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Impacts of nitrogen emissions on ecosystems and human health: A mini review

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Abstract

Increased inputs of reactive nitrogen (N) by fertiliser production cause adverse effects on terrestrial and aquatic ecosystems as well as human health, through impacts on air, soil and water quality. The best quantified adverse impacts include: (i) the loss of plant diversity in terrestrial ecosystems and excess algal growth in aquatic ecosystems, leading to oxygen-deficient 'dead zones', by N-induced eutrophication and acidification and (ii) human health impacts due to increased concentrations of nitrogen dioxide, NO_x-induced ozone and N-induced particulate matter. Considering that the economic benefits of improved air and water quality outweigh the costs of reductions measures, there is ample reason to reduce N emissions, both from agriculture and from traffic and industrial sources.

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Air pollution, Biodiversity, Human health, Nitrogen, Ozone, Particulate matter.

Introduction

Human activities, such as fertiliser production and fossil fuel combustion, have strongly increased the conversion of atmospheric nitrogen gas, N_2, to 'reactive nitrogen (N)', defined as all biologically, radiatively and/or photochemically active forms of nitrogen [1]. Most important N forms in the air are nitrogen oxides, NO_x, emitted mainly from traffic and industry, and ammonia, NH_3, mainly emitted from agriculture. Most important N forms in soil water and surface water are nitrate, NO_3^-, and ammonium, NH_4^+, being the predominant forms of N taken up by organisms and added to the soil by mineral and organic fertilizers. Another relevant N form is nitrous oxide, N_2O, emitted primarily in response to enhanced mineral and organic fertilizer use [2]. This is the third most important long-lived greenhouse gas after carbon dioxide and methane [3], thus affecting human health indirectly by climate change. Furthermore, N_2O is currently the most important agent in the depletion of the stratospheric ozone layer [4,5], with implications for the increased occurrence of skin cancers [4,6].

Emission of N compounds to air is also responsible for an increased production of tropospheric ozone, O_3, and fine particle pollution [7–9]. Emissions of NO_x play a key role in the formation of O_3 [10], being one of the most important air pollutants affecting human health. Wang and Jacob [11] state that the O_3 increase since 1900 is determined for 60% by an increase in NO_x emissions and for the remaining part by an increase in CO, CH_4 and NMVOC emissions. Furthermore, NO_x and NH_3 emissions affect the formation of secondary particles in the atmosphere, such as ammonium sulphate and ammonium nitrate, that contribute to the regional exposure of humans to both PM_{10} and $PM_{2.5}$, where PM stands for particulate matter and 10 and 2.5 refer to the size of the particles (less than 10 and 2.5 μm, respectively). The relative contribution of reactive atmospheric N to overall particulate is estimated to be on average 30% in urban areas and 15% in rural areas for $PM_{2.5}$ [12]. Considering all those effects, the European Green Deal aims for a reduction of nitrogen losses to air and water by at least 50% in 2030.

This paper presents a mini review of adverse impacts of reactive N on the following (Table 1):

- Terrestrial ecosystems distinguishing: (i) direct effects on plant through elevated exposure to NH_3, NO_x and NO_x-induced O_3 and (ii) soil-mediated effects by N enrichment and acidification, with related impacts on plant species diversity and plant (tree) growth.
- Aquatic ecosystems including eutrophication and acidification of surface waters, due to N enrichment,

Table 1

Effects of major forms of nitrogen in the environment on air, soil and water quality and—through these media—on terrestrial and aquatic ecosystems and human health. PM is particulate matter including NH_4^+ and NO_3^- particulates. NO_x is a mixture of NO and NO_2.

Impacts	Air quality					Soil quality	Water quality	
	Primary pollutants		Secondary pollutants		GHGs	Soil solution	Groundwater	Surface water
	NH_3	NO_x	O_3	PM	N_2O	NO_3^-, NH_4^+, pH, Al	NO_3^-, Al	N total, NH_4^+, pH, Al
Terrestrial ecosystems	x	x	x			x		
Aquatic ecosystems	(x)	(x)						x
Human health	x	x	x	x	(x)		x	(x)

PM is particulate matter including NH_4^+ andNO_3 particulates. NOx is a mixture of NO and NO_2. GHGs, green house gases.

leading to toxic algal blooms, a decrease in floristic and aquatic species diversity and fish kills.

- Human health due to: (i) direct impacts of elevated NO_2 concentrations, (ii) NO_x-induced O_3 formation, (iii) NH_3 and NO_x-induced formation of particulate matter (PM), (iv) pollution of groundwater and drinking water due to NO_3-leaching and (v) N_2O-induced depletion of the stratospheric ozone layer.

Impacts on terrestrial ecosystems

Impacts of gaseous nitrogen—or nitrogen-induced compounds (NO_x, NH_3 and O_3) on terrestrial ecosystems occur via direct above-ground exposure and uptake and via soil-mediated N deposition impacts, as summarized in the following:

Direct impacts of exposure to ammonia, nitrogen oxides and ozone

Ammonia impacts

Adverse effects of elevated NH_3 concentrations on higher plants, due to direct exposure and uptake, include damage of the epicuticular wax layer, increased susceptibility for drought stress, induced by increased stomatal opening causing higher transpiration rates, and an enhanced risk for fungal infection and pests attacks related to increased nitrogen levels in plant tissue [13]. Direct adverse effects on vegetation occur when the foliar uptake rate of NH_3 is higher than the detoxification rate by the plants [14]. The most sensitive species for gas-phase effects of NH_3, in combination with SO_2, NO_2, are epiphytic lichens, as shown mainly by observational correlative studies [15]. Based on evidence from experimental studies in open-top chambers, free-air exposure experiments and correlative field studies, a long-term (several year) average critical level for NH_3 of 1 and 3 mg NH_3 m^{-3} is now proposed for lichens and higher plants, respectively [14]. The low value for lichens is especially substantiated by correlations between cover indices of epiphytic lichens on trees and NH_3 concentrations, either in space or time [16].

Nitrogen oxide impacts

Apart from human health impacts, high NO_x concentrations also have adverse impacts on the growth of (semi)natural vegetation and agricultural crops, which may lead to considerable reductions in crop yield in high concentration areas [17]. For NO_x, separate critical levels have not been set for different vegetations because of a lack of information, although the sensitivity is thought to decrease going from (semi)natural vegetation to agricultural crops and forests. The long-term critical level for NO_x is set at 30 ug m^{-3} NO_x, expressed as NO_2 [18]; however, a lower uncertainty bound of 15 ug m^{-3} NO_x expressed as NO_2 has been suggested for the most sensitive vegetation [19]. Considering those critical levels, direct toxicity impacts of NO_2 are rare in Europe and North America, except in highly urbanized regions, but they occur in large areas of Asia, especially in China and India [20].

Ozone impacts

Negative impacts of ozone on terrestrial ecosystems include crop yield losses and reduced seed production, with the most severe effects being caused by ozone uptake through the stomata into the leaf interior [21,22]. An overview of adverse ozone impacts, based on observational and experimental studies, in agriculture, forests and grasslands has been given in Emberson [23], including exposure—response relationships for agriculture, with a focus on regions where O_3 is likely to threaten food supply, including the USA, Europe, South Asia and Eastern China. The global yield losses of staple crops, that is, wheat, rice, maize and soybean, have been estimated at 3—16%, causing economic losses of 14—26 billion US dollars in the year 2000 [24]. Based on meta-analysis results of 263 articles, Wittig et al. [25]

estimated impacts of O_3 concentrations on the biomass, growth, physiology and biochemistry of trees. Their analysis showed that current ambient O_3 concentrations (40 ppb on average) reduced total tree biomass by 7% compared with trees grown in approximate preindustrial O_3 concentrations, while the loss was 11% at an elevated O_3 concentration (64 ppb on average). Their results are in line with estimates of 11–13% reduction in annual forest tree biomass growth in China [26].

Soil-mediated impacts of nitrogen deposition

Apart from direct impacts of N gases, soil-mediated impacts can affect terrestrial ecosystems. In this context, it is relevant to make a distinction between forests and other ecosystems. In forests, N deposition may first enhance growth and productivity through enhanced N availability, but in a later stage, it may cause eutrophication and acidification, negatively affecting nutrient balances and leading to an increased susceptibility to drought, diseases and pests. In other ecosystems, growth enhancement is only a threat, as it causes a decrease in plant species diversity, also being the trade-off in forest ecosystems.

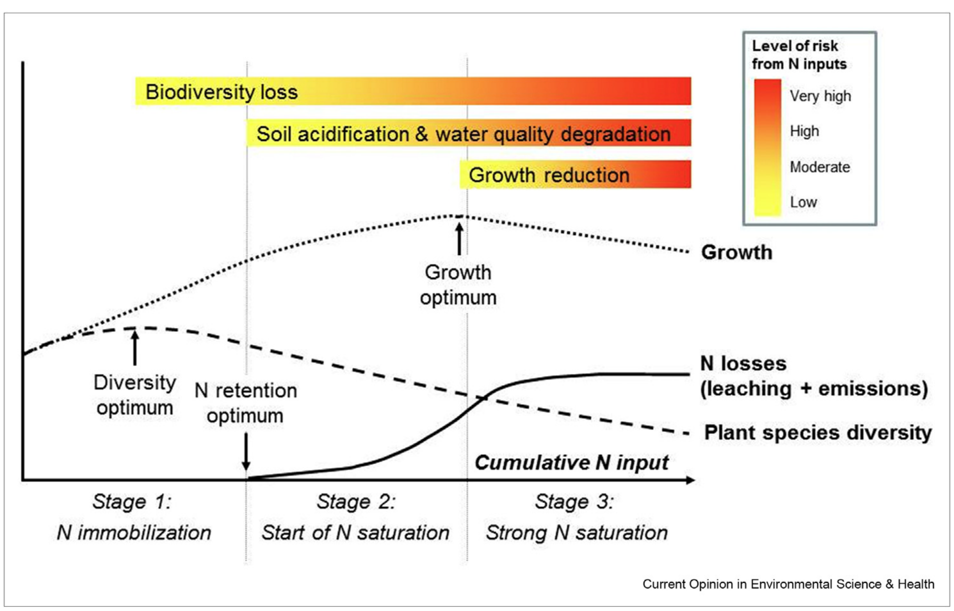
Impacts on plant species diversity

Figure 1 illustrates the conceptual relationships between (cumulative) N input and ecosystem impacts in terrestrial (forest) ecosystems. Only at extremely low N deposition levels, plant species diversity may increase with enhanced N deposition, but at levels above 5–10 kg N ha^{-1} yr^{-1}, plant species diversity generally starts to decrease and change towards more nitrophilic species [27]. This is because, in oligotrophic systems, in which N is generally the most important growth-limiting element, an increase in the availability of N induces an increase in few nitrophilous species that out-compete the species adapted to N deficiency. Plant species diversity loss induced by increased N inputs is thus mainly due to indirect soil-mediated effects by N enrichment, accompanied by eutrophication and acidification [28,29]. In addition, direct toxic effects of oxidized and reduced N gases and aerosols may also play a role, as discussed before. There is ample evidence by experimental N addition studies, synthesized in various meta-analyses, that increasing N availability causes an overall decline in plant species diversity [30–32]. Similar results are found based on field surveys along a gradient of N deposition, including a regional survey in acid grasslands in Great Britain [33] and a more extensive survey in acid grassland habitats across western Europe [34]. Sala et al. [35] thus identified N deposition as the third most important driver of global biodiversity change, after land-use change and climate.

Impacts on forest growth

Forest growth generally still increases at N input levels where adverse impacts on plant species diversity and soil quality already occur (Figure 1). At higher N deposition levels, however, above 10–15 kg N ha^{-1} yr^{-1}, N leaching starts to increase as the forest approaches 'nitrogen saturation' [36], associated with soil acidification and elevated leaching of base cations. Long-term

Figure 1



Conceptual relationships between the stage of N saturation and the effects on terrestrial ecosystems in terms of soil processes, vegetation changes and growth. This figure is an update of the original figure by Aber et al. [37] and taken from De Vries and Schulte-Uebbing [38].

elevated N deposition levels may result in nutrient imbalances in roots and leaves and release of aluminium (Al) by soil acidification, with toxic effects on fine roots and mycorrhiza. Furthermore, strong accumulation of N in foliage may decrease frost hardiness, increase the intensity and frequency of insect and pathogenic pests, and increase the risk of drought stress as a result of increased canopy size, increased shoot/root ratio and loss of mycorrhizal infection [39,40]. Owing to those effects, forest growth is reduced at high N input, generally above 20–30 kg N ha^{-1} yr^{-1} [41].

Impacts on aquatic ecosystems

Eutrophication

Elevated N concentrations in surface waters and coastal/marine waters contribute to the phenomenon of eutrophication with related impacts on phytoplankton and benthic algae, zooplankton, water plant communities (macrophytes) and fishes. Specifically, in marine ecosystems, where N is considered to be the most important element in limiting phytoplankton growth, effects can be considerable and include many negative effects, such as [42–44]:

- Changes in species composition and macrophyte vegetation and reduction in species diversity;
- Increased biomass of phytoplankton, microalgae and macroalgae (seaweed);
- Loss of subaquatic vegetation, due to excessive growth of phytoplankton and algae, which reduces light penetration;
- Decline in health and occurrence of coral reef communities, as increased nutrient levels suppress coral larvae due to enhanced algae growth;
- Harmful algal blooms, which cause nuisance conditions such as odours and discolouration or produce toxic effects on aquatic organisms, such as fish;
- Formation of hypoxic (oxygen-depleted) waters, which can lead to reduction in harvestable fish, increased incidence of fish kills and ecosystem collapse.

The severity of eutrophication of freshwaters by nutrient enrichment largely depends on the characteristics of the aquatic system considered. Until one decade ago, there was a common belief that phosphorus (P) is the nutrient that limits primary production, but recent evidence has shown that limitation by N can also play an important role in lakes [45], and similarly, both P and N can limit primary production in rivers [46]. When attempting to restore the ecological status in lakes and rivers, both N and P should thus be considered [45,47].

Acidification

Acid deposition, due to both N and S compounds, causes Al release from nonagricultural acidic soils (see previous sections) that leaches from watersheds into lakes and streams, thus causing surface water acidification. This has led to death of fish populations in the early 1970s in Norway, Sweden, Finland, Canada and the USA [48,49], increasing to large scale fish die-back in the 1980s, especially in Scandinavia [50]. The mechanisms inducing fish kills and other biological effects are linked to low pH [51] in combination with high Al concentrations [52], which are directly toxic to fish. Effects include mortality of adult fish and recruitment failure [53]. It should be noted that S compounds played a dominant role in these historical impacts on aquatic ecosystems. Fish kills due to acid deposition are currently thus much less frequent, but now the still ongoing acidification is largely driven by nitrogen.

Impacts on human health

Air quality: nitrogen oxides, ozone and PM

Nitrogen oxides impacts

In a review of health impacts of air pollution, the World Health Organisation (WHO) [54] concluded that there is evidence that nitrogen dioxide (NO_2) has direct effects on health, based on the following: (i) time-series studies on associations between variations in NO_2 concentrations and hospital admissions with respiratory symptoms and (ii) epidemiological studies reporting associations of adverse health effects with elevated NO_2. Insight into the extent to which NO_2 contributes to health effects is, however, challenging because of various methodological challenges, as recently summarized by Gowers et al. [55]. High NO_2 concentrations can lengthen and worsen common viral infections and cause severe damage to the lungs [56]. Several studies, published since 2004, as reviewed by the WHO [54], have documented associations between NO_2 exposure and hospital admissions with respiratory symptoms and mortality. Both short- and long-term studies [56] have found these associations with adverse effects at concentrations at or below the current EU limit value of 40 μg m^{-3}, which is equal to the WHO Air Quality Guidelines [57]. Recently, it was estimated that NO_2 pollution causes 4.0 (range, 1.8–5.2) million new paediatric asthma cases annually, being equal to 13% (range, 6–16%) of the global asthma incidence [58].

Ozone impacts

Ozone is an important pollutant affecting human health through inhalation [59,60]. Adverse health impacts include asthma (reactive airways diseases) and chronic respiratory disease [59,60]. Children who live in areas with high O_3 concentrations have 40% more chance to develop asthma [61], a disease that is spreading in many parts of the world [62]. An overview of health risks of ozone by the WHO indicates an increase in mortality and respiratory morbidity rates due to adverse impacts on lung function [9]. A study by Turner et al. [63] suggests that long-term ambient ozone concentrations contribute to the risk of respiratory and circulatory mortality. An estimated 13,600 premature deaths are associated with ozone exceeding 35 ppb, measured as a maximum daily 8-h average, in EU member states [64]. Ozone is also associated with 14,000 respiratory hospital admissions yearly in the EU member states [9]. Worldwide, the number of premature deaths from exposure to ground-level ozone is estimated to increase from 142,000 to 358,000 between 2010 and 2050 [65].

PM impacts

Exposure to PM, especially those with a diameter less than 2.5 μm ($PM_{2.5}$), causes respiratory and cardiovascular morbidity, as summarized recently by Kelly and Fussel [66], who also reviewed the underlying pathways causing the impacts. There has been some doubt whether secondary inorganic aerosols, including ammonium sulphate and ammonium nitrate, contribute to the human health effects of fine particulates [67,68]. However, epidemiological studies have frequently found adverse health effects of secondary inorganic aerosols [69], which may be due to several mechanisms, including an effect on the hygroscopicity of PM enhancing the exposure to toxic PM components, such as soluble transition metals [69]. Based on research over the past 20 years, it has thus been concluded that N particle components do not contribute less to the health risks than other particles [70–72]. Current experimental and epidemiological studies do not allow to relate specific health effects to individual components [66].

A recent study showed that a 50% reduction of agricultural emissions would reduce the annual mean $PM_{2.5}$ concentrations, and the related mortality attributable to PM pollution, by 19% in Europe [73]. Pollution by fine particles is associated with approximately 350,000 premature deaths every year in the EU member states, corresponding to more than 3.5 million years of life lost [74]. The estimated global premature mortality from PM exposure has been projected to increase from just over 3.3 million in 2010 to 6.6 million in 2050, with most deaths occurring in China and India [65].

Water quality: nitrate in drinking water

The potential health effects of high nitrate levels in drinking water include reproductive problems, methemoglobinemia, colorectal cancer, thyroid disease and neural tube defects [75,76]. Infants are especially at risk for methemoglobinemia ('blue-baby' syndrome). However, mortality in Europe because of this syndrome is extremely rare, and in other regions, symptoms of the syndrome are often related to pathogens in drinking water [77]. Although epidemiological data supporting these links are increasing, there has been an ongoing debate on the interpretation of inconsistencies between epidemiological and clinical findings [76,78,79]. However, a recent overview of epidemiologic studies indicates a clear risk of nitrate in drinking water, often even below regulatory levels [75].

Other impacts of reactive nitrogen on human health

An indirect health effect of nitrous oxide emission is the destruction of the stratospheric ozone layer, thereby increasing UV radiation causing increased occurrence of skin cancers. Ravishankara et al. [4] estimated that worldwide, the ozone layer had been reduced by about 6% from what it was before industrialization. They showed that N_2O emissions are currently the most important ozone-depleting cause and are expected to remain so throughout the 21st century. Other hypothesized health effects induced by increased N availability include an increase in allergenic pollen production, malaria, cholera and schistosomiasis [80], but impacts are generally less well-documented. Eutrophication of coastal and marine ecosystems, as discussed before, may also affect human health by harmful algal blooms, associated with shellfish poisoning and the production of toxins by cyanobacteria and estuarine dinoflagellates [81].

Concluding remarks

This short overview shows that the nitrogen losses to air and water play a key role in adverse impacts on human health and ecosystem functioning. Emissions of NH_3 and NO_x affect ozone and PM production in the atmosphere, affecting human health and terrestrial biodiversity, while nitrogen losses to groundwater and surface water affect drinking water quality and the biodiversity of aquatic ecosystems.

Nitrogen emissions from agriculture play an important role in this context, but agricultural production without mineral and organic N fertilizer use is not an option considering the need to feed an ever increasing world population of up to 10 billion expected by 2050 [82]. However, ambitious changes in management approaches, improving the N use efficiency throughout the food chain, are key to reduce the losses of reactive N to the environment and its related impacts [83,84]. Similarly, substantial health benefits are only to be expected from ambitious reduction policies with respect to the emissions of air pollutants and greenhouses gases [85,86]. It has been estimated that population exposure to $PM_{2.5}$ can be reduced by about 75% relative to 2015 by ambitious policies on pollution control, related to both energy and agricultural production, thus avoiding a large share of the current 3–9 million premature deaths [86].

Several studies indicate that the total economic benefit from avoided impacts on ecosystems and health by improved air quality outweighs the costs of measures to reduce N losses to air. For example, Van Grinsven et al. [87] estimated the annual cost of pollution by agricultural N losses in Europe in the range of €35–230 billion, being higher than the estimated annual economic benefit of N by agricultural production of €20–80 billion. A comparable conclusion was drawn in a recent study, on the impact of ammonia emission reductions on $PM_{2.5}$ concentrations with associated impact on avoided premature mortality for Europe [88]. The authors estimated the benefit in reduction in ammonia emissions by reduced premature deaths at a potential €14,837 million. In contrast, the annual costs of the ammonia emission abatement options (low-nitrogen feed, covered manure storage, urea fertilizer application and low-emission animal housing) were €4307 million. Considering that economic benefits of improved air quality outweigh the costs of compliance, there is a rationale behind the 'Farm to Fork' strategy of the European Green Deal, which aims for a reduction of nutrient losses by at least 50% in 2030.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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