Consequences of human modification of the global nitrogen cycle

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The demand for more food is increasing fertilizer and land use, and the demand for more energy is increasing fossil fuel combustion, leading to enhanced losses of reactive nitrogen (Nr) to the environment. Many thresholds for human and ecosystem health have been exceeded owing to Nr pollution, including those for drinking water (nitrates), air quality (smog, particulate matter, ground-level ozone), freshwater eutrophication, biodiversity loss, stratospheric ozone depletion, climate change and coastal ecosystems (dead zones). Each of these environmental effects can be magnified by the ‘nitrogen cascade’: a single atom of N can trigger a cascade of negative environmental impacts in sequence. Here, we provide an overview of the impact of Nr on the environment and human health, including an assessment of the magnitude of different environmental problems, and the relative importance of Nr as a contributor to each problem. In some cases, Nr loss to the environment is the key driver of effects (e.g. terrestrial and coastal eutrophication, nitrous oxide emissions), whereas in some other situations nitrogen represents a key contributor exacerbating a wider problem (e.g. freshwater pollution, biodiversity loss). In this way, the central role of nitrogen can remain hidden, even though it actually underpins many trans-boundary pollution problems.

1. Introduction

Reactive nitrogen (N\textsubscript{r}) is created from N\textsubscript{2} naturally by biological nitrogen fixation, biomass burning and lightning. Nitrogen is an essential nutrient for the growth and functioning of plants, animals and humans, and an essential element for food security [1,2]. However, limited amounts of natural nitrogen fixation have led to the world’s ecosystems becoming adapted to low rates of N\textsubscript{r} supply, with limited productivity but high biodiversity. Because of their limited availability, some essential N\textsubscript{r} molecules are efficiently conserved and re-used in most natural environments. Nitrogen is commonly a limiting factor for the production of food. Humankind has sought different ways to increase crop production to provide food to sustain a growing population. This has led to the development of synthetic fertilizer production based on the Haber–Bosch process [3,4]. Nitrogen currently provides many benefits to society, in particular to agriculture and industry [5].

While the industrial fixation of N\textsubscript{2} is essential for food production, it is not without costs for the environment and human health. The amount of N\textsubscript{r} used to produce food is on average about 10-fold higher than its consumption, owing to inefficiencies in the food production–processing–consumption chain [6–8]. Agricultural sources of N\textsubscript{r} produce atmospheric emissions of ammonia (NH\textsubscript{3}),...
nitrogen oxides (NOx) and nitrous oxide (N2O) from agriculture to the air, and nitrate (NO3) to groundwater [8]. At the same time, combustion processes in energy production, transport and industry have led to the formation of new N fertilizer through the emission of NOx as an unintentional waste product.

Ny is highly mobile. Most of it dissipates into the environment and cascades through air, waters and terrestrial ecosystems where it contributes to a multitude of effects, including adverse impacts on human health, ecosystem services, biodiversity and climate change [4,7,8]. The endpoint of the cascade is ultimately the conversion back to unreactive N2 gas, although Ny is being produced more rapidly than it is being converted back to N2 so in many regions Ny is accumulating in the environment.

Overall, as human fixation of nitrogen continues to rise, the direct public health benefits through food production will probably continue to rise. However, the negative health consequences on ecosystems and people may become more diverse, and might in total increase more rapidly than the benefits.

This paper presents an overview of the consequences of Ny in the global environment. In the following sections, we elaborate in more detail on the impacts of Ny on (i) air quality and human health, (ii) aquatic and terrestrial ecosystems, and (iii) climate change, including global overviews whenever available.

### 2. Impacts on air, water quality and human health

#### (a) Impacts on human health: air quality

When released into the lower atmosphere, NOx can increase tropospheric ozone (O3) formation, smog, particulate matter (PM) and aerosols. Particulate nitrate can be formed following the oxidation of NOx to nitric acid (HNO3), which can then further react with NH3 to form ammonium nitrate, NH4NO3. NOx and NH3 are two of the major inorganic components in urban aerosol particles. In the atmosphere, NH3 reacts not only with HNO3 but also with aerosols and other acid gases such as H2SO4 and HCl to form ammonium-containing particles (e.g. (NH4)2SO4; NH4NO3; NH4Cl). NOx can also contribute to formation of the secondary organic aerosol particles in photochemical smog.

Table 1 provides an overview of N-related health impacts. The direct impacts of NH3 are mainly of importance within or close to Ny sources such as animal housing units or manure storage tanks. Direct impacts of NOx exposure and indirect impacts through PM and O3 exposure are most important for health. NOx is an irritant gas and can cause severe damage to the lungs if inhaled. High indoor NOx levels can also induce a variety of respiratory illnesses. Concentrations above 60–150 ppm can cause coughing and a burning sensation deep inside the lungs. Damage to the lungs can be visible after 2–24 h. These concentrations are, however, an order of magnitude higher than ambient levels and occur in special conditions. Continuous exposure to low concentrations of NOx can cause a cough, headache, loss of appetite and stomach problems. Environmental studies have shown that children exposed to chronically elevated NOx in their environment are more likely to develop respiratory diseases and reduced breathing efficiency [9].

Concentrations of NOx are often strongly correlated with those of other toxic pollutants with similar sources in industry and transport, and, being relatively simple to measure, NOx is often used as a surrogate for the pollutant mixture as a whole [10]. Achieving guideline concentrations for individual pollutants such as NOx may, therefore, reduce the level of many other pollutants that have the same source.

### Table 1. Overview of Ny emission-related health impacts and a summary of limit values for concentrations in air, as set by EU policies [9,10]. AOT40, accumulated exposure over a threshold ozone concentration of 40 ppb; MAC, maximum allowable concentration.

<table>
<thead>
<tr>
<th>emission routes</th>
<th>health impacts</th>
<th>indicators</th>
<th>limit values/targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx</td>
<td>inhalation:</td>
<td>asthma, respiratory disorder, inflammation of airways, reduced lung functions, bronchitis, cancers</td>
<td>NOx</td>
</tr>
<tr>
<td></td>
<td>— direct impacts of NO2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>— impacts via O3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>— impacts via PM visibility (PM)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH3</td>
<td>inhalation: see NOx</td>
<td>18 ppm (MAC value)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>— direct impacts (negligible)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>— impacts via PM odour</td>
<td>modest odour contribution</td>
<td>—</td>
</tr>
<tr>
<td>N2O</td>
<td>health impact due to global warming, often enhanced by eutrophication health impact due to loss of stratospheric ozone depletion</td>
<td>enhancement of vectors for infectious diseases (e.g. malaria) and frequency of infestations (e.g. algae blooms, insects)</td>
<td>—</td>
</tr>
</tbody>
</table>
O3 is an important pollutant affecting human health, almost exclusively through inhalation [9,11]. Adverse health impacts that can be initiated and exacerbated by O3 exposure include coughs and asthma, short-term reductions in lung function and chronic respiratory disease [9,11]. A recent overview of health risks of ozone by the World Health Organization (WHO) indicates a clear increase in mortality and respiratory morbidity rates with increasing levels of ozone in the environment [12]. An estimated 21 000 premature deaths in the EU member states are associated with ozone levels exceeding a maximum daily 8-h average of 35 ppb. Ozone is also associated with an estimated 21 000 premature deaths in the EU [12]. A statistically significant increase in mortality risk has been observed at O3 concentrations above 70 μg m⁻³ (35 ppb). Outdoor air pollution contributes to 5 per cent of all cardiopulmonary deaths worldwide [13]. In many countries approximately 20–40 deaths per 100 000 population are reported to be due to cardiopulmonary illness. In 2008, urban outdoor air pollution was responsible for an estimated 1.3 million annual deaths, representing 2.4 per cent of the total deaths in the world, mainly in the Euro-Asia region and in urban areas. Worldwide, urban air pollution is estimated to cause about 9 per cent of lung cancer deaths, 5 per cent of cardiopulmonary deaths and about 1 per cent of respiratory infection deaths [13].

PM is the most significant contributor to adverse health effects from air pollution [13]. It is an environmental health problem that affects people worldwide, but middle-income countries disproportionately experience this burden. According to a recent study on behalf of the European Environment Agency, pollution of fine particles is associated with more than 455 000 premature deaths every year in the EU27 member states [14]. The scattering and absorbing of light owing to particles also affects visibility in cities and scenic areas.

Apart from direct effects on humans, ozone damages crops and forests, and leads to reduced agricultural yields [15–17]. O3 is absorbed into plants via stomatal pores on the leaf that open during the day to allow CO₂ absorption for photosynthesis and evaporation of water. O₃ damages cell walls and membranes leading to cell death and reduction in photosynthesis rates [17]. This negatively affects crop and horticultural plant yields and CO₂ uptake. Global relative yield losses owing to ozone exposure are estimated to range from 7 to 12 per cent for wheat, 3 to 4 per cent for rice, 3 to 5 per cent for maize and 6 to 16 per cent for soybeans. In Europe, the regionally aggregated yield losses for these crops are estimated to be 5 per cent, 4 per cent, 5 per cent and 27 per cent, respectively [15].

(b) Impacts on human health: nitrogen enrichment of drinking water and food

It is important to note that a healthy immune system requires adequate nutrition, thus one of the most important links between fixed nitrogen and many tropical diseases may be that better access to nutrients in undernourished regions increases the overall health and disease resistance of the population [18]. However, when in excess, different forms of Nᵢ can cause human health problems.

Nitrate pollution of groundwater poses a recognized risk to human health. The WHO standard for drinking water is 50 mg NO₃⁻ l⁻¹ (as NO₃⁻) for short-term exposure, and 3 mg NO₃⁻ l⁻¹ for chronic effects [13]. Agriculture puts the largest pressure on both groundwater and surface water pollution owing to reactive N [19,20]. Although nitrate concentrations have slightly decreased over the past decades in some European rivers, levels have remained high in others and, overall, nitrate levels in groundwater have remained constant. Although some improvements have been made in reducing nutrient inputs from wastewater discharge, diffuse pollution of agricultural origin remains a major threat for waters in the EU [19]. From 2000 to 2003, nearly 40 per cent of the groundwater monitoring stations in the EU exceeded average values of 25 mg NO₃⁻ l⁻¹, and almost 50 per cent of the surface water monitoring stations exceeded average values of 10 mg NO₃⁻ l⁻¹ [19]. Similar high levels occur in other parts of the world where high levels of fertilizer are used [20].

There are other impacts related to the intake of Nᵢ through our food system. Diets in developed countries generally contain more protein than required for human health [8,21,22]. The WHO reports that current knowledge of the relationship between protein intake and health is insufficient to enable clear recommendations about either optimal intakes for long-term health or to define a safe upper limit [22]. High protein uptake can lead to high urea production and elevated blood pH, leading to an overreaction of the immune system. Furthermore, the kidneys can be overloaded causing possible kidney failure. A high blood pH can lead to loss of bone mass. Gout has also been associated with high purine foods such as meat [22].

People normally consume more nitrates from vegetables than from cured meat products. Spinach, beets, radishes, celery and cabbages are among the vegetables that generally contain very high concentrations of nitrates [23]. Nitrates can be reduced to nitrites by certain micro-organisms present in foods and in the gastrointestinal tract. This has resulted in nitrite toxicity in infants fed vegetables with a high nitrate level. No evidence currently exists implicating nitrite itself or nitrate as a carcinogen [24]. There are both experimental and epidemiologic studies that indicate possible chronic health effects associated with consumption of elevated levels of nitrate in drinking water, although results are inconsistent. Likewise, there are no good estimates of damage to health related to methaemoglobinaemia owing to drinking water nitrate. Evidence is emerging for possible benefits of nitrate or nitrite as a potential pharmacological tool for cardiovascular health [18].

The available evidence supports a positive association between nitrite and nitrosamine intake and gastric cancer, between meat and processed meat intake and gastric and oesophageal cancer, and between preserved fish, vegetable and smoked food intake and gastric cancer, but is not conclusive [25]. A diet high in red meat is associated with the formation of nitrosamines through the additives (sodium nitrite) that increase the red colour of the meat. The natural breakdown products of proteins can combine with nitrates to form compounds such as nitrosamines. There are many different types of nitrosamines, most of which are known carcinogens in test animals. It is unknown at what levels, if any, nitrosamines are formed in humans after they eat cured meat products, or what constitutes a dangerous level in meat or in humans.

3. Impacts of Nᵢ on natural ecosystems

Nᵢ can both acidify and eutrophy ecosystems. The impact of Nᵢ on a species or ecosystem depends on several factors, including the duration of exposure, total amount and form of nitrogen;
the sensitivity of the species; and intrinsic ecosystem properties such as fertility and acid neutralizing capacity [26]. High concentrations of N\textsubscript{0} (especially reduced N) can be toxic to organisms that adsorb elements directly from the environment, such as sensitive algae, lichens or bryophytes [27]. More commonly, N\textsubscript{0} acts indirectly on organisms through factors such as nutrient enrichment, oxygen depletion (in aquatic ecosystems), soil or water acidification, altering nutrient ratios, or intensifying the impact of other stressors such as pathogens or climate change. In this section, major impacts of N\textsubscript{0} on aquatic and terrestrial ecosystems are presented.

(a) Aquatic ecosystems

(i) Acidification

Aquatic ecosystems with a low acid neutralizing capacity (primarily freshwater) can be acidified by atmospheric deposition of reactive N and S. With a sharp decline in sulfur emissions beginning in the mid-1980s, N\textsubscript{0} has become the major component of acidic deposition in many areas of Europe and North America, and a growing problem in many developing countries. With persistent acidification, species composition at the base of the food chain is shifted, and often simplified, to favour acid-tolerant macrophytes and phytoplankton. Early life stages of fish and aquatic invertebrates can be especially sensitive to acidification, but direct and indirect impacts have been reported at all higher trophic levels, including zooplankton, benthic invertebrates, amphibians and birds [28,29].

(ii) Eutrophication

Nutrient enrichment of freshwater and coastal ecosystems usually originates from surface sources such as fertilizer runoff, erosion of nutrient-rich sediments or sewage discharge. In oligotrophic ecosystems, biomass or diversity may increase with increasing nutrient load [30]. However, as levels of N\textsubscript{0} and P increase, phytoplankton capable of efficiently assimilating these nutrients are increasingly favoured over species more limited by other factors (e.g. diatoms, requiring silica, or benthic primary producers, requiring light). Low-diversity algal or cyanobacterial blooms can result, leading to surface water hypoxia and the release of toxic compounds. This in turn impacts sensitive higher trophic level organisms, such as invertebrates and fish [27,31]. Sedimentation and decomposition of biomass from phytoplankton blooms can deplete oxygen in bottom waters and surface sediments, especially in ecosystems with low rates of water turnover [31]. This further shifts the benthic community towards fewer tolerant species. Changes in the benthic community alter nutrient cycling in the sediments and overlying water, feeding back to further alter the rest of the aquatic ecosystem ([32], and references therein).

Coastal eutrophication has recently emerged as a global issue of serious concern, with a steady growth in the extent and persistence of eutrophic, hypoxic and anoxic coastal waters [31,33], and related incidences of toxic algal blooms such as red tides [34]. Coral reefs, sea grass beds, wild or farmed fish and shellfish can be particularly sensitive to eutrophication and oxygen depletion. Similar to acidification, impacts on lower trophic levels can move up the food chain to seabirds, mammals and other marine animals.

A recent estimate identifies 415 eutrophic and hypoxic coastal systems worldwide [33], with 169 documented hypoxic areas, 233 areas of concern and only 13 systems in recovery. These numbers are very likely to be underestimates owing to low data availability in many areas, particularly Asia, Africa, Latin America and the Caribbean. The most underrepresented region is probably Asia, with relatively few documented eutrophic and hypoxic areas despite large increases in intensive farming methods, industrial development and population growth over the past 20 years.

(b) Terrestrial ecosystems

In high concentrations, N\textsubscript{0} can cause direct foliar damage, primarily to lower plants. NH\textsubscript{3}, NO\textsubscript{3} and NH\textsubscript{4} are especially phytotoxic [35]. This is a particular problem downwind of direct sources such as intensive livestock production. Whereas direct foliar damage is usually due to high local concentrations of N\textsubscript{0}, broader ecosystem-scale changes to soil and vegetation often arise from chronically elevated regional N\textsubscript{0} deposition. N\textsubscript{0} is the limiting nutrient for plant growth in many natural and semi-natural terrestrial ecosystems. Over time, species composition changes, and diversity often declines, as characteristic species of oligotrophic, mesotrophic or circumneutral habitats are out-competed by more nitrophilic or acid-resistant plants. Forbs, bryophytes, lichens and nutrient-poor shrubs are the most impacted functional types; graminoids adapted to higher nutrient levels are the main beneficiaries of elevated N\textsubscript{0} deposition.

Chronically elevated N\textsubscript{0} deposition can also enhance susceptibility to stress, such as frost damage, herbivory or disease ([36] and references therein). Northern temperate, boreal, arctic, alpine, grassland, savannah and Mediterranean biomes are particularly sensitive to N\textsubscript{0} deposition [37]. As with aquatic ecosystems, effects of N\textsubscript{0} have been identified at all trophic levels, including indirect impacts on above-ground fauna such as insects and birds.

Within the soil, N\textsubscript{0} fertilization can reduce the allocation of organic carbon from the vegetation to mycorrhizal fungi, because the increasing supply of N\textsubscript{0} from above reduces the plant’s dependence on mycorrhizae for scavenging N\textsubscript{0} from the soil [38]. Free-living fungi and N-fixing bacteria are also sensitive to N\textsubscript{0}. Changes in the microbial community in turn impact soil processes such as organic matter mineralization and nutrient cycling. The soil flora—protozoa, worms, insect larvae, etc.—primarily react to N\textsubscript{0} indirectly, through changes in the microbial community, microbial-driven processes or vegetation growth and composition [39,40]. Changes in macrobionta in turn influence the physical properties of soil, such as soil aggregation, water infiltration and organic matter turnover [41,42].

Exceedance of critical loads for nutrient nitrogen is linked to reduced plant species richness in a broad range of ecosystems and 5–10 kg N ha\textsuperscript{-1} yr\textsuperscript{-1} has been used as a threshold value for sensitive ecosystems, although effects may occur over the long-term at lower levels ([26,36] and references therein). Combining global modelled N deposition with the spatial distribution of protected areas (PAs) under the convention on biological diversity, Bleeker et al. [43] showed that 40 per cent of all PAs (11% by area) are projected to receive N deposition higher than 10 kg N ha\textsuperscript{-1} yr\textsuperscript{-1} by 2030 (figure 1). These cover almost all of southern Asia and the eastern USA, as well as parts of Africa and South America.

(i) Ozone exposure

As with impacts on food crops (described above), O\textsubscript{3} also affects natural ecosystems. The most prominent effect is that
it reduces forest productivity and thereby carbon sequestration. In a meta-analysis, Wittig et al. [44] estimated the magnitude of the impacts of current and future O₃ concentrations on the biomass, growth, physiology and biochemistry of trees representative of northern hemisphere forests. They found that current ambient O₃ concentrations (40 ppb on average) significantly reduced the total biomass of trees by 7 per cent compared with trees grown in charcoal-filtered controls, which approximates pre-industrial O₃ concentrations. Their results are in line with estimates of forest yield losses of 6 per cent for Norway spruce in Europe due to current exceedances of O₃ critical levels [16,45].

(c) Interactions

Nᵣ also acts with other human-influenced impacts on natural ecosystems, such as land-use change, climate change, sulfur deposition, ground-level O₃ enrichment and exotic species invasion. Research on the impacts of multiple stressors is increasing, but much more understanding is needed; an in-depth review of the existing studies is beyond the scope of this paper. Effects may be additive, synergistic or antagonistic. For instance, a recent evaluation suggests that enhanced exposure of ground-level O₃ to acid grasslands in Europe may impact different plants, and in different ways, than Nᵣ deposition, thus making Nᵣ an additive stress [46].

4. Reactive nitrogen and climate change

Nᵣ has many direct and indirect links to climate (summarized by Erisman et al. [47]). The most important warming effects of Nᵣ on climate are:

— N₂O formation during industrial fertilizer production, incomplete combustion or microbial denitrification and nitrification—notably after fertilizer and manure application to soils. Excess Nᵣ can also lead to hypoxia and anoxia in the ocean and surface waters, enhancing rates of denitrification and N₂O release;
— ground-level O₃ formation from NOₓ. O₃ is an important greenhouse gas. It is also formed in the troposphere as a result of NOₓ and volatile organic compound (VOC) emissions. O₃ reduces plant productivity, and therefore reduces CO₂ uptake from the atmosphere; and
— changes in ecosystem CH₄ production and consumption. Nᵣ deposition to wetlands may increase vascular plant production, thus increasing root exudation of low-molecular weight carbon compounds such as acetate, a major substrate source for some groups of methanogenic Archaea. A shift towards vascular plants such as sedges also increases the rate of release of CH₄ to the atmosphere through stems, bypassing CH₄ oxidation in the soil. Nᵣ may also increase rates of CH₄ consumption by methanotrophic bacteria in wetlands; however, the opposite may be the case in upland soils, with the balance depending on the background levels of both CH₄ and nutrients.

The most important cooling effects of Nᵣ on climate include:

— enhancement of the biospheric CO₂ sink owing to increased supply of Nᵣ. Because N (often together with P) is commonly a growth-limiting element, increased Nᵣ increases primary productivity, and thus CO₂ uptake from the atmosphere, in many terrestrial ecosystems, rivers, estuaries and areas of the open ocean. Nᵣ may reduce productivity in very high N deposition areas; however, these are fairly rare. Increasing Nᵣ may increase or reduce the rate of organic matter breakdown, dependent upon the background level of Nᵣ in the environment and the type of organic matter. Estimates of the quantitative importance of N on carbon sequestration vary widely;
— N-containing aerosols. This occurs both directly via absorbing terrestrial radiation and scattering solar radiation, and indirectly, e.g. by influencing cloud formation;
— changes in CH₄ production and emission from ruminants. Increased Nᵣ supply can be associated with more digestible diets, potentially reducing CH₄ emission from these animals. This effect is, however, small; and
— effects of O₃ on CH₄. Elevated tropospheric O₃ increases the formation of the hydroxyl radical (•OH), which is a major sink for atmospheric CH₄. However, O₃ can also reduce the emission of CH₄ from wetland plants, possibly by impacting photosynthesis and reducing root exudation of carbon [42].
Table 2. Societal costs of nitrogen emissions in ranges based on the references [49–51]. Units are euro per kg N.

<table>
<thead>
<tr>
<th>N(_x) flux</th>
<th>health</th>
<th>ecosystem/ coastal systems</th>
<th>crop decline O(_3)</th>
<th>climate</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO(_x)-N to air</td>
<td>10–30</td>
<td>2–10</td>
<td>1–3</td>
<td>13–43</td>
<td></td>
</tr>
<tr>
<td>NH(_x)-N to air</td>
<td>1.1–20</td>
<td>2–10</td>
<td></td>
<td>3.1–30</td>
<td></td>
</tr>
<tr>
<td>N(_x) to water</td>
<td>0–4</td>
<td>5–50</td>
<td></td>
<td>5–54</td>
<td></td>
</tr>
<tr>
<td>N(_x)O-N to air</td>
<td>1–3</td>
<td></td>
<td></td>
<td>1–15</td>
<td>2–18</td>
</tr>
</tbody>
</table>

Estimating the net effect of these major interactions between N\(_x\) on climate at the global scale, Erismann et al. [47] calculated an overall small net cooling effect of \(-0.24\) W m\(^{-2}\), but with a large uncertainty range of \(-0.5\) to \(+0.2\) W m\(^{-2}\). This cooling effect should not be taken as indicating that N\(_x\) is not an issue for climate policies. We should conclude from this that, whatever measures are taken that affect N\(_x\) emissions, potential climate effects should be evaluated to ensure that the role of N\(_x\) does not change to make it more of a contributor to climate warming. Furthermore, it is very relevant to include the climate effect when addressing N\(_x\) reduction for environmental reasons in order to prevent trade-offs or pollutant (issue) swapping. The reason for this is that environmental policies will affect different sources and sectors, which all contribute to only a part of the nitrogen cycle.

Climate change is, however, of central importance to the N\(_x\) budget. At a direct level, enriching the atmosphere in CO\(_2\) can enhance net primary production rates and thus accelerate nitrogen cycling. In addition, when the climate changes, many factors such as temperature, precipitation, run-off, sea level, ocean chemistry and wind may change: these factors can strongly influence nitrogen/nutrient dynamics. For example, nitrification rates in the ocean appear to be reduced by ocean acidification resulting from increased CO\(_2\) dissolution [48]. The consequence of this is not only reduced availability of nitrogen for phytoplankton and other micro-organisms, but also a reduction in N\(_x\)O emissions.

(a) Cost–benefit analysis for N\(_x\)

Comparing the societal costs of different effects of N\(_x\) provides a means of evaluating these different effects on the same scale. Recently cost–benefit analyses of N\(_x\) have been attempted for the Chesapeake Bay in the USA [49], for Europe [50] and as a broad overview for the USA [51]. Table 2 shows the ranges of estimated societal costs per N\(_x\) component loss and impact, based on the ‘willingness to pay’ method [50]. Based on these costs, the most important component of the N\(_x\) cycle is the emission of NO\(_x\), owing to the health impacts of both particulates and ozone. Ammonia is also important, but the health effects are less certain. There is a large uncertainty for the cost of N\(_x\) enhancement of surface- and groundwater. Brink et al. [50] estimated that the agricultural benefits of N\(_x\) in Europe are €25 and €130 billion per year, whereas the total environmental costs based on the numbers in table 2 add up to €13 and €65 billion per year and are appreciable compared with the benefits.

(b) Synthesis and importance of the N\(_x\) effects

Figure 2 is a first attempt by expert judgement to describe the major consequences of human induced N\(_x\) losses to the environment as synthesized in this paper. This figure shows two parameters: (i) the exceedance of the effects levels of N\(_x\) for ecosystems or human population and (ii) the contribution of N\(_x\) to the total effect, relative to other components or causes (e.g. natural) of the problem. For each problem an attempt is made to define the level above which effects are expected and its exceedance. The figure extends from the local scale, through the regional scale, to the global/stratospheric scale and hence represents the cascade of N\(_x\) through the environment. Overall the figure provides direct insight in where N\(_x\) is an issue and if it needs attention based on the exceedance and relative to the other stresses needing to be addressed. Note that the two parameters are not necessarily related! The following problems are included and explained:

— **Nitrates or nitrites intake by humans.** The figure describes the estimated fraction of the global population with a nitrate or nitrite intake above recommended levels. The intake comes from drinking water with excess nitrate, air pollution inhalation of nitrate particles and nitrate in food. Food and drinking water are by far the major sources for nitrate, and cured meat is the major source for nitrite [22]. We estimate that about 70 per cent of the global population has a higher intake than recommended. The human induced N\(_x\) share of the total intake of health-impacting substances through food and drinking water is large at 80 per cent, 20 per cent being of natural origin.

— **Air pollution (human health).** This is expressed as the fraction of the world’s population exposed to levels above health thresholds, such as described by WHO [9,10] (table 1). According to WHO 60 per cent of the global population in urban areas is exposed to PM, NO\(_x\), and other toxic (N) substances (such as nitrosamines) at levels above the thresholds, and a substantial fraction of rural dwellers are exposed to O\(_3\) and PM levels above the thresholds. Nitrogen constitutes a major source of O\(_3\) precursor emissions: 60 per cent of the O\(_3\) increase since 1900 is due to an increase in NO\(_x\), with the remaining owing to an increase in emissions of CO, CH\(_4\) and non-methane VOCs [10]. N\(_x\) globally contributes about 20 per cent to the formation of fine particles [13]. All health impact assessments (e.g. by WHO) show that particle pollution dominates total health impacts (approx. 95%).

— **Air pollution (crop loss).** Crop loss owing to air pollution is mainly caused by increased levels of surface O\(_3\) [15,17]. The range of crop losses given in the literature is 6–11% [45]; with a NO\(_x\) contribution of 70 per cent, we set this to 4 per cent. We estimate that the N\(_x\) (as air pollution) contribution to air pollution-based crop loss, not including other stresses such as water stress, is above 50 per cent.

— **Freshwater pollution.** Freshwater eutrophication is defined as areas where the concentration of nitrate exceeds 1 mg NO\(_3\)-N l\(^{-1}\) [20,27,52]. The Millennium Ecosystem
Assessment shows that in most of the continents, apart from North and South America, this level is exceeded (60% of freshwater systems). Based on the Global Environmental Outlook (GEO-4, [20]) we estimate that globally about 10 per cent of the freshwater area exceeds the 1 mg limit. The contribution of N₂O relative to other freshwater pollution is 40 per cent; most of the other pollution results from industrial leaching of toxic substances and run-off of fertilizers, and faecal and organic pollution where apart from N₂O, also P and other pollutants are of concern.

— Biodiversity loss. Biodiversity loss owing to N₂O deposition has been linked to the critical load for N₂O, which, for sensitive terrestrial ecosystems, is between approximately 5 and 10 kg N ha⁻¹ yr⁻¹ [26]. If we take the global deposition estimates by Dentener et al. [53] and the distribution of biodiversity hot spots or eco-regions, the global exceedance of 5 kg N ha⁻¹ yr⁻¹ is 50 per cent [43]. Overall, biodiversity loss is primarily caused by land-use change, probably followed by climate change, with N₂O deposition estimated to account for about 5–15% of current global biodiversity loss [36,37]. Food production and its associated N use drives land-use change, although on the other hand land change is avoided by intensified production through N use. These land-use change effects on biodiversity are not taken into account here.

— Coastal dead zones. The reported number of coastal dead zones has increased from nine in the 1960s to 460 currently [33]. There are currently 64 Large Marine Ecosystems (LMEs), defined as relatively large areas of ocean space of approximately 200,000 km² or greater. These LMEs are located in coastal waters adjacent to continents; primary productivity is generally higher than in open ocean areas [54]. The LMEs produce about 80 per cent of the annual world’s marine fisheries catch. Globally they are centres of coastal ocean pollution, nutrient over-enrichment, habitat degradation (e.g. sea grasses, corals, mangroves), overfishing, biodiversity loss and climate change effects. According to the National Oceanic and Atmospheric Administration of the United States, most LMEs are subject to significant eutrophication in coastal waters [54]. There is a N₂O problem in about 80 per cent of the LMEs [54]. Compared with other pollution issues of coastal zones, such as phosphorus, the contribution of N₂O is estimated to be about 50 per cent.

— Climate change. Radiative forcing due to N₂O is expressed as the current N₂O concentration level (325 ppb) above the pre-industrial level (approx. 270 ppb; [55]), which is regarded as the ‘safe’ level because there are currently no thresholds defined [56,57]. The exceedance of the pre-industrial level is 20 per cent. The contribution of all N₂O emissions to the total radiative forcing is a net cooling of 15 per cent as determined by Erisman et al. [47] and explained in this paper. This assumes that the short-lived cooling effect lasts for a hundred years if no emission reduction measures are taken. Additionally, the long-term N₂O effects will outweigh the other long-term effect, the additional carbon stored per kg N, which is also much more uncertain.


