as the acid-neutralising capacity of soils gets depleted, the ecosystems become increasingly sensitive to additional acid inputs. More generally, ecosystem responses to the form of nitrogen (e.g. NO_3^-, NH_3, NH_4^+, nitrogen-containing aerosols, ground-level ozone) are complex and habitat dependent, with conversion between nitrogen forms resulting from the activities of soil microbes.

Habitat changes caused by nitrogen excess may affect all taxonomic groups. Hernández et al., 2016 showed that 78 of the 1 400 species of invertebrates, vertebrates and plants listed under the US Endangered Species Act were affected by the direct toxicity of nitrogen, by eutrophication of their habitat or by the spread of non-native plant species due to nitrogen pollution.

Little recognition has been given to the environmental consequences of nutrients that fall from the air as wet and dry deposition onto aquatic ecosystems. Even if nitrogen deposition rates were to be significantly reduced in the future, habitat recovery can be very slow (Stevens, 2016).

Excess nitrogen (and phosphorus) in water can cause overstimulation of growth of aquatic plants and algae. Excessive growth of these organisms, in turn, can use up dissolved oxygen as they decompose, and block the passage of light to deeper waters. Eutrophication of lakes and coastal areas can occur, which produces unsightly scums of algae on the water surface, can occasionally result in fish kills, and can even "kill" a lake by depriving it of oxygen.

Table 1. **KEY THREATS OF EXCESSIVE RELEASE OF NITROGEN INTO THE ENVIRONMENT**

Environmental issue	Adverse impact on health and the environment	Main form of nitrogen involved	Main activity
Water	Freshwater and marine water pollution	Nitrate (NO_3^-)	Agriculture, atmospheric deposition, sewage discharge
Air	Effects on human health and vegetation	Nitrogen oxides (NO_x) Ammonia (NH_3) Particulate matter Ground-level ozone	Burning fossil fuels to a large extent Manure storage and spreading Formed from NO_x and NH_3 precursors Formed from NO_x precursor
Greenhouse balance and ozone layer	Climate change and ozone layer depletion	Nitrous oxide (N_2O)	Agriculture to a large extent
Ecosystems and biodiversity	Eutrophication and acidification of terrestrial ecosystems and freshwater and marine ecosystems	Nitrate, ammonium (NH_4^+) and organic nitrogen	Agriculture, atmospheric deposition, sewage discharge
Soil	Soil acidification	Chemical fertilisers and organic nitrogen	Agriculture

2 Understanding the "Nitrogen Cascade"

In contrast with many other pollutants, nitrogen can change form and go a long way once released into the environment. As it moves through the biogeochemical pathways, the same nitrogen atom can cause a sequence of negative effects – in the atmosphere, in terrestrial ecosystems, in freshwater and marine systems, and on the climate.

For example, the biogeochemical path of a nitrogen atom from its point of formation could be the following. NO_x emissions from cars and power plants can form NO_2, a vector of asthma, then create ground-level ozone (O_3), a component of smog, and then be converted to nitric acid (HNO_3), a major component of acid deposition; or, NO_x can combine with NH_3 to form fine particles of ammonium nitrate (NH_4NO_3), the inhalation of which can cause serious health problems. Once removed from the atmosphere, nitric acid and ammonium nitrate particles can cause both fertilisation and acidification of soils, which in turn (via NO_3^- runoff and leaching) can lead to acidification and eutrophication of freshwater. NO_3^- can then be transported to coastal areas, where it contributes to the formation of dead zones: when fishermen trawl in these areas, little to nothing is caught. Finally, bacteria can convert reactive nitrogen in soil and water into N_2O, contributing to the greenhouse effect in the troposphere and the destruction of the ozone layer in the stratosphere. This complex web of transformations has been called the "nitrogen cascade" (Figure 1).

Did you know?

Nitrogen dioxide (NO_2) and ammonia (NH_3) are not only air pollutants, but they can also form ammonium nitrate (NH_4NO_3) particles that are particularly harmful to health.

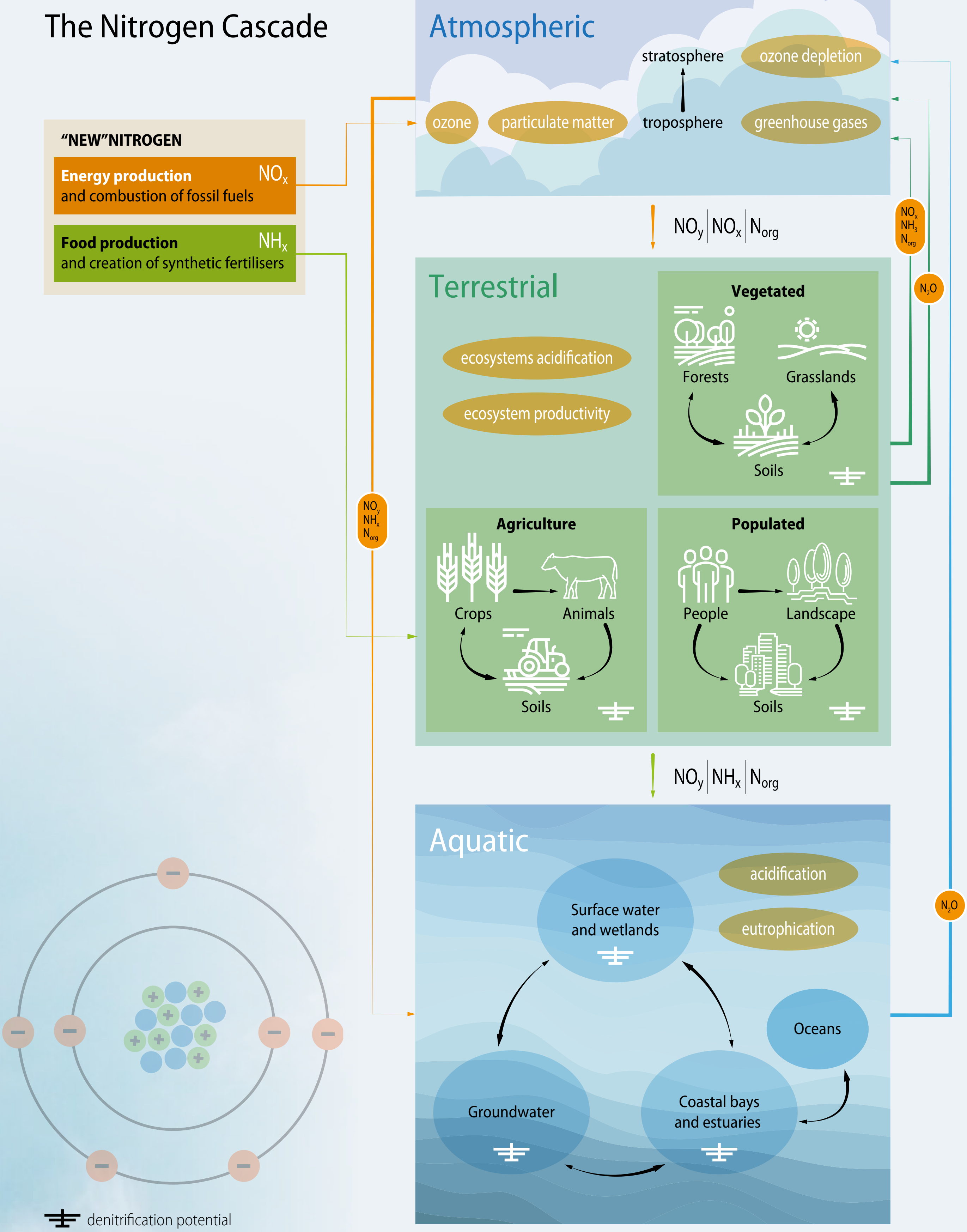
Many transformations of nitrogen in various forms contribute to its movement within and between terrestrial, atmospheric, and aquatic ecosystems. As a result, the intended beneficial effects of a policy for one ecosystem may become unintended detrimental effects for adjacent ecosystems, or even within the ecosystem in which nitrogen is released.

Agricultural practices, in particular, can have unintended consequences if the nitrogen cascade is not taken into account. Increased use of commercial nitrogen fertiliser in the United States, by 72% between 1970 and 2010, for example, has fuelled an increase in yields but has also posed increased risks to environmental quality. The Natural Resource Conservation Service (NRCS) of the U.S. Department of Agriculture evaluated the use of conservation practices on U.S. cropland in major river basins using survey data collected over 2003-06. The NRCS found that, on the whole, a great deal of improvement was needed. For example, injecting or incorporating inorganic and organic nitrogen fertiliser into the soil reduces atmospheric losses, but can increase nitrate leaching. Fertilising only during the growing season can reduce nitrate loss to water but may increase nitrous oxide emissions to the atmosphere.

The "cascading nature" of nitrogen flows in the environment suggests there are benefits to coordination of practices, and of policies to incentivise them, rather than piecemeal control. Focusing on one particular environmental medium, such as air, can create incentives for management that result in degradation in a different medium, such as water.

In general, not creating pollution in the first place avoids the problems posed by trying to control different nitrogen pathways. In the case of cropland, application of the 4R concept (the right type of fertiliser at the right rate applied at the right time in the right place) to achieve better nitrogen use efficiency reduces nitrogen loss along all pathways, avoiding the trade-offs characteristic of most other conservation practices.

Figure 1. **THE NITROGEN CASCADE AND ITS IMPACTS**



Source: US EPA Science Advisory Board (undated), nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_008785.pdf.

Nitrogen pathways analysis and risk management

Three approaches exist to counter nitrogen pollution:

- **The spatially targeted risk approach** seeks to better manage well-documented risks of air, soil and water pollution and associated ecosystems through a detailed analysis of the biogeochemical pathways between nitrogen sources and impacts ("impact-pathway analysis").

- **The global risk approach** addresses the steady increase in nitrous oxide concentrations in the atmosphere. Nitrous oxide, which affects climate change and the stratospheric ozone layer, is the only form of nitrogen that has a global impact. It is a long-lived and well-mixed gas in the atmosphere, so the challenges it poses can only be tackled globally.

- **The precautionary approach** takes into account the uncertainty of cascading effects and anticipates potentially significant long-term impacts, such as the risk of undermining the resilience (of exceeding the coping capacity) of ecosystems to nitrogen overload. It aims to monitor and manage trends in the excess of nitrogen entering the environment by measuring the overall effect of the two previous approaches on the national nitrogen balance.

THE SPATIALLY TARGETED RISK APPROACH: USING IMPACT-PATHWAY ANALYSIS

Policies aimed at managing the risks posed by nitrogen often focus on a specific impact without fully considering the biogeochemical pathways that contribute to this impact. Better knowledge of these pathways can improve risk management by identifying the points of cost-effective policy intervention. For example, for a given risk of water pollution, reducing the NO_x emissions that contribute to the risk (by atmospheric deposition) may prove more beneficial than reducing nitrogen from land-based sources when NO_x also causes health problems prior to deposition.

Impact-pathway analysis (IPA) evaluates the pathways that generate an impact (including through modelling) to estimate the expected benefits of possible emissions changes. IPA recognises that nitrogen can move between environmental media (air, water, soil and biota) as it travels along pathways from one or more sources to a receptor.

IPA can be carried out in four steps:

- **First**, identify and delineate the different "nitrogen emission zones" of relevance to the impact (i.e. the "risk area").

- **Second**, estimate the potential for new or additional emission reductions in each emission zone.

- **Third**, compare the cost-effectiveness of emission reductions in the different emission zones.

- **Fourth**, estimate the co-benefits of reducing nitrogen emissions in the different emission zones – that is, the damage avoided in all of the regions through which that nitrogen would cascade.

The feasibility of IPA raises the issue of cost. As a general principle, the level of IPA sophistication should match the expected level of nitrogen pollution risk. When major impacts are at stake, a precise and detailed IPA is required (Boxes 1 and 2). On the other hand, when risk levels are low, a basic IPA can be used.

To implement the spatially targeted risk approach, policies need to be not only economically efficient, but also practically feasible. Public acceptability is vital, including the agreement of stakeholders to delineate risk areas and emission zones. Administrative feasibility issues may also arise: nitrogen pathways seldom follow administrative boundaries.

THE GLOBAL RISK APPROACH: MANAGING NITROUS OXIDE

IPA does not apply to N_2O, because risk exposure – be it the risk of climate change or the risk of depleting the ozone layer – is global. Delineating emission zones, even if possible, would be of no use. Indeed, the more sources to compare, the more likely it is to find the one for which emission reduction is the most cost-effective. In other words, as many sources of N_2O as possible should be identified, wherever they are in a given country, so as to compare the costs – and if possible the ancillary benefits – of reducing their emissions.

Applying a global approach does not necessarily mean that each government must aim for a reduction in N_2O emissions. The climate change mitigation goal set out in the Paris Agreement does not set an individual reduction target for each GHG, but rather a global temperature target. N_2O is part of a basket of GHGs under the United Nations Framework Convention on Climate Change (UNFCCC) and countries will decide how to prioritise GHG emission reductions across different sectors and gases in their nationally determined contributions, informed by the five-yearly global stocktakes envisaged under the Paris Agreement.

THE PRECAUTIONARY APPROACH: ANTICIPATING LONG-TERM IMPACTS

The increased amount of reactive nitrogen produced by humans, intentionally (for food production) and unintentionally (result of fossil fuel combustion and industrial processes) has enhanced the speed of nitrogen cycling – the rates at which nitrogen is being added to and lost from the environment. There remains uncertainty about exactly what this acceleration of the nitrogen cycle means for the pathways that nitrogen takes – the "nitrogen cascade" and consequently the extent of damages to human health and ecosystems. But the "precautionary principle" suggests that this uncertainty should not stop us from acting to limit the amount of nitrogen entering the environment. According to the precautionary principle, when an activity raises threats of harm to human health or the environment, precautionary measures should be taken, even if some cause and effect relationships are not fully established scientifically.

Managing uncertainty does not necessarily require a reduction in all emission sources. Rather, the precautionary approach should be closely associated with the risk approach as part of a dual method of managing human impacts on the nitrogen cycle. A precautionary approach would aim to limit the total reactive nitrogen load entering the system and, where appropriate, propose measures in addition to and in line with risk management measures.

The precautionary approach raises the thorny question of the limit to be set in terms of the nitrogen balance of a country, or even of the planet. It is too early to discuss any such limit but in the meantime, countries could establish an economy-wide nitrogen balance and begin to monitor and, as appropriate, manage trends. This would involve assessing the total amount of nitrogen introduced into the environment from all sources and monitoring these sources in order to report – both by source and overall – the amount of nitrogen released each year, also taking into account denitrification. This should be undertaken in parallel with risk-based efforts to manage specific nitrogen impacts.

4 Targeted policies to halt nitrogen pollution

Nitrogen emissions have been reduced in the OECD area over the past three decades, but there are hotspots of nitrogen pollution in air, soil and water.

OECD countries have adopted measures to reduce long-range transported air emissions as well as targeted measures to reduce local emissions (e.g. in cities and to protect sensitive ecosystems). Similarly, measures have been taken to reduce nitrogen discharges into water.

Emissions of NO_x – from stationary combustion installations in the energy sector and from the transport sector – felt by 46% between 1990 and 2016; during this period, N_2O emissions decreased by 12% (OECD.stat, accessed 3 October 2018). Agricultural nitrogen surplus, as measured by the OECD nitrogen balance indicator, was reduced on average from 85 kg/ha in 1992 to 67 kg/ha in 2014 (OECD, 2018a).

However, air quality standards with regard to NO_2, ground-level ozone and PM are still being exceeded regularly, particularly in large urban centres. Terrestrial ecosystems are still being affected by eutrophication and, to a lower extent, by acidification. Although N_2O emissions have decreased, the cumulative concentration of N_2O in the atmosphere continues to increase (by 6% between 1990 and 2016 according to the National Oceanic and Atmospheric Administration of the US Department of Commerce). Many groundwater bodies are still highly affected by NO_3^- contamination. Overall, there is little indication of any fundamental improvement in the eutrophication situation in coastal waters as Florida's red tide blooms reminded us in the summer of 2018. Florida had to declare the state of emergency, the spread of toxic algae killing many fish, threatening to upturn Florida's vital summer tourist season.

Two case studies show how impact-pathway analysis (IPA) can help manage impacts more cost-effectively by fostering evidence-informed policy making: deposition analysis in urban smog control in Paris, and combined management of atmospheric, ocean and land-based nitrogen inputs to avoid eutrophication of the Chesapeake Bay coastal zone in the United States (see Boxes 1 and 2).

Box 1. MONITORING URBAN SMOG IN PARIS

In March 2014, Paris suffered a major peak of particle pollution that lasted for ten days (Figure 2). IPA revealed that half of the coarse particles (PM_{10}) were NH_4NO_3, secondary particles formed by a combination of NO_x emitted mainly by urban transport and NH_3 originating from farming activity in distant geographical areas. The other half of the PM_{10} originated mainly from primary particles formed by combustion of biomass (wood heating) and fuel combustion (including transport).

This IPA finding had a direct implication for policy. It led the French authorities to argue that it was just as justified to restrict fertiliser application as it was to restrict traffic in order to curb urban air pollution. Measures taken included setting speed limits on roads, making residential parking free of charge, calling on farmers to temporarily limit fertiliser use and firms to limit industrial activity, and promoting the use of public transport.

This example shows how IPA led policymakers to address pollution emanating not only from the household heating and transport sectors, but also – and this is more unusual – from agriculture, which had historically not been considered when thinking about reducing urban air pollution. Other studies have since revealed that agricultural emissions have a significant impact on air quality in many cities. For example, agriculture contributes to 23% of the background concentration levels of $PM_{2.5}$ in the 150 urban areas surveyed in the EU-28, Norway and Switzerland (Thunis et al., 2017).

Figure 2. **PARTICLE ALERT THRESHOLD EXCEEDED IN PARIS IN MARCH 2014**

Note: On the left, the Eiffel Tower before the particle pollution episode. On the right, a photo taken at the same place on 14 March 2014.

Source: http://www.natura-sciences.com/environnement/particules-fines-pics-pollution810.html.

Box 2. CONTROLLING FOR EUTROPHICATION IN CHESAPEAKE BAY

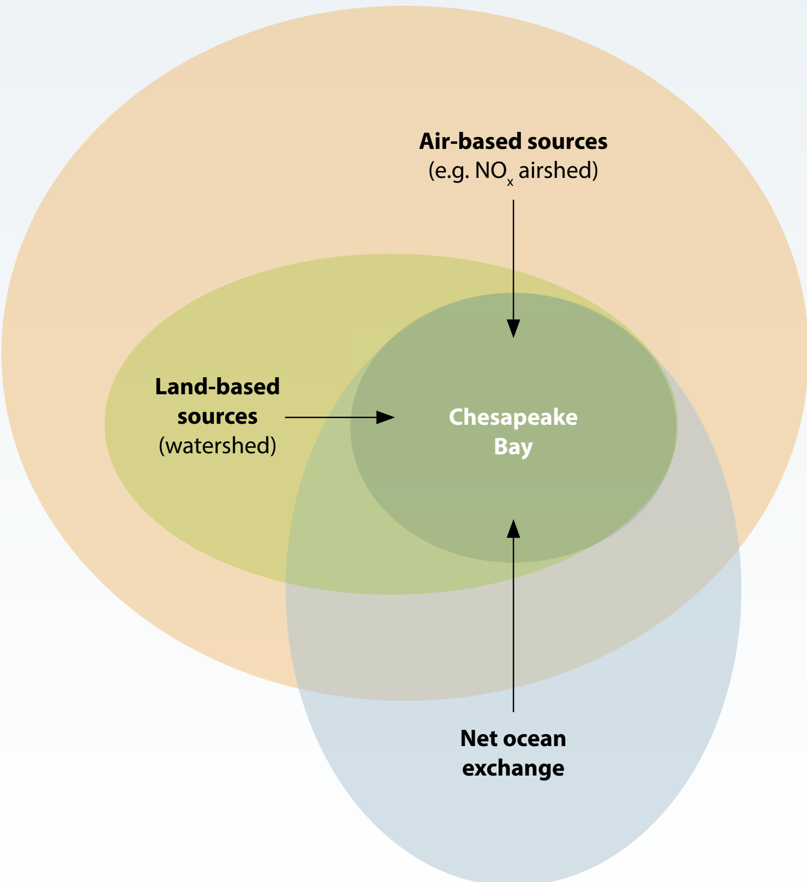
The Chesapeake Bay Watershed covers 90 000 square miles (23 million hectares) across six U.S. states (Delaware, Maryland, Pennsylvania, New York, Virginia, West Virginia) and Washington D.C. Land use is forest (64%), agriculture (24%), urban (8%) and other (4%). Nitrogen, phosphorus and sediment wash from the watershed into the tidal waters of the Bay, resulting in little or no dissolved oxygen in the bay and tidal rivers every summer. The low dissolved oxygen content results mainly from the excessive growth of algae caused by nutrients such as nitrogen and phosphorus. The decomposition of dead algae consumes oxygen, depriving fish and other forms of aquatic life.

In December 2010, a total maximum daily load (TMDL) of nitrogen and phosphorus allowed to enter the tidal Bay was set. TMDL applies to land-based nutrient sources in the watershed (agriculture, urban runoff, sewage) and, a first in the United States, to atmospheric nitrogen deposition in the watershed. The relevant "airshed" — the area where emission sources contribute most to deposition in the Bay's watershed — was delineated for NO_x and NH_3 to model nitrogen deposition. Another TMDL has been established for direct atmospheric deposition of nitrogen in tidal waters. Bay pollution management also considers nitrogen exchanges between the Bay and the ocean.

IPA analysis involves a step-by-step approach. First, data from a watershed-scale land use change model and an airshed model as well as other metrics (meteorology, topography, soils, point sources of nitrogen) are transmitted to a watershed model. The watershed model then predicts the loads of nitrogen, phosphorus, and sediment that result from the given inputs. The estuarine Water Quality and Sediment Transport Model (WQSTM) (also known as the Chesapeake Bay Model) predicts changes in bay water quality due to the changes in input loads provided by the watershed model. As a final step, dissolved oxygen, chlorophyll and water clarity are measured to assess whether Bay water quality standards were attained.

The combined management of atmospheric, land-based and ocean-based nitrogen inputs in Chesapeake Bay reflects the reality of the nitrogen cycle (Figure 3). Such an IPA makes the risk management of oxygen loss in the bay's waters more cost-effective. The Chesapeake Bay Programme has been effective as a whole since the TMDLs were introduced, although progress remains to be made to meet the nitrogen load target of 2025. Estimated nitrogen loads in the bay watershed decreased by 9% between 2009 and 2016.

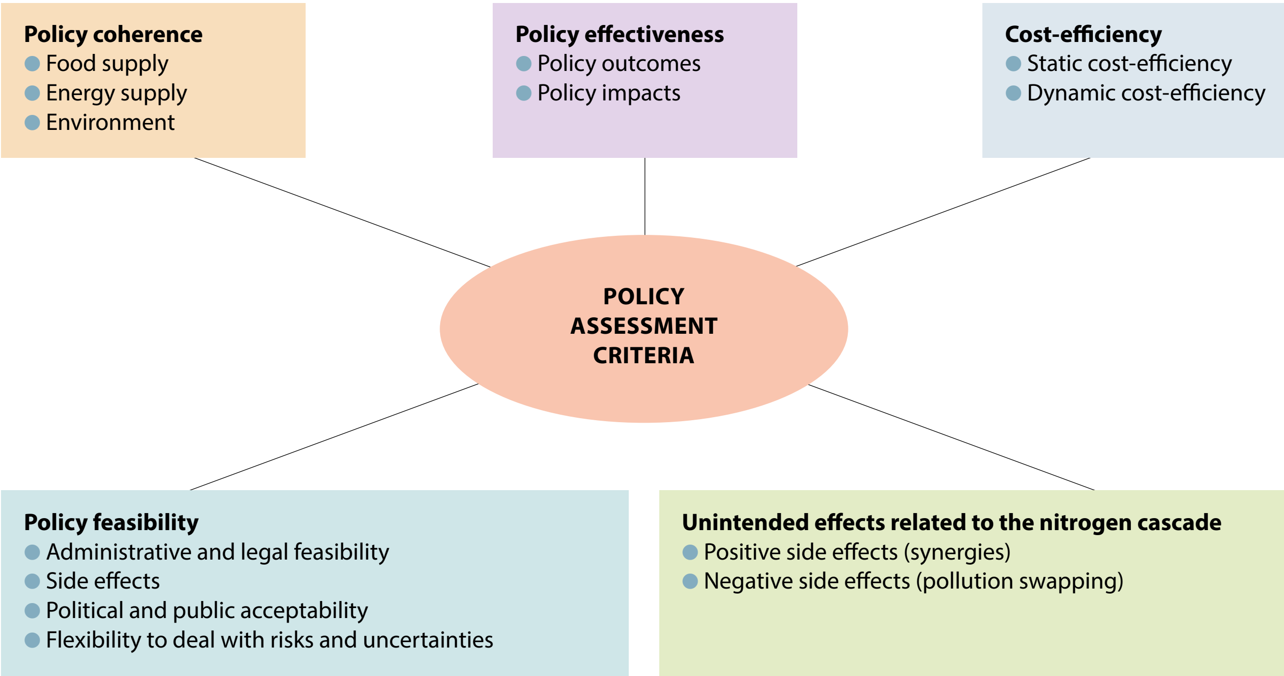
Figure 3. **REGULATED NITROGEN SOURCES IN THE CHESAPEAKE BAY**



Did you know?

The first reported ocean dead zone was the Gulf of Mexico in the 1960s; today the gulf is still affected by eutrophication and 883 other coastal areas have been added to the list of dead zones, not counting undeclared areas (e.g. in the tropics).

Figure 4. **CRITERIA TO GUIDE NITROGEN POLICY MAKING**



A FRAMEWORK FOR ANALYSING THE MERITS OF NITROGEN MANAGEMENT POLICY INSTRUMENTS

Evaluation criteria are needed to select the right risk management or uncertainty management tools (Figure 4). First, it is necessary to evaluate and address the coherence of sectoral policies (e.g. agricultural policy, energy policy) and environmental policies (climate policy and others) with the management of nitrogen pollution.

This first step is crucial to avoid having to introduce additional policy measures to counter the undesired effects of other existing policies (e.g. the imposition of a fertiliser tax to counter support to farm inputs), which would obviously not be economically and perhaps not even environmentally effective. Second, nitrogen policy instruments that are cost-effective and whose feasibility of implementation is not problematic may then be selected. Third, due to the nitrogen cascade, the effects of an instrument targeting one impact or one form of nitrogen on other impacts or forms of nitrogen should be estimated, in order to promote synergies and avoid "pollution swapping".

POLICY COHERENCE

Just as some forms of agricultural support can distort input use and agricultural production and thus have negative environmental impacts (such as increased nitrogen pollutant emissions), some forms of energy support can distort energy production and use, such as fossil fuel subsidies. Before designing targeted policies on nitrogen pollution, it is therefore essential to monitor and evaluate policies with other aims and their unwanted effects on nitrogen emissions.

For example, China has taken steps to phase out fertiliser subsidies and aims to cap fertiliser use by 2020. The 2020 Zero-Growth Action Plan for Chemical Fertilisers and Pesticides aims to reduce the annual growth of chemical fertiliser use to below 1% for the 2015-19 period and achieve zero-growth by 2020 for major agricultural crops. However, these policy developments need to be weighed against a backdrop of growing support for Chinese farmers, including forms of support that distort agricultural production and can encourage increased fertiliser use (OECD (2018b).

Policy coherence must also be sought with environmental policies that are not primarily aimed at reducing nitrogen pollution. For example, in New Zealand, a policy to reduce CO_2 emissions has helped reduce the leaching of NO_3^- into water. An Emissions Trading Scheme (ETS) allows GHG emitters who do not want to reduce their emissions to enter into agreements with farmers who agree to sequester carbon. With financial compensation, farmers undertake to convert pastoral lands into forests, thereby helping to reduce the leaching of NO_3^- into water. GHG emitters receive ETS credits in exchange for pastoral land converted to forestry.

EFFECTIVENESS, COST-EFFICIENCY AND FEASIBILITY

The full report provides a typology of different nitrogen management policy instruments (e.g. pricing instruments, direct environmental regulation, financial support instruments, information measures, and voluntary schemes). Existing policy analysis methodologies tend to assess the performance of a policy instrument against the criteria of environmental effectiveness and economic efficiency. But such a view neglects "real world" complications that often act to limit policy effectiveness, the "feasibility" criterion.

Effectiveness gauges whether a policy intervention has led to successful practical measures (e.g. the use of catalytic converters in vehicles) or overall benefits (e.g. reduced disturbance of the nitrogen cycle). **Cost-efficiency** asks whether the intervention's objective is being achieved at the least cost to society.

Feasibility of instrument implementation is essential if an instrument is to be introduced and function effectively. The concept may be broken down into five general aspects: administrative feasibility; side effects (e.g, on equity, competitiveness, health and the environment); political and public acceptability; legal compatibility and institutional feasibility, and the flexibility of an instrument (its ability to respond to changes and uncertainty).

Broader policy assessment criteria are required to capture these nuances and allow for a more rounded evaluation of the relative desirability of policy instruments for different applications. The full report evaluates in detail the effectiveness, cost-efficiency and feasibility of seven categories of policy instruments (see for example Boxes 3 and 4), and their combinations. The evaluation leads to six conclusions.

- Instruments should be based on their impact and applied as close as possible to the point of emission to maximise effectiveness and cost-efficiency.
- **Pricing** and **direct environmental regulation** are often most effective in reducing pollution, when subject to credible monitoring and enforcement.
- "Beneficiary pays" instruments (e.g. **public financial support**), along with voluntary and informational instruments, are often more politically feasible than "polluter pays" instruments (e.g. **pricing mechanisms**), although they are likely to be less effective.
- Combining "polluter pays" with "beneficiary pays" instruments may be more politically feasible to achieve a given level of environmental effectiveness than either employed individually.
- Combining **pricing** or **public financial support** instruments with **direct environmental regulation** may be mutually beneficial for various reasons (e.g. it reduces vulnerability to market distortions (such as split-incentives and environmentally harmful subsidies) as well as the potential to create pollution hotspots).
- **Voluntary** and **information instruments** may require the lowest administrative capacity (and produce the least transaction costs). The use of information instruments is likely to increase the effectiveness, cost-efficiency or feasibility (or a combination of these assessment criteria) when combined with all other instrument categories.

Box 3. USING A TRADEABLE PERMIT SYSTEM IN THE GREAT MIAMI RIVER WATERSHED

Around 40% of surface waters in the Great Miami River watershed of around 10 000 km^2 in Southwest Ohio, United States, were consistently failing to meet regulatory water quality standards. In response, the regional water management agency, the Miami Conservancy District (MCD), in 2004 introduced the Great Miami Watershed Trading Programme (GMWTP) as a pilot scheme for a cost-effective approach to improving water quality, in anticipation of regulatory measures to set nutrient release limits on point-source wastewater treatment plants (WWTPs).

Agricultural activities cover around 70% of land in the watershed, are the primary contributor to the excess nutrient release and are able to achieve nutrient reductions at a lower cost than WWTPs. The GMWTP encourages farmers to adopt voluntary "best practice" measures to generate Emission Reduction Credits (ERCs), which may be traded to WWTPs to allow for future regulatory compliance.

Effectiveness. By mid-2014, 397 agricultural projects were contracted, generating over 1.14 million credits worth over USD 1.6 million, and producing an estimated 572 metric ton reduction in nutrient discharges to surface waters in the watershed.

Cost-efficiency. Trades completed have thus far produced a cost of USD 1.48/lb of nutrient abated. This is significantly less than the estimated USD 4.72/lb abated estimated for measures implemented directly by WWTPs, suggesting significantly higher cost-efficiency than a regulatory approach applied to point sources only.

Feasibility. The cost-effective nature of the GMWTP makes it popular amongst WWTPs. During formulation of the GMWTP, over a hundred meetings took place with a wide range of stakeholders, leading to wide acceptance and support for the instrument.

Box 4. DIRECT ENVIRONMENTAL REGULATION: JAPAN'S AUTOMOBILE NO_x AND PM LAW

In Japan, levels of NO_x pollution continued to rise throughout the 1980s as a result of increasing vehicle traffic. In response, the 1992 Law Concerning Special Measures for Total Emission Reduction of Nitrogen Oxides from Automobiles in Specified Areas (NO_x Law) was enacted.

The law required the prefectures of the large urban areas of Tokyo and Osaka to establish and implement local plans to reduce NO_x emissions from vehicles. In 2001 PM was added as a target substance, and Nagoya was added as an additional obligated prefecture.

Effectiveness. NO_x emissions decreased around 20% between 2000 and 2009 in the areas subject to the revised law, twice the rate experienced outside the obligated prefectures. Regulating vehicle types – including banning the registration of high-polluting vehicles and enforcing the replacement of those already in circulation – was the key factor behind this result.

Cost-efficiency. The NOx Law cost up to JPY 521 billion (around USD 5 billion). The total social benefits of the regulation – including reduced health impacts and spillover effects in neighbouring, non-obligated regions – are likely to have exceeded this cost by at least double.

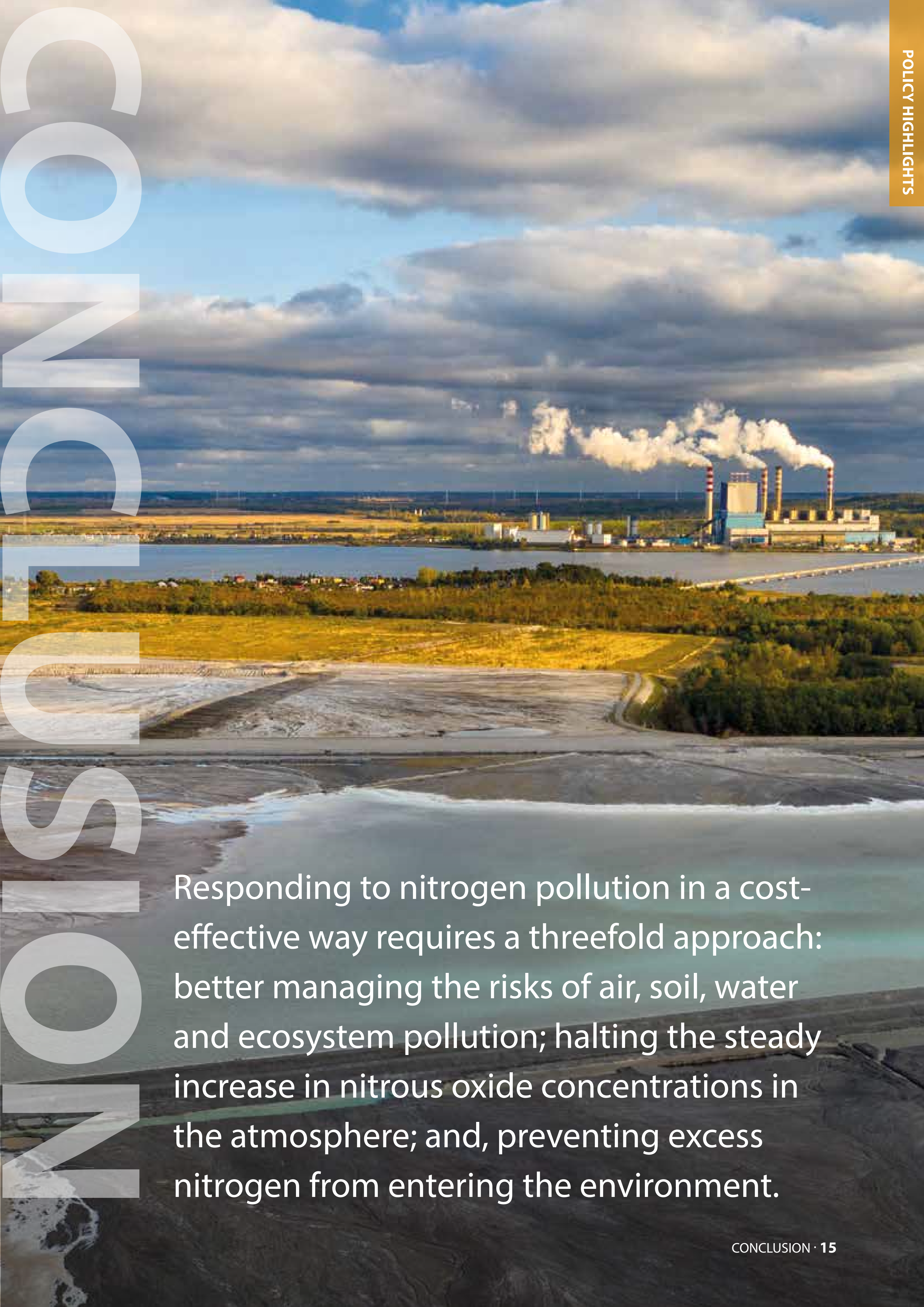
Feasibility. Public pressure, along with an increasing number of successful lawsuits filed by organisations representing victims of pollution-related health damage, had already led to a succession of anti-pollution laws from the 1960s onwards. The resulting awareness of pollution-related health issues in the population is likely to have provided support for the NO_x and PM law.

NITROGEN AS A "CASCADING TARGET"

Whatever the policy approach – risk or precautionary – nitrogen policy instruments also need to be refined by evaluating their unintended effects on other forms of nitrogen due to the nitrogen cascade – the fact that once fixed, nitrogen tends to change form. In particular, efforts to lessen the impacts caused by nitrogen in one area of the environment should (i) not result in unintended nitrogen impacts in other areas ("pollution swapping"), and (ii) seize opportunities to reduce other nitrogen impacts ("synergy" effects).

It is therefore necessary to assess risk-risk trade-offs of various policies or best management practices, whether in agriculture, fossil fuel combustion, industrial processes or treatment of wastewater.

For example, using selective catalytic reduction (SCR) systems to reduce NO_x emissions from vehicles raises new concerns about emissions of the by-products NH_3 and N_2O. In contrast, tertiary treatment of sewage to remove NO_3^- also reduces N_2O emissions from sewage. However, the incineration of sewage sludge (as is the norm in Switzerland, for example) releases NO_x.



CONCLUSION

Responding to nitrogen pollution in a cost-effective way requires a threefold approach: better managing the risks of air, soil, water and ecosystem pollution; halting the steady increase in nitrous oxide concentrations in the atmosphere; and, preventing excess nitrogen from entering the environment.

REFERENCES

Altieri, A.H. and K.B. Gedan (2015), "Climate Change and Dead Zones", *Global Change Biology*, 21(4), Wiley, Hoboken.

Fowler, D. et al. (2013), "The Global Nitrogen Cycle in the Twenty-first Century", *Phil. Trans. R. Soc. B*, 368(1621), The Royal Society, London, http://rstb.royalsocietypublishing.org/content/368/1621/20130164.

Hernández, D. L. et al. (2016), "Nitrogen Pollution is Linked to US Listed Species Declines", *BioScience*, 66(3), Oxford University Press, Oxford, https://academic.oup.com/bioscience/article/66/3/213/2468675.

Houlton, et al. (2018), "Convergent Evidence for Widespread Rock Nitrogen Sources in Earth's Surface Environment", *Science*, 360(6384).

Huang, X. et al. (2017), "Chemical Characterization and Synergetic Source Apportionment of $PM_{2.5}$ at Multiple Sites in the Beijing–Tianjin–Hebei Region, China", *Atmospheric Chemistry and Physics,* 17, European Geosciences Union, Munich, www.atmos-chem-phys.net/17/12941/2017/.

OECD (2018a), "Agri-environmental Indicators: Nutrient Balances", paper presented to the Joint Working Party on Agriculture and the Environment at its meeting on 22-23 October 2018, (COM/TAD/CA/ENV/EPOC(2018)5/REV1).

OECD (2018b), *Agricultural Policy Monitoring and Evaluation 2018*, OECD Publishing, Paris, doi.org/10.1787/agr_pol-2018-en.

OECD (2017), *Green Growth Indicators 2017*, OECD Publishing, Paris, doi.org/10.1787/9789264268586-en.

Posch, M. et al. (2018), "The 2017 Critical Loads Data: Differences to Earlier Estimates and Implications for Current and Future Ecosystems Protections", CIAM Report 1/2018, Centre for Integrated Assessment Modelling, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, www.unece.org/fileadmin/DAM/env/documents/2018/Air/EMEP/CIAM-2018_report.pdf.

Ravishankara, A.R. et al. (2009), « Nitrous Oxide (N_2O): the Dominant Ozone-depleting Substance Emitted in the 21st Century", *Science*, 326(5949).

Roy, R. and N. Braathen (2017), "The Rising Cost of Ambient Air Pollution thus far in the 21st Century: Results from the BRIICS and the OECD Countries", *OECD Environment Working Papers*, N° 124, OECD Publishing, Paris, doi.org/10.1787/d1b2b844-en.

Schullehner, J. et al. (2018), « Nitrate in Drinking Water and Colorectal Cancer Risk: A Nationwide Population-based Cohort Study", *International Journal of Cancer*, 23 February (Epub ahead of print).

Sinha, E. et al. (2017), "Eutrophication will Increase During the 21st Century as a Result of Precipitation Changes", *Science*, 357(6349), American Association for the Advancement of Science, Washington, D.C., http://science.sciencemag.org/content/357/6349/405.

Stevens, C.J. (2016), "How Long do Ecosystems Take to Recover from Atmospheric Nitrogen Deposition?", *Biological Conservation*, 200.

Stocker, B.D. et al. (2016), "Terrestrial Nitrogen Cycling in Earth System Models Revisited", *New Phytologist*, 210(4), doi.org/10.1111/nph.13997.

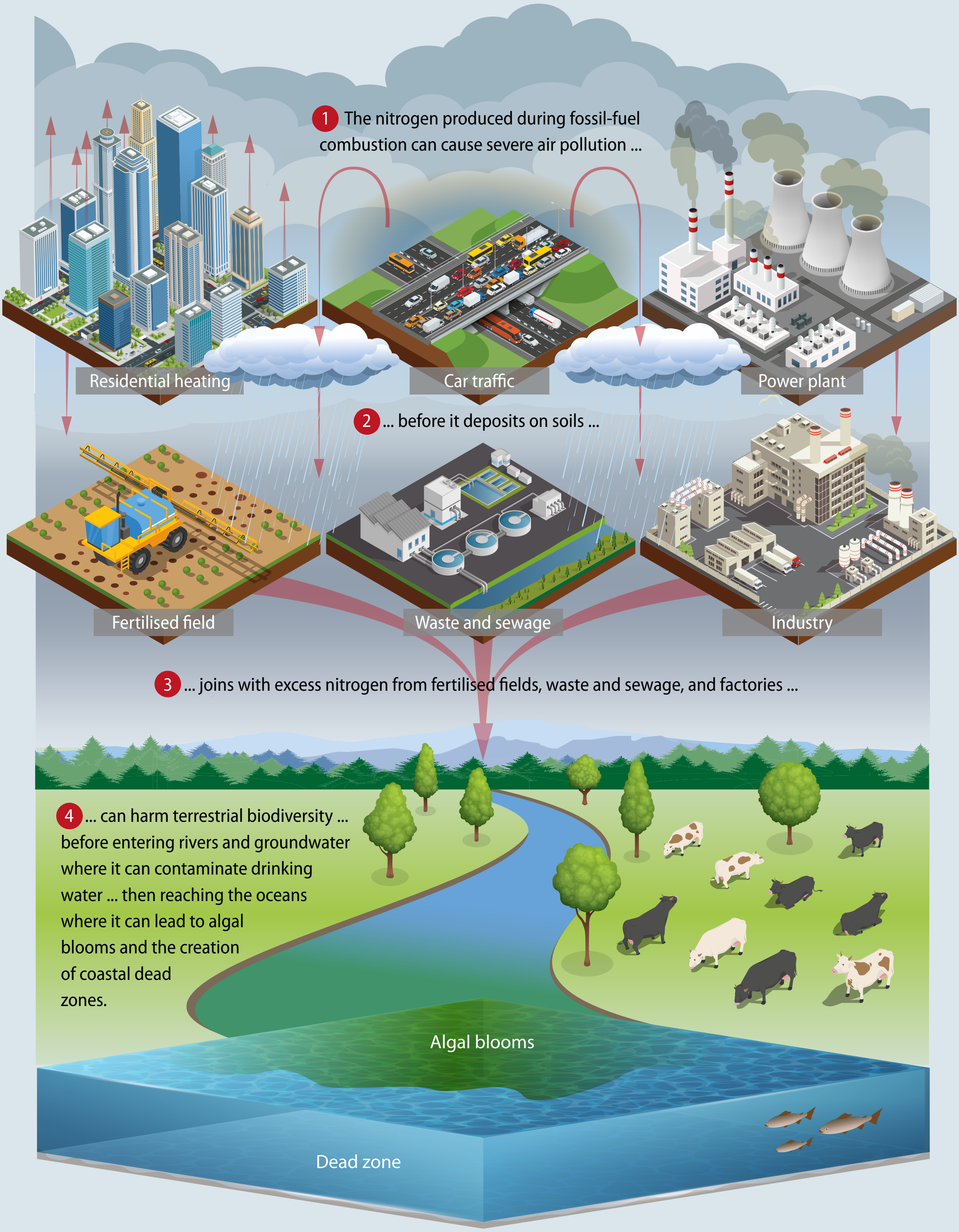
Thunis, P. et al. (2017), *Urban $PM_{2.5}$ Atlas - Air Quality in European Cities*, European Commission, Joint Research Centre, JRC108595, EUR 28804 EN, Publications Office of the European Union, Luxembourg.

Townsend, A.R. and R. W. Howarth (2010), "Fixing the Global Nitrogen Problem", *Scientific American,* (302)2.

USEPA-SAB (2011), *Reactive Nitrogen in the United States: An Analysis of Inputs, Flows, Consequences and Management Options*, U.S. Environmental Protection Agency's Science Advisory Board, EPA-SAB-11-013, USEPA, Washington D.C., yosemite.epa.gov/sab/sabproduct.nsf/WebBOARD/INCFullReport/$File/Final%20INC%20Report_8_19_11(without%20signatures).pdf.

NITROGEN'S DARK SIDE

N_2 gas, the most abundant component of the earth's atmosphere, is harmless. But, reactive forms emanating from the burning of fossil fuels in power plants, cars and residential heating, from overuse as inputs for agricultural production and certain industrial productions, and from waste and sewage create risks and generate uncertainty for human health and the environment.



In soils and water, denitrifying bacteria reconvert the reactive forms of nitrogen to inert N_2. In doing so, however, they often generate nitrous oxide, a potent greenhouse gas that also depletes the stratospheric ozone layer.

Source: Adapted from Townsend and Howarth (2010).

The OECD publication *Human Acceleration of the Nitrogen Cycle: Managing Risks and Uncertainty* examines the risks associated with the release of excessive nitrogen into the environment (climate change, depletion of the ozone layer, air pollution, water pollution, loss of biodiversity, deterioration of soil quality). The report also examines the uncertainty associated with the ability of nitrogen to move from one ecosystem to another and cause "cascading effects". In addition to better management of nitrogen risks at the local level, there is a need to consider the global risks associated with the continued increase in nitrous oxide concentrations and to prevent excess nitrogen in all its forms by developing cost-effective strategies for all its sources. Other than the reduction of nitrogen pollution, this report provides guidance on the use of nitrogen policy instruments and how to ensure coherence with objectives such as food security, energy security and environmental objectives.

OECD
BETTER POLICIES FOR BETTER LIVES

For more information:

https://doi.org/10.1787/9789264307438-en

Gérard.Bonnis@oecd.org
Simon.Buckle@oecd.org

http://oe.cd/nitrogen-report

@OECD_ENV