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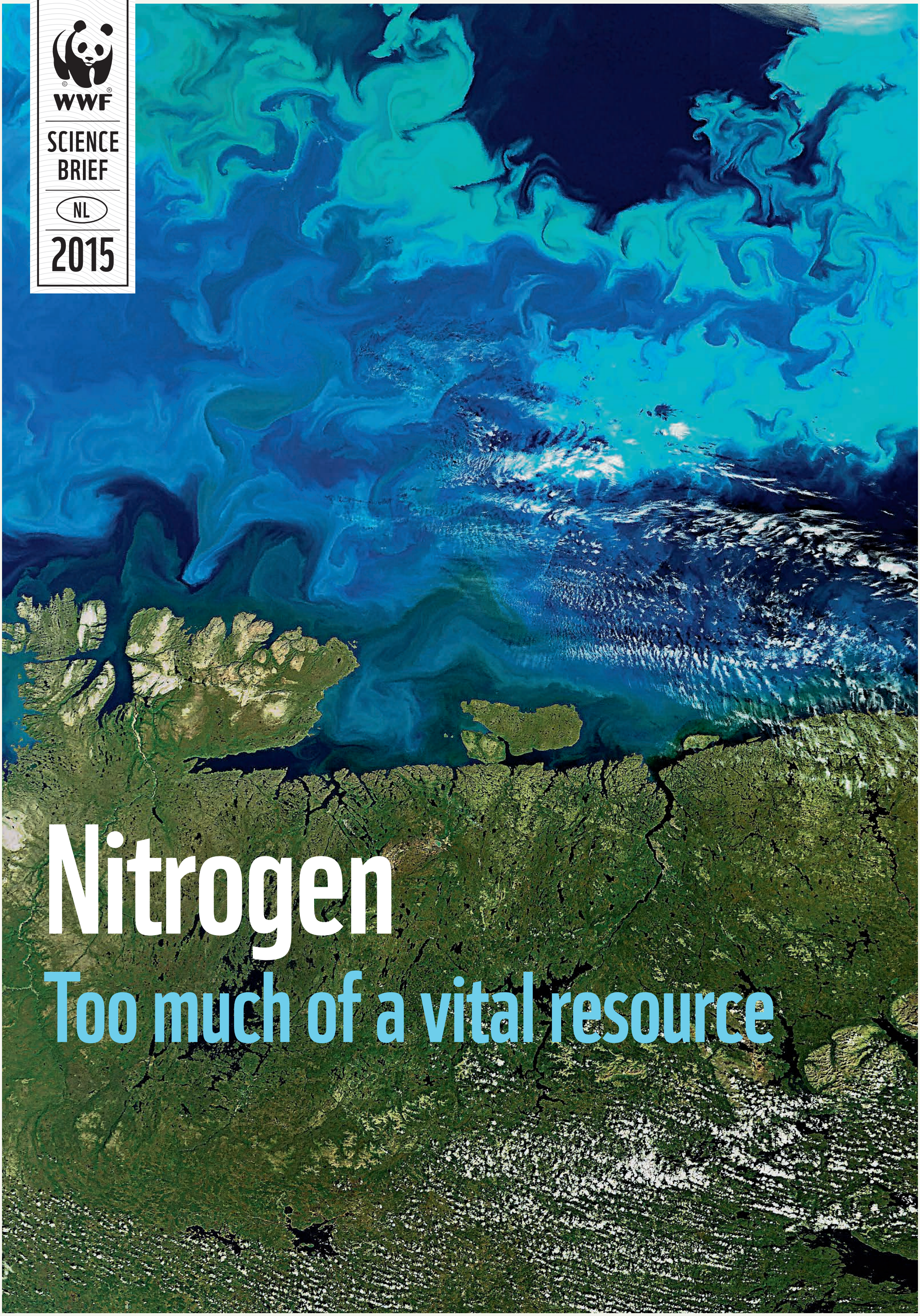

Nitrogen

Too much of a vital resource

WWF is one of the world's leading nature conservation organizations with over 5 million supporters and a global network active in more than 100 countries. WWF's mission is to stop degradation of the planet's natural environment and to build a future in which humans live in harmony with nature, conserving the world's biological diversity, ensuring that the use of renewable natural resources is sustainable, and promoting the reduction of pollution and wasteful consumption.

WWF-NL Science brief
Humanity's enormous and increasing demand for the planet's natural resources has resulted in a dramatic loss of biodiversity. Many of the pressures and underlying causes affecting ecosystems interact at a variety of scales from local to global. Trying to reverse or prevent further detrimental effects on nature within such a complex web of interdependent processes is a formidable challenge. WWF Netherlands is committed to promoting science that will lead to new insights and solutions for intractable problems affecting nature conservation. We support critical research to inform evolving solutions and sound decision-making that might benefit all forms of life on our one and only planet.

Human modification of the nitrogen cycle is one of the central global challenges affecting ecosystem integrity and biodiversity. In recognition of the urgent need to address this issue, WWF Netherlands has funded the Professorship of Integrated Nitrogen Studies within the Faculty of Earth and Life Sciences at VU University Amsterdam. The Professorship is currently held by Prof. dr. Jan Willem Erisman.

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NITROGEN: TOO MUCH OF A VITAL RESOURCE

EXECUTIVE SUMMARY

Nitrogen: a key resource

Nitrogen (N) is a key nutrient, vital for the survival of humans and all other living organisms. While di-nitrogen gas (N_2) is abundant in the atmosphere, most organisms are unable to use this chemically unreactive form. First it must be converted or "fixed" into a reactive form such as ammonia (NH_3) or nitrogen oxide (NO_x). These and other forms of reactive nitrogen (N_r) are comparatively scarce and represent a limiting resource in most natural ecosystems and in farmlands. In fact, the composition of much of the world's terrestrial biodiversity is the result of limitations in the availability of reactive nitrogen.

NITROGEN (N) IS VITAL FOR THE SURVIVAL OF HUMANS AND ALL OTHER LIVING ORGANISMS

By the turn of the 19th century, the natural sources of fixed nitrogen were not sufficient for the food production needs of a rapidly increasing human population in Western Europe. The development and adoption of a process to produce and use synthetic N fertilizers, led to a dramatic increase in agricultural productivity. However, because of the generally low efficiency in nitrogen fertilizer use in agriculture, much of industrially fixed nitrogen is released into the biosphere. The burning of fossil fuels also releases large amounts of reactive nitrogen oxide emissions into the atmosphere. Because of these releases, and the fact that we convert more nitrogen from the atmosphere into reactive forms than all of the Earth's natural processes in terrestrial systems combined, we have now dramatically altered the global nitrogen cycle-even more than we have altered the global carbon cycle.

Consequences

On the positive side, the human creation of reactive N has enabled the production of more foods and a change to more protein rich diets. However, there are still large parts of the world where there is a shortage of food and people suffer from malnutrition.

On a global scale, the negative consequences of human-generated nitrogen are becoming ever more apparent. Numerous, often interlinked, thresholds for human and ecosystem health have been exceeded due to excess reactive nitrogen pollution, including thresholds for drinking water quality (due to nitrates) and air quality (smog, particulate matter, ground-level ozone). Eutrophication of freshwater and coastal ecosystems (dead zones), climate change and stratospheric ozone depletion are also consequences of the human modified N_r cycle. Each of these environmental effects can be magnified by a 'nitrogen cascade' whereby a single atom of reactive nitrogen can trigger a sequence of negative environmental impacts through time and space.

DUE TO EXCESS REACTIVE NITROGEN POLLUTION, NUMEROUS, OFTEN INTERLINKED, THRESHOLDS FOR HUMAN AND ECOSYSTEM HEALTH HAVE BEEN EXCEEDED

REACTIVE NITROGEN IS A SIGNIFICANT DRIVER OF BIODIVERSITY LOSS

Reactive nitrogen is a significant driver of biodiversity loss through acidification and eutrophication. Under conditions with high inputs of N_r, faster-growing species that can rapidly assimilate N and acid-tolerant species are favoured. Biodiversity loss at the plant and habitat level can affect biodiversity of insects or other animals dependent on those plants and habitats. When N_r contributes to reduction of biodiversity, it can also lead to reduced ecosystem resilience. Currently, N deposition affects biodiversity in some parts of the world more than in others: highly affected areas include central and western Europe, southern Asia and the eastern US, as well as parts of Africa and South America.

Regional perspectives are therefore of vital importance for understanding the differing nature and priority of the consequences of excess nitrogen. While over-fertilization causes severe environmental problems in some parts of the world, in other regions - such as large parts of Africa - there is a serious lack of N-fertilizer.

Lack of attention

NITROGEN PLAYS AN IMPORTANT ROLE IN FOOD SECURITY

It is now clear that the nitrogen problem is one of the most pressing environmental issues that we face. But in spite of the enormity of our influence on the N cycle and consequent implications for the environment and for human well-being, there is surprisingly little attention paid to the issue. While biodiversity loss and climate change have spawned huge budgets to create national and multidisciplinary programs, global organizations, political and media attention, the N challenge remains much less apparent in our thinking and actions. This is because we are educated with the important role that N plays with regard to food security. Or perhaps we are unaware because - compared with climate change or biodiversity loss - there is little scientific communication about N overuse and emissions. Furthermore, the complexity of the interactions and links between the sources and chemical forms of N, human alterations to the N cycle, and the effects arising from the scale of alteration are difficult to translate into communicable messages to a wider audience.

What we can and should do

Given the above circumstances, immediate action is needed to reduce the use of reactive nitrogen, to better manage nitrogen losses in order to limit its cascading effects, and to educate people about synthetic nitrogen and the trade-offs that it represents. Options for improving nitrogen management must incorporate the need to optimize food production, consumption, and the use of energy, while limiting nitrogen impacts. Efforts to reduce the use of reactive N should be holistic and should minimize undesirable outcomes contributing to global warming, land use change, biodiversity loss, water eutrophication, ocean acidification and other environmental consequences. For example, intensification of agricultural production through the use of N-fertilizer seems to be a good strategy for feeding a growing world population. However, doing so involves large amounts of fossil fuels to produce the fertilizer - resulting in an increase of greenhouse gas (GHG) emissions - and often leading to large nitrogen losses into the environment, affecting the resilience of agro-ecosystems. The most effective and integrated solutions comprise increasing nitrogen use efficiency in agriculture, reducing waste in the food chain, promoting diets with less animal protein in developed countries, and a shift from fossil fuels to sustainable renewable energy sources such as solar and wind energy.

SOLUTIONS COMPRISE IMPROVEMENTS IN AGRICULTURE, DIETS AND A SHIFT AWAY FROM FOSSIL FUELS

Aim of this paper

This paper aims to contribute to the understanding of the N challenge, and to provide options for decreasing the negative impacts of excess N. We describe the pre-industrial, ‘natural’ N cycle, and compare it with the anthropogenically-altered cycle that exists today. We then present the societal and environmental consequences of this massive alteration. To reduce the current level of anthropogenic nitrogen in the Earth System we must understand what drives the need for it. And we must look into the inefficiencies in agriculture, industry, transport and energy that produce excess reactive N. Understanding these drivers and inefficiencies will improve the prospects for living within the N planetary boundary and for reducing the negative impacts of N_r on biodiversity, ecosystems and human health.

Eco-efficient nitrogen fixing legumes at a trial plot at CIAT’s headquarters in Colombia.

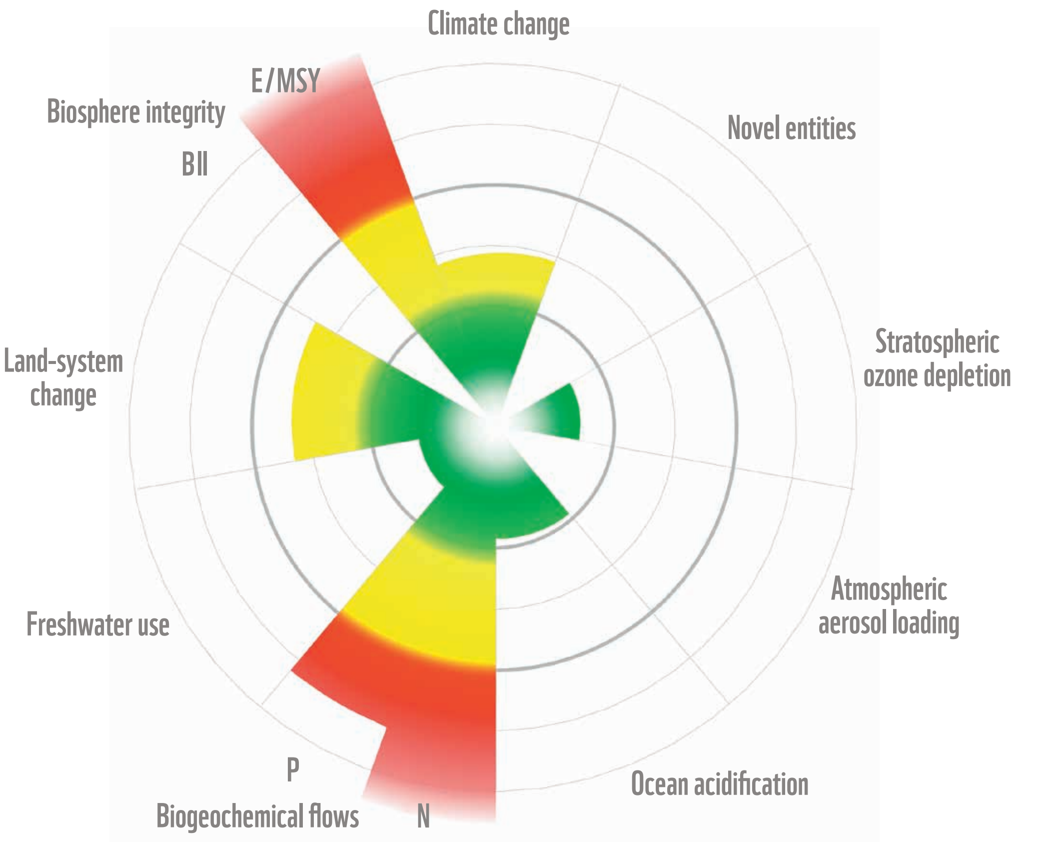
PLANETARY NITROGEN BOUNDARY EXCEEDED

Human pressure on the Earth system has reached a point where environmental change is global and in many respects irreversible. An ever-growing population, a rapid increase in per-capita consumption and a concomitant depletion of resources make it imperative that human society adopts more sustainable behaviour. Only then can we be sure that our planet's climatic, geophysical, atmospheric biochemical, and ecological processes will support our long-term well-being.

The concept of Planetary Boundaries, introduced by Rockström et al. (2009), provides a useful framework for examining the Earth's vulnerability to human pressure. The authors identified nine Earth subsystems or processes and associated each with critical thresholds of key biophysical variables. If thresholds were to be breached, unacceptable and irreversible changes affecting our limited planetary resources would ensue. Based on these critical thresholds, the authors estimated planetary boundaries to represent limits to guide activities associated with human production and consumption. The subsystems or processes identified by Rockström et al. include climate change, stratospheric ozone, land use change, freshwater use, biological diversity, ocean acidification, nitrogen and phosphorus inputs to the biosphere and oceans, aerosol loading, and chemical pollution. The boundaries of three of the systems - climate change, biological diversity, and interference with the global nitrogen (N) cycle - have already been breached due to human activity.

The parameter defining the nitrogen boundary is the amount of reactive nitrogen removed from the atmosphere for human use. Since the Rockström paper was published, the calculation of the N-boundary was refined and a link established between the phosphorus and nitrogen boundaries based on the coupling of these elements by the N:P ratio in growing plant tissue and aquatic organisms (De Vries et. al., 2013; Steffen et al., 2015). As a result, the original 2009 boundary was shifted outward. However, the estimated current level of reactive nitrogen removed for human use still far surpasses the new boundary, exceeding the critical threshold by a wide margin (Figure 1). Next to nitrogen, the new publication of Steffen et al. (2015) also indicates the exceedance of the boundaries for land-system change, climate change and P flows.

THE BOUNDARIES OF CLIMATE CHANGE, BIOLOGICAL DIVERSITY AND THE GLOBAL NITROGEN CYCLE HAVE BEEN BREACHED DUE TO HUMAN ACTIVITY



E/MSY	Extinction rate (Extinctions per Millions Species-Years)
BII	Biodiversity Intactness Index
N	Industrial and intentional biological fixation of N
P	P flow from freshwater systems into the ocean (global) & P flow from fertilizers to erodible soils (regional)
(red)	Beyond zone of uncertainty (high risk)
(yellow)	In zone of uncertainty (increasing risk)
(green)	Below boundary (safe)

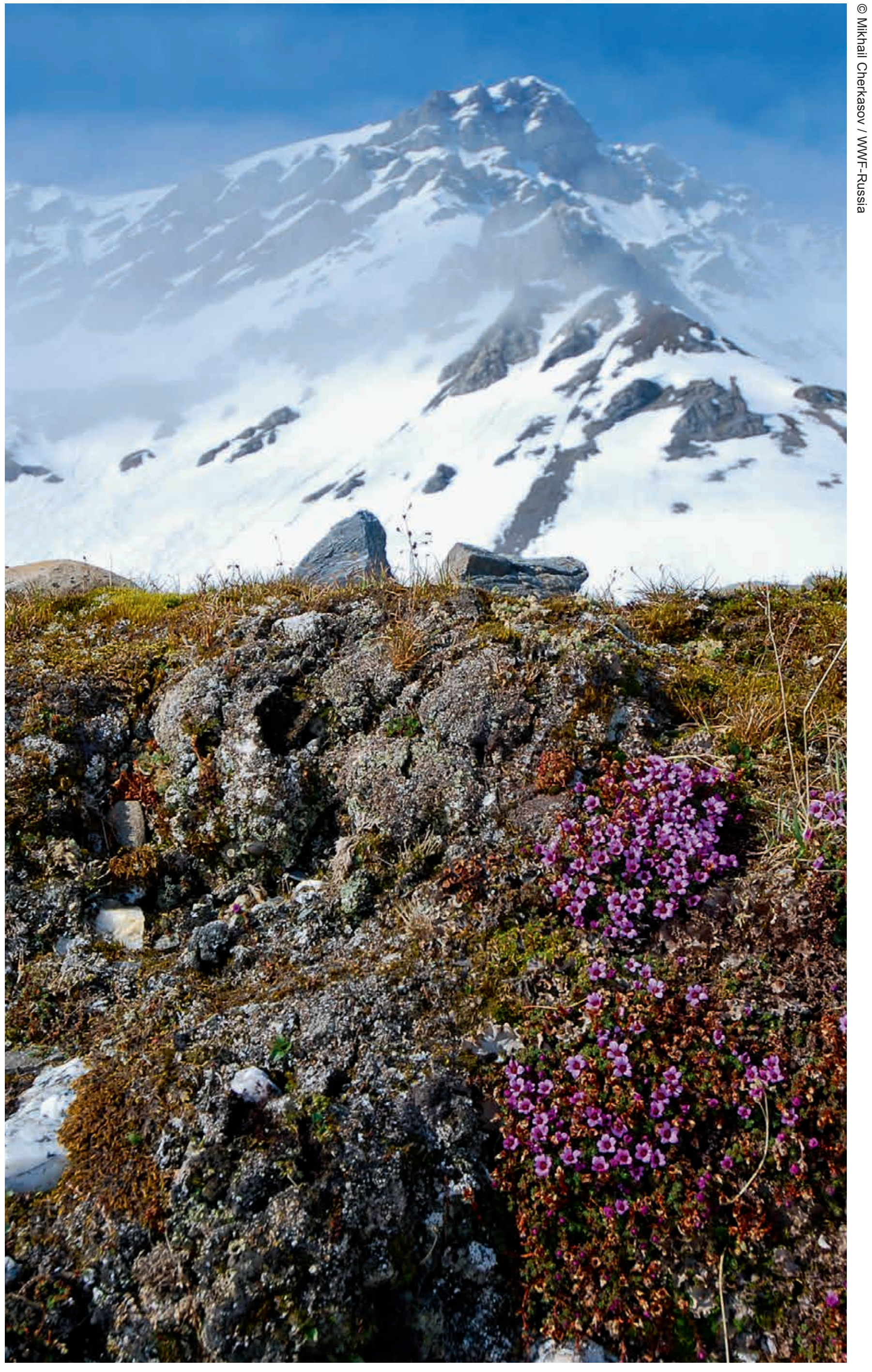
Figure 1: Planetary boundaries
The green zone is the safe operating space (below the boundary), yellow represents the zone of uncertainty (increasing risk), and red is the high-risk zone. The planetary boundary itself lies at the inner heavy circle. The control variables have been normalized for the zone of uncertainty (between the two heavy circles); the center of the figure therefore does not represent values of 0 for the control variables. Processes for which global-level boundaries cannot yet be quantified are represented by transparent wedges; these are atmospheric aerosol loading, novel entities and the functional role of biosphere integrity. The boundaries for biosphere integrity (related to biodiversity loss), climate change, land-system change and the nitrogen and phosphorus flows have already been exceeded (Steffen et al., 2015.

Human alteration of the N cycle has created serious air and water pollution leading to multiple health, climate and environmental consequences (Galloway et al., 2003; 2008; Erisman et al., 2013a). Moreover, after habitat conversion and climate change, nitrogen deposition is considered the third most important driver of terrestrial biodiversity loss (Sala et al., 2000; Xiankai et al., 2008; Alkemade et al., 2009). Because of the multiple links between nitrogen use, pollutants, climate change, land use change, and biodiversity loss, attempts to reduce the level of one boundary violation might have the opposite effect on one or more of the other boundary categories.

NITROGEN DEPOSITION IS CONSIDERED THE THIRD MOST IMPORTANT DRIVER OF TERRESTRIAL BIODIVERSITY LOSS

In spite of the enormity of human influence on the N cycle and its interlinkages with other global challenges, there has been comparatively little attention paid to the global risks and problems that this creates. While the exceedance of other Planetary Boundaries such as biodiversity loss and climate change have spawned huge budgets to create national and multidisciplinary programs, global organizations, political and media attention, the N challenge remains much less apparent in our thinking and actions. The reason for this is the important role that N plays with regard to food security. It is difficult for those working in conservation or development to challenge a practice that feeds almost half the world (Erisman et al. 2008). Also, we are unaware because - compared with climate change or biodiversity loss - there is little scientific communication about N overuse and emissions. Furthermore, the complexity of the interactions and links between the sources and chemical forms of N, human alterations to the N cycle, and the effects arising from the scale of alteration are difficult to translate into communicable messages to a wider audience.

IN SPITE OF THE ENORMITY OF HUMAN INFLUENCE ON THE N CYCLE AND ITS INTERLINKAGES WITH OTHER GLOBAL CHALLENGES, THERE HAS BEEN COMPARATIVELY LITTLE ATTENTION PAID TO THE GLOBAL RISKS AND PROBLEMS THAT THIS CREATES



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Svalbard. Much of the world's terrestrial biodiversity is a result of limitations in the availability of reactive nitrogen.

A CLOSER LOOK AT THE NITROGEN CYCLE

The chemical element nitrogen (N) is a basic requirement for all living organisms. It is a key component of certain essential amino acids and proteins, vitamins and DNA itself. Moreover, 78% of the Earth's atmosphere is comprised of the molecule di-nitrogen (N_2). This atmospheric gas is in an unreactive or inert form. That is, it is chemically unavailable to most living organisms. Far more important to life are reactive forms of nitrogen (N_r); single- or double-bonded nitrogenous compounds such as ammonium and nitrates. Because only a small proportion of the Earth's biota can convert N_2 to N_r, reactive nitrogen is the limiting nutrient within most natural ecosystems and almost always within agricultural systems.

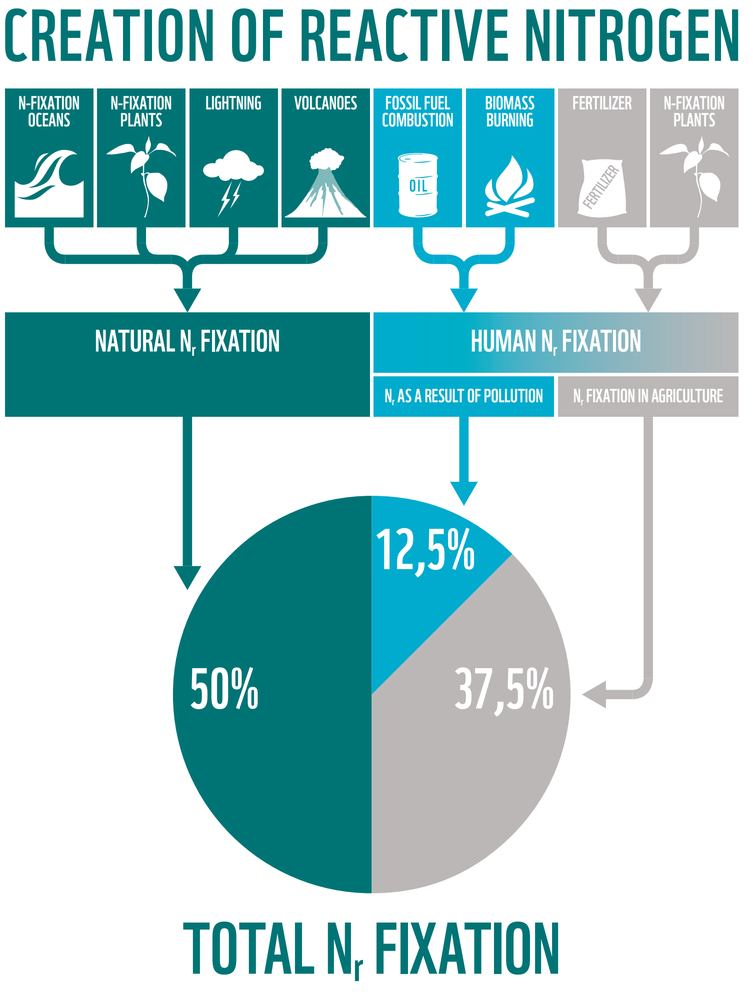
REACTIVE NITROGEN IS THE LIMITING NUTRIENT WITHIN MOST NATURAL ECOSYSTEMS AND ALMOST ALWAYS WITHIN AGRICULTURAL SYSTEMS

Natural creation of reactive nitrogen

In terrestrial ecosystems, nitrogen must be 'fixed' or bound into a reactive form before animals and plants can use it. There are three natural ways for this to occur: biological N fixation, volcanic eruptions, and lightning (Galloway et al. 2003). Biological fixation is the dominant natural source, which produces ammonia in the soil, therewith producing 90% of the total natural N_r in terrestrial ecosystems (Fowler et al. 2013). This process is performed by microorganisms, both free-living and living in symbiosis with higher organisms - most often plants from the legume family. Lightning produces oxidized forms of nitrogen (NO_x) in the troposphere (the lowest portion of the atmosphere), which is then deposited onto the Earth's surface. Volcanic eruptions release stored N_r from the earth's crust in the form of ammonia (NH_3). Taken together all three natural processes of fixation are estimated to produce around 65 Tg N per year in terrestrial ecosystems (Fowler et al. 2013). The marine biological nitrogen fixation amounts to 140 Tg N/yr, some of which is buried in sediments, the remainder eventually being denitrified back to the atmosphere as N_2 or N_2O.

Human creation of reactive nitrogen

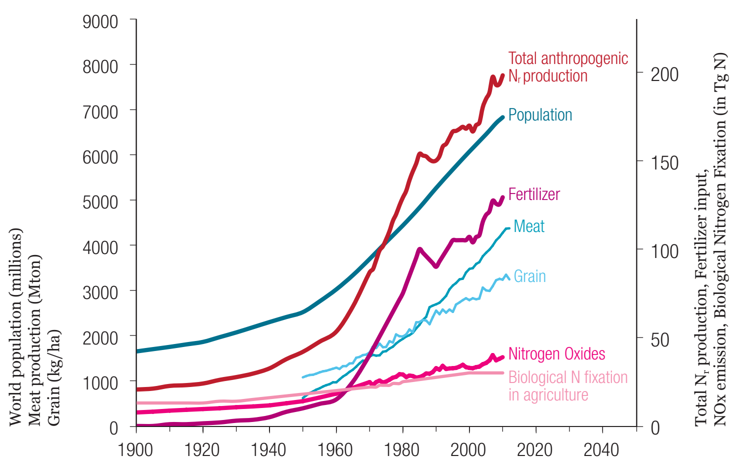
Reactive nitrogen has always been the most limiting nutrient in agriculture, requiring enhanced biological N fixation and recycling of N_r to increased crop production. Farmers applied manure or guano to fields or used the enzyme nitrogenase, or bacteria such as *Rhizobium spp* (associated with leguminous plants) and *Spirillum lipoferum* (associated with cereal grasses) which can fix atmospheric N_2 into a form that can be used by plants. These bacteria exist in a symbiotic relationship with leguminous plants (clover, beans, soy). However, biological N fixation is a slow process and provides only limited amounts of N_r to the biosphere.



By the 20th century, it was becoming clear that in populated areas the traditional methods for supplying N_r to crops could not meet the growing demand for food. The discovery of a method for creating industrial N_r for fertilizer was critical for increasing agricultural productivity. The breakthrough came in 1908 when Fritz Haber discovered and patented the process and conditions to create ammonia from unreactive nitrogen. Ammonia (NH_3) is the main component from which nitrogen fertilizers are produced. By 1913 Carl Bosch extended Haber's laboratory system for ammonia production to an industrial scale. The combined discoveries of these men led to what is known as the Haber-Bosch process.

About 40 years later the Haber-Bosch process was widely introduced as a primary component of the Green Revolution in agriculture. Almost immediately, global food production began to rise exponentially, and along with it, human population (Figure 2). By the 1970s, artificial ammonia production became more important than terrestrial biological N fixation in unmanaged ecosystems worldwide. Industrially produced ammonia is now abundantly available and affordable throughout the developed world. It has been estimated that without the additional N_r produced by the Haber-Bosch process, only 3 billion people - less than 50% of the current global population - would have enough food given current diets and agricultural practices (Smil, 2001; Erisman et al., 2008).

Globally, around 75% of anthropogenic N_r production stems from industrial N fixation and 25% from fossil fuel and biomass burning (in the form of nitrogen oxides) (Galloway et al. 2008; Fowler et al., 2013). Total modern N_r production in agriculture is more than twice the pre-industrial natural amount produced in terrestrial ecosystems.



IT HAS BEEN ESTIMATED THAT WITHOUT THE ADDITIONAL N_r PRODUCED BY THE HABER-BOSCH PROCESS, ONLY 3 BILLION PEOPLE WOULD HAVE ENOUGH FOOD GIVEN CURRENT DIETS AND AGRICULTURAL PRACTICES

Figure 2: Global trends between 1900 and 2012 in human population and total anthropogenic reactive nitrogen creation throughout the 20th century (Erisman and Larsen, 2013)
The graph also includes average fertilizer production, the increase in NO_x emissions from fossil fuel burning, and meat and grain production in the world. Current N_r production by humans is combarable to total natural production (terrestrial and oceans) (After Galloway et al., 2008 and Fowler et al., 2013).

Corn crop field, Ontario, Canada. Agriculture and consumption patterns are the main driver of the disruption of the N-cycle and the consequent impacts on our natural environment.

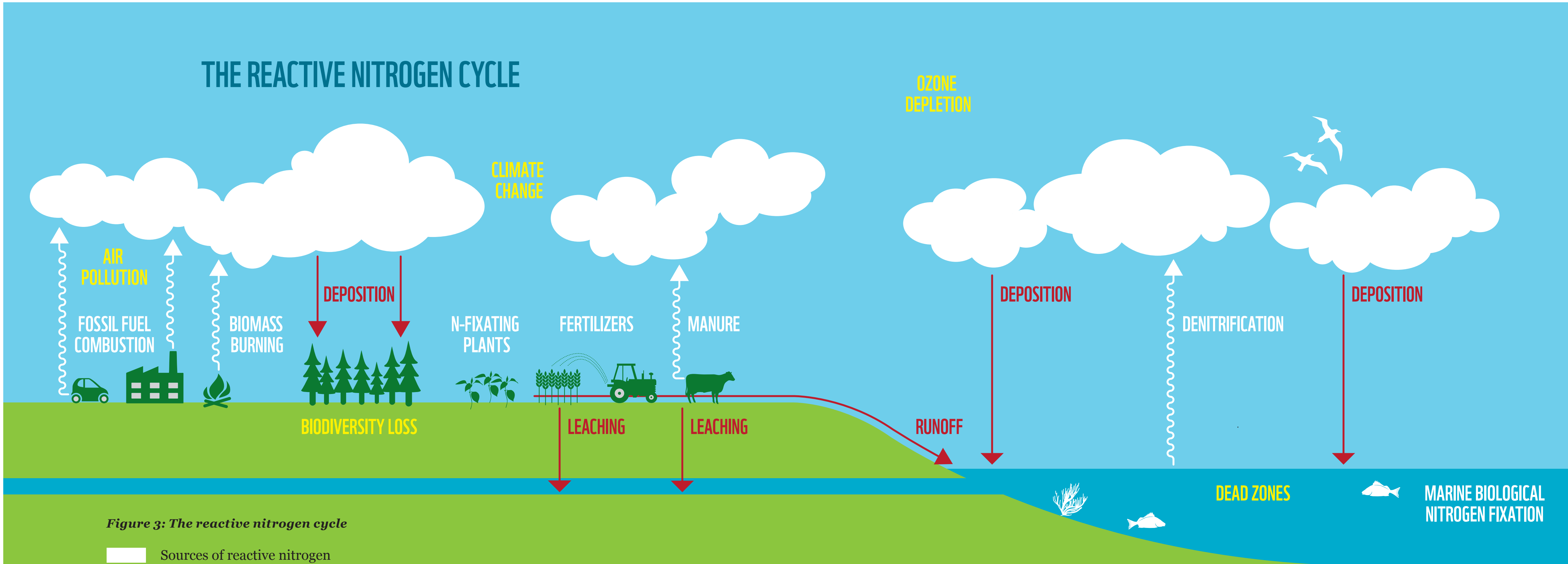


Figure 3: The reactive nitrogen cycle

- Sources of reactive nitrogen
- Reactive nitrogen processes
- Consequences of reactive nitrogen

The reactive nitrogen cycle

Reactive nitrogen (N_r) circulates from the atmosphere into the terrestrial and aquatic biosphere into organic compounds and then back into the atmosphere in what is known as the reactive N cycle (Figure 3).

Plants can assimilate N_r directly in the form of nitrates and ammonium that may be present in soil from natural mineral deposits, from artificial fertilizers, animal manure, decaying organic matter or atmospheric deposition. A significant fraction of N-fertilizer applied in agriculture is released into the environment.

Livestock also release large amounts of N_r in the form of ammonia (the result of a reaction between manure and urine). The excess N_r enters the hydrological system through leaching, groundwater flow and runoff, or is emitted to the atmosphere. Once released, N_r cascades through the biota and the physical environment, changing forms, flowing across soil, water and air, and triggering a range of impacts (See Figure 6 and Galloway et al. 2003).

Human use of mineral N-fertilizers, manure and fossil fuels have dramatically altered the global N cycle. We have in fact altered the N cycle far more than the carbon cycle; doubling the creation of N_r as opposed to increasing the concentration of CO_2 in the atmosphere by 20-30%, with huge consequences.

THE CONSEQUENCES OF THE HUMAN ALTERATION OF THE NITROGEN CYCLE

The negative consequences of human-generated change in the N cycle have only recently become apparent. However, in the last few decades, concern over the increased number of dead zones in the ocean, acid rain, smog, stratospheric ozone depletion and other effects has grown rapidly. Human health, ecosystem integrity and resilience, biodiversity and climate are already suffering serious and potentially irreversible effects (e.g. Vitousek et al. 1997; Townsend et al. 2003; Erisman et al., 2011; 2013).

HUMAN HEALTH, ECOSYSTEM INTEGRITY AND RESILIENCE, BIODIVERSITY AND CLIMATE ARE ALREADY SUFFERING SERIOUS AND POTENTIALLY IRREVERSIBLE EFFECTS

Impacts on the atmosphere: air pollution and ozone depletion

Combustion of fossil fuel leads to the formation of NO_x, a by-product of combustion, which contributes to air pollution and total N_r in the atmosphere. NO_x is primarily emitted in the atmosphere from motor vehicles and industrial activity. Global inputs of NO_x gases (nitric oxide, NO and nitrogen dioxide, NO_2) and ammonia (NH_3) to the atmosphere have tripled since the pre-industrial era. Regionally, there are even more substantial increases; emissions from large parts of North America, Europe and Asia rose by a factor of more than ten during the past century (van Aardenne et al. 2001). NO_x emissions contribute to air pollution (tropospheric ozone and particulate matter) and climate change.

Globally, NO_x emissions have increased in tandem with fossil fuel use (see Figure 2). In the atmosphere the gases form ozone (O_3), and particulate matter (such as ammonium nitrate and ammonium sulphate) that is eventually deposited to the Earth's surface.

NH_3 emissions also contribute to particulate matter in the atmosphere. Particles are formed through the reactions with sulphuric and nitric acids. Because the chemical reactions for NO_x in the atmosphere are relatively slow, NO_x can be dispersed and deposited more broadly than NH_3. Large areas of the world now receive average N_r deposition rates well above natural background levels, which can lead to eutrophication and acidification of terrestrial, freshwater and marine habitats (Bobbink et al., 2010; Payne et al. 2013). In turn, these processes cause leaching of base cations and metals from soil and sediments, biodiversity loss, ecological community shifts and changes to the food web.

LARGE AREAS RECEIVE N_r DEPOSITION WELL ABOVE THE NATURAL BACKGROUND LEVEL, LEADING TO EUTROPHICATION AND ACIDIFICATION OF TERRESTRIAL, FRESHWATER AND MARINE HABITATS

Impacts on freshwater and marine ecosystems: eutrophication

Diffuse sources of nitrogen, such as nitrate (NO_3^-) and organic N compounds from fertilizer and manure application in agriculture, enter groundwater through leaching and reach surface water through runoff. Point sources, such as effluents from wastewater treatment plants and sewerage systems, are discharged directly into surface waters. Atmospheric nitrogen deposition (from ammonia and NO_x) further contributes to N_r enrichment of lakes, coastal waters and the open ocean.

Part of the anthropogenic nitrogen entering the water system is removed by the process of denitrification (Seitzinger et al. 2006) that transforms N_r in N_2 (unreactive nitrogen) but also produces a fraction of N_2O (nitrous oxide), an important greenhouse gas (see next section). The rest is transported and transformed through the river system and contributes to increase nitrogen concentration in water bodies.

EXCESS NITRATE IN DRINKING WATER HAS NEGATIVE EFFECTS ON HUMAN HEALTH

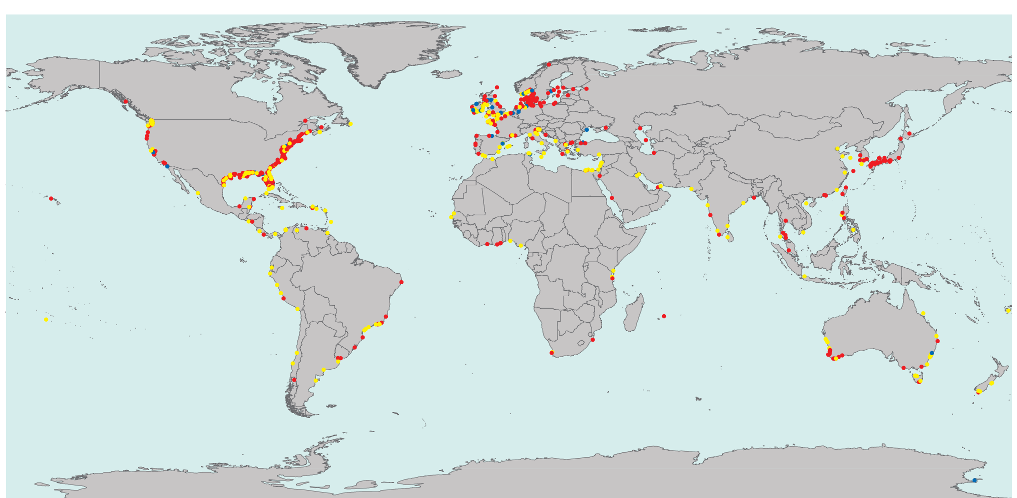
Excess nitrate in drinking water has negative effects on human health. Infant methaemoglobinaemia and colon cancer have been related to high concentration of nitrate in drinking water (Van Grinsven et al. 2010). For this reason, the World Health Organisation has set specific recommendations (WHO, 2007) and many countries have adopted strict limits on permissible nitrate concentrations in drinking water. However, the limits for NO_3- and other N contaminants have been exceeded in many groundwater aquifers across the world (UNEP 2007).

Excess nitrogen also has negative effects on aquatic ecosystems. The increase in nutrients concentration in water systems generates a dense growth of algae, vascular plants and bacteria. As a result, biomass sedimentation and microbial decomposition are enhanced, consuming the oxygen in the bottom water layers. This phenomenon is known as eutrophication. Hypoxic (low oxygen) conditions kill fish, invertebrates and other aquatic organisms (Rabalais, 2002; Selman et al., 2008; Figure 4). In coastal and marine ecosystems, eutrophication changes the algal species composition, reducing the species diversity (Smith and Schindler, 2009), and can lead to toxic algal blooms known as red tides (Anderson et al., 2008; Rabalais, 2002). Currently over 500 estuaries have been reported as eutrophic worldwide (Diaz et al., 2013). These "dead zones" are growing in both magnitude and geographical extent (Selman et al. 2008). Algal blooms also affect corals by depleting oxygen in the water and by covering the corals (Bauwman et al., 2010).

The effects of nitrogen enrichment in water bodies are related to the availability of nitrogen with respect to other nutrients, such as phosphorus and silica. In Europe, the use on nitrogen fertilizers in agriculture and the contemporary reduction of phosphorus emissions to water due to improved wastewater treatment, has led to a slight increase of the N:P ratio in the nutrient load exported to coastal water (Grizzetti et al., 2012). Changes in the nutrients' relative abundance might affect the ecological functioning of the aquatic ecosystem.

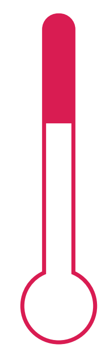
Further concerns about the effects of nitrogen on freshwater and marine ecosystems are related to N deposition, which can contribute to the acidification of surface waters (Curtis et al., 2005).

Figure 4: World hypoxic and eutrophic coastal areas
The map shows three types of eutrophic zones:
● Documented hypoxic areas – Areas with scientific evidence that hypoxia was caused, at least in part, by an overabundance of nitrogen and phosphorus. Hypoxic areas have oxygen levels low enough to inhibit the existence of marine life.
● Areas of concern – Systems that exhibit effects of eutrophication. These systems are possibly at risk of developing hypoxia.
● Systems in recovery – Areas that once exhibited low dissolved oxygen levels and hypoxia, but are now improving.
source: http://rs.resalliance.org/2008/01/28/mapping-coastal-eutrophication/



Impacts on climate change: increased emissions and sequestration

N_r contributes to climate change but the different processes involved can produce contradictory effects: some processes result in net warming and some in net cooling.



Warming

Nitrous oxide (N_2O) is a compound emitted from fertilizer production facilities, gaseous emission from agricultural soils, runoff from fertilized fields (especially along riparian zones), or from other N_r-rich soils, particularly if the water table fluctuates at or near the surface. N_2O is the third most important greenhouse gas and has a global warming potential 310 times greater than CO_2 (UNEP, 2013), contributing about 8% to the total of anthropogenic greenhouse gases (IPCC, 2013, Erisman et al., 2011).

Methane (CH_4) emissions can be increased or decreased in response to enhanced N_r deposition, depending on the carbon nitrogen and redox status of the soil, the vegetation composition, and the duration of exposure to N_r (Bodelier, 1999, Schimel, 2000; Eriksson et al. 2010). In wetlands where CH_4 is produced in abundance and N_r is limiting (e.g. most bogs and nutrient-limited fens, marshes and rice paddies) adding N_r over the short term can stimulate N-limited methane-oxidising bacteria and thus reduce CH_4 emission (Schimel, 2000). However, over the longer term, N can increase vascular plant biomass which increases CH_4 emission (Eriksson et al. 2010). On balance, the long-term effects of N_r on vegetation species composition probably outweigh the short-term impacts on microbial community dynamics, resulting in a net increase in CH_4 emission from nutrient-poor wetlands, and a warming effect (see Bodelier et al 2014).

Nitrogen dioxide (NO_2) is the dominant source of the oxygen atoms required for ozone (O_3) formation in the troposphere. Thus NO_2 is a major contributor to the greenhouse gas O_3, with a warming effect.

Cooling

Carbon dioxide (CO_2) uptake and sequestration in vegetation and soils can increase as a result of increased nitrogen levels. Because of the use of fertilizer and through the N deposition in N-limited areas there is more biomass growth (just as in agriculture). This is particularly true for forest ecosystems. It has been estimated that on average one kg of deposited N_r increases CO_2 sequestration by 10-50 kg C/kg N (de Vries et al., 2009, 2014), the lower values being more representative for tropical forest ecosystems. On a global scale about 10% more CO_2 is sequestered due to N_r deposition than would occur under completely natural conditions (Erisman et al., 2011; de Vries et al., 2014), with a net cooling effect.

Furthermore, through air pollution, N_r affects the radiative balance of the atmosphere through the formation of particulate matter that prevents solar radiation from reaching the earth. In this way, N_r leads to cooling.

Overall effect on climate

Over the short-to medium turn, it is not clear what the net impact of N deposition on climate is. A review in the European Nitrogen Assessment (Butterbach-Bahl et al., 2011) suggested a slight cooling effect for Europe and a similar conclusion was drawn at global scale by Erisman et al (2011) but the uncertainty is too large for a definitive conclusion. Over the long term, however, it is likely that the N_r fertilisation effect on CO_2 uptake by vascular plants will decline (De Vries et al., 2014), and the enhanced emission of the long-lived greenhouse gas N_2O will ultimately dominate, with a net global warming effect.

OVER THE LONG TERM, REACTIVE NITROGEN WILL HAVE A NET GLOBAL WARMING EFFECT

Impacts on terrestrial ecosystems and biodiversity

MUCH OF THE WORLD'S TERRESTRIAL BIODIVERSITY IS A RESULT OF LIMITATIONS IN THE AVAILABILITY OF REACTIVE NITROGEN

Nitrogen deposition can have both immediate and long-term impacts on species composition and abundance (Dise et al., 2011; Stevens et al. 2010; Field et al. 2014). Much of the world's terrestrial biodiversity is a result of limitations in the availability of N_r (Dise et al., 2011). Organisms have evolved in response to N-poor habitats in a wide variety of ways. Ecosystem-wide changes to soil and vegetation arise when levels of regional N_r deposition are chronically elevated or when N_r accumulates in the soil for decades, giving an advantage to above- and below-ground species adapted to acidic or nutrient-rich conditions (Dise et al. 2011).

Under conditions with high inputs of N_r, faster-growing plants that can rapidly assimilate N outcompete slower-growing plants adapted to low nutrient levels. Further, both ammonium (NH_4^+) and nitrate (NO_3^-) can acidify soils, favouring more acid-tolerant species over those adapted to circumneutral conditions. Finally, high concentrations of dry-deposited N_r (especially ammonia) can physically damage sensitive vegetation, particularly bryophytes and lichens that take up most of their nutrients directly from the atmosphere (Sheppard et al 2011).

Northern temperate, boreal, arctic, alpine, grassland, savannah, and Mediterranean biomes are particularly sensitive to N_r deposition because of the limited availability of N_r in these systems under natural conditions (Sala et al., 2000). Evidence is mounting that elevated N_r deposition exerts a proportionally stronger impact in nutrient-poor habitats and can reduce the abundance of individual species at levels of N_r that are below the critical load. This suggests that critical load thresholds might be lowered ((Bobbink et al., 2010, Dise et al., 2011 and references therein; Payne et al., 2013).

NORTHERN TEMPERATE, BOREAL, ARCTIC, ALPINE, GRASSLAND, SAVANNAH, AND MEDITERRANEAN BIOMES ARE PARTICULARLY SENSITIVE TO N_r DEPOSITION

Over time, species composition changes and diversity often declines, as characteristic species of nutrient-poor habitats, habitats with moderate fertility or nearly pH neutral habitats are out-competed by more nitrophilic or acid-resistant plants. Forbs, bryophytes, lichens and nutrient-poor shrubs are the functional types most affected; grass types such as graminoids adapted to higher nutrient levels are the main beneficiaries of elevated N_r deposition, just as blackberries (Rubus *spp*) and nettles (Urtica *spp*). Chronically elevated N_r deposition can also enhance susceptibility to stress such as frost damage, herbivory or disease (Dise et al., 2011 and references therein).

Long term excess N_r deposition and N_r accumulation in soil or water bodies also induces biodiversity changes through the food chain. Insects, birds or other animals with specific diets can suffer when their main source of food is affected by N_r (Erisman et al., 2013a). For example, research in the Netherlands demonstrates a direct relation between changes in butterfly communities and excess nitrogen affecting the plants they feed upon (WallisDeVries, 2014).

Biodiversity loss can reduce ecosystem resilience; the ability of an ecosystem to recover from a perturbation (MEA, 2005). Therefore, when N_r contributes to reduction of biodiversity, it usually leads to reduced resilience. Furthermore, through the detrimental effects on soil, water and air quality and ecosystem services, ecosystem resilience is further reduced and therewith accompanying ecosystem services (Erisman et al., 2013a).

RESEARCH SHOWS A DIRECT RELATION BETWEEN CHANGES IN BUTTERFLY COMMUNITIES AND EXCESS NITROGEN AFFECTING THE PLANTS THEY FEED UPON

BIODIVERSITY LOSS CAN REDUCE ECOSYSTEM RESILIENCE ; THE ABILITY OF AN ECOSYSTEM TO RECOVER FROM A PERTURBATION

Mechanisms explaining how additional N_r affects biodiversity

- Acute toxicity of N gases and aerosols. High concentrations of airborne N species have an adverse effect on the physiology and growth of aboveground plant parts of certain sensitive plants, particularly non-vascular plants such as bryophytes and lichens. These effects are most pronounced at high concentrations near large point sources.

- Accumulation of N compounds and higher N availability affects plant species interactions, ultimately leading to changes in species composition, plant diversity, and N cycling. This effect chain can be strongly influenced by other soil factors, including the availability of phosphorus.

- Chronic toxicity of reduced N forms (ammonia and ammonium). Increased ammonium availability can be toxic to sensitive plant species, especially in habitats where nitrate is the dominant N form and there was originally very little ammonium. Poor root and shoot development occurs in sensitive species in weakly buffered habitats (pH 4.5–6.5).

- Soil-mediated effects of acidification. Nitrification of N_r in the soil leads to a lower soil pH, increased leaching of base cations, increased concentrations of potentially toxic metals (e.g., reactive forms of aluminum), a decrease in nitrification, and an accumulation of litter. Certain sensitive plants will not survive in acidified soils.

- Increased susceptibility to secondary stress and disturbance factors. The resistance to plant pathogens and insect pests can be lowered because of the lower vitality of individuals as a consequence of N-deposition effects. Furthermore, increased N contents of plants can result in increased herbivory. Finally, N-related changes in plant physiology, biomass allocation (root/shoot ratios), and mycorrhizal infection can influence the susceptibility of plant species to drought or frost.

(source: Bobbink et al., 2010)

Reactive nitrogen deposition affecting protected areas and Global 200 Ecoregions

Phoenix et al. (2006) showed that half of the world's 34 biodiversity hotspots, to which more than 50% of the world's plant diversity is restricted, could by 2050 have between 10 and 100% of their area receiving N deposition above 15 kg N/ha/y, a rate exceeding critical loads for many sensitive ecosystems.

Bleeker et al. (2010) demonstrated that a large part of the world's protected areas - as defined by the World Database on Protected Areas in 2008 (UNEP-WCMC - and the WWF Global 200 Ecoregions receive N deposition well above the critical load. Bleeker et al. (2010) combined modelled global N_r deposition (Dentener et al., 2006) with the spatial distribution of the world's protected areas (UNEP-WCMC, 2008). They showed that 40% of all protected areas (11% by area surface) are projected to receive N deposition higher than 10 kg N/ha/yr by 2030 - i.e., the largest amount that nearly all natural system can absorb without affecting the ecosystem and its services (Figure 5). Highly affected protected areas are concentrated in southern Asia and the eastern US, as well as parts of Africa and South America. N_r deposition is projected to increase over large regions of South America, Africa and Eastern Europe.

A LARGE PART OF THE WORLD'S PROTECTED AREAS RECEIVE N DEPOSITION WELL ABOVE THE CRITICAL LOAD

These works by Phoenix et al. (2006) and Bleeker et al. (2010) are first attempts, using coarse resolution, modelled estimates of N_r deposition and a single critical load value rather than ecosystem-specific values. Therefore, this research reveals a general trend but clearly further study and quantification using more detailed data is needed.

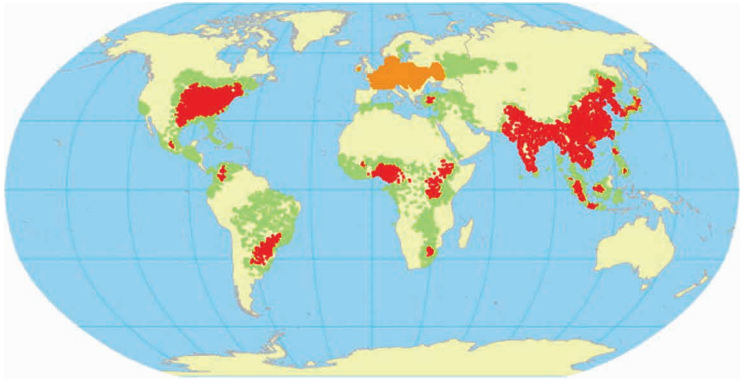
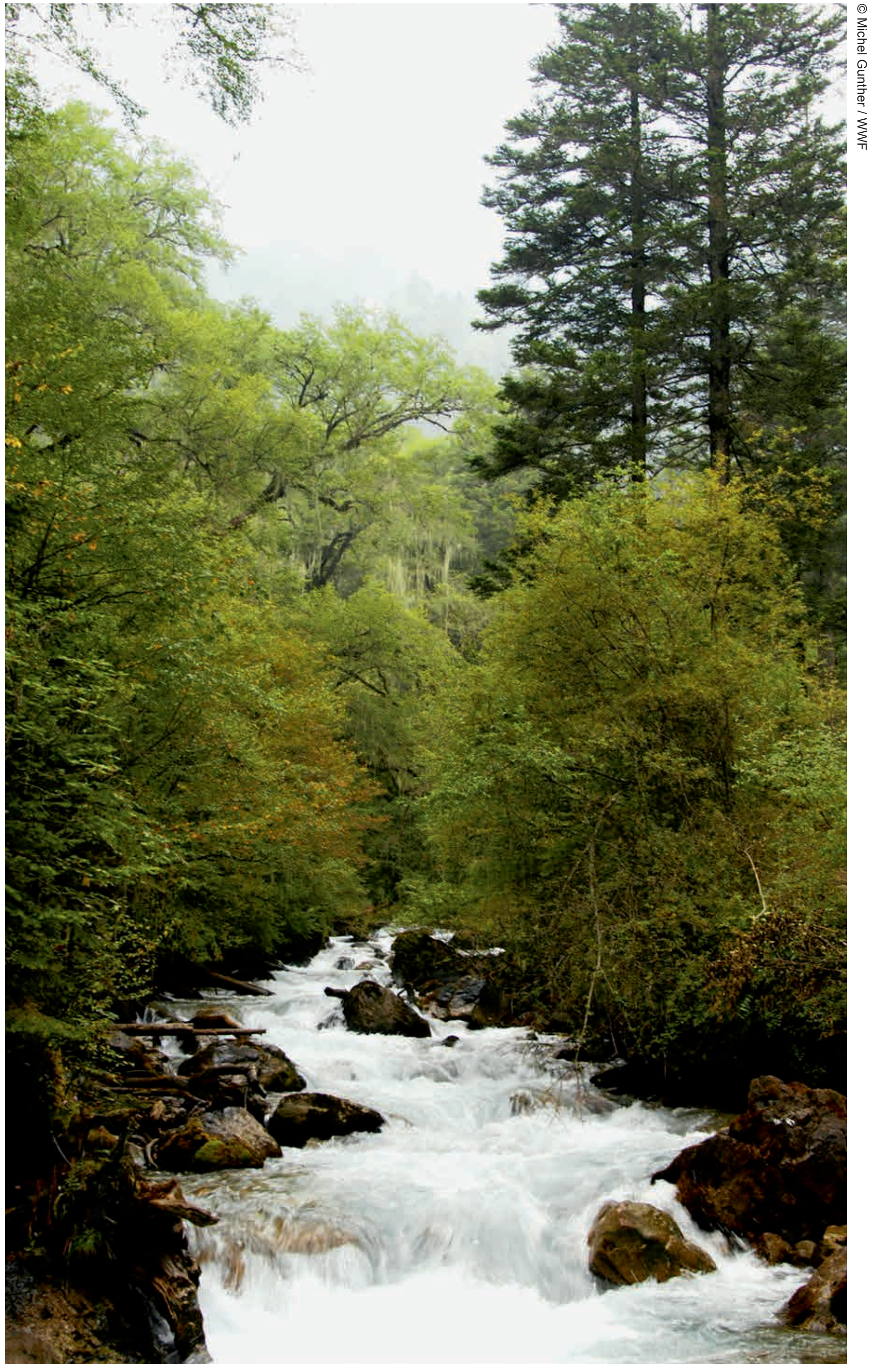


Figure 5: Distribution of N_r deposition classes and exceedance of deposition levels in the period 2000–2030 on Protected Areas (PAs) under the Convention on Biological Diversity
Red PAs show an exceedance of 10 kg N/ha/y and deposition in 2030 higher than 2000. Orange PAs show a current exceedance, but deposition in 2030 lower than 2000. Green PAs might be under threat in the near future since N_r deposition exceeds 5 kg N/ha/y, but is increasing over the period 2000–2030 (Bleeker et. al., 2010).



Wanglang Nature Reserve, Sichuan Province, China. A large part of the world's protected areas receive N deposition well above the critical load.

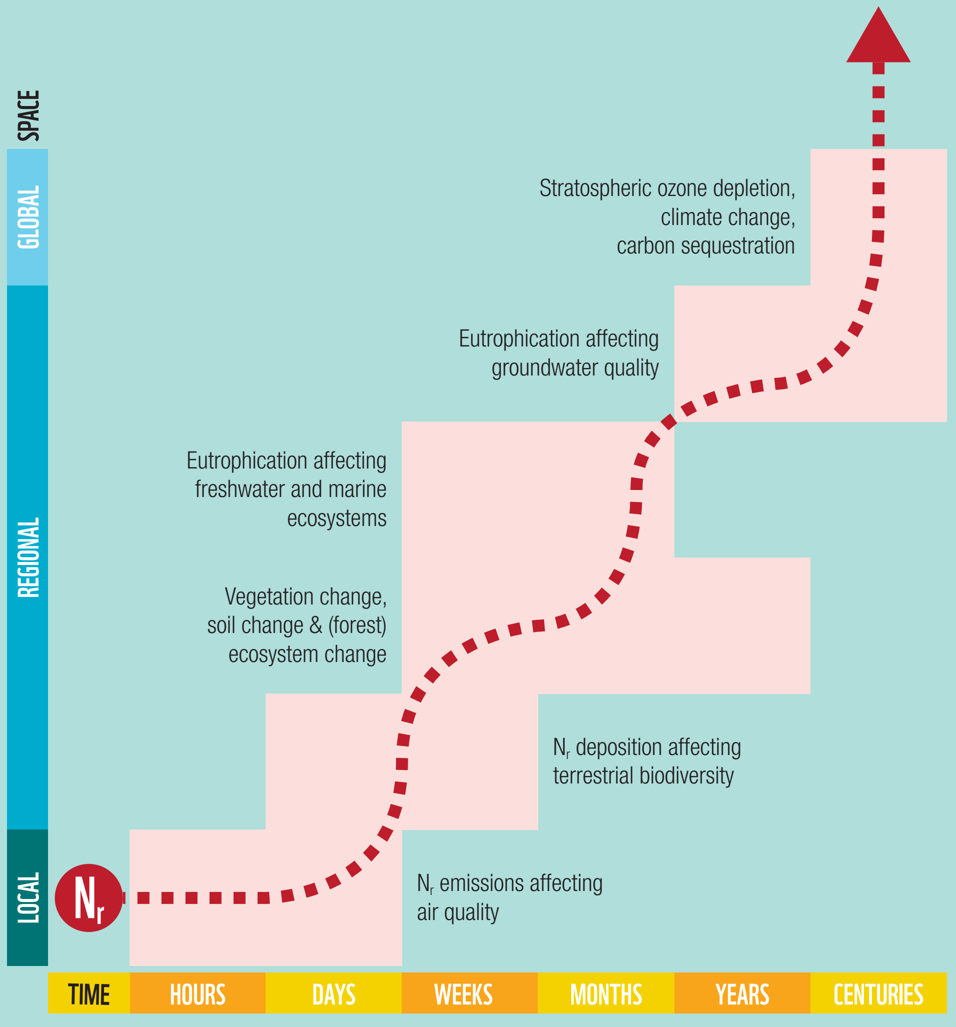


Figure 6: Nitrogen cascade
This figure shows how the nitrogen cascade amplifies N_r effects through both time and space.

The nitrogen cascade: one nitrogen atom can have multiple impacts

The sum of both natural and manufactured N_r within the Earth System - regardless of origin - eventually contributes to the cascade of fluxes and detrimental effects (Galloway et al., 2003; Erisman, 2004). In general, the spatial extent of N_r effects increases with time. For example, N_2O remains present for more than 100 years in the atmosphere and contributes to climate change on a planetary scale.

Over a shorter time period, N_r effects are mainly local or regional in nature and its different forms (e.g. NH_3, NO_x, NO_3) have distinct and specific effects. Also, over time, the same atom of N_r can cause multiple effects in the atmosphere, in terrestrial ecosystems, in freshwater and marine systems and on human health. We call this sequence of effects the N cascade (Galloway et al., 2003), further illustrated in Figure 6.

For example, reactive nitrogen released to the atmosphere from fuel combustion can lead to the following sequence: an increase in tropospheric ozone levels, a decrease of visibility, and an increase of atmospheric acidity. Upon deposition from the atmosphere by precipitation, N_r can acidify water and soil, over-fertilize grassland, forests, and coastal ecosystems, followed by re-emission to the atmosphere as nitrous oxide, again contributing to climate change and the depletion of stratospheric ozone.

As long as N_r remains in the environment, this cascading effect will continue. As it moves down the cascade, the original source of N_r becomes unrecognizable because of the many transformations and interactions (Erisman, 2004). At some point N_r is returned to atmospheric N through the denitrification processes. Denitrification is the process of transforming reactive N, commonly by soil bacteria or by bacteria used in sewage treatment, that usually results in the escape of unreactive N into the air.

DRIVERS BEHIND THE DISRUPTION OF THE N CYCLE

The N problem is caused by the elevated sum of all forms of N_r that are released into the environment. To reduce the negative impacts and to remain within a safe operating space for humanity, anthropogenic N_r production should be reduced by at least 50% globally (De Vries et al., 2013; Steffen et al, 2015). The level of decrease necessary, spatially varies greatly and depends on the current regional and local situation. When (and if) N_r production is reduced, there will be a considerable lag time before built-up N_r is lost from the biosphere. In order to lower the quantity of N_r, global society needs to understand and mitigate the drivers determining the total amount of N_r produced and released into the environment.

TO REMAIN WITHIN A SAFE OPERATING SPACE FOR HUMANITY, REACTIVE NITROGEN PRODUCTION SHOULD BE REDUCED BY AT LEAST 50% GLOBALLY

The main drivers contributing to the N impacts can be categorized as:

1. The inefficient and unsustainable use of N-fertilizer and manure leading to large losses to terrestrial and aquatic ecosystems;
2. Increased global consumption levels as a result of human population growth, increase in per capita consumption and a diet shift towards more protein-rich food. This has led to an increased demand for agricultural products and consequently a rise in the use of N-fertilizers (and its inefficient use);
3. Increased demand for fossil fuels, and the resulting release of N_r in the atmosphere during combustion.

Low efficiency of reactive nitrogen fertilizer

The notion of efficiency is central for our understanding of the mechanisms of N_r loss in agriculture. Fertilizers now provide about 40% of all N_r taken up by crops (e.g. Hatfield and Prueger, 2004). Yet a relatively small proportion of the fertilizers applied to food production systems ends up in the food that is consumed by people. Nitrogen use efficiency (NUE) represents a measure of the effective uptake of N by agricultural crops versus the total input (e.g. N-fertilizer). Since unused N_r is released into the environment, maintaining production with low levels of input and high NUE is desirable.

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Sunlight illuminates the coral at the Great Barrier Reef. Catchment run-off is one of the biggests threats. Water running off catchments collects farm fertilizer, pesticides and soil, and flushes these pollutants out onto the Reef. The impact on corals and seagrass, and the species that rely on them, is immense.

With few exceptions, the nitrogen use efficiency in European agriculture in the mid 1990s ranged from 30 to 75% (Erisman et al., 2005). However, NUE varies considerably depending on farm management, input use and environmental and climate conditions (Hatfield and Prueger, 2004). NUE generally decreases as the input increases. This means that there is relatively more loss to the environment per kg N_r input.

Second only to industrially produced fertilizer, manure is an important N_r source for agriculture. Different chemical compositions and amounts of manure generated by different animals and on different farm types where animals are raised (ranging from extensive to intensive breeding situations) produces N_r hot spots around the globe (Steinfeld et al. 2006). During the production, management and application of manure to agricultural fields, the NUE is low and therefore contributes substantially to N_r emissions to air, groundwater and surface water.

MANURE CONTRIBUTES SUBSTANTIALLY TO N_r EMISSIONS TO AIR, GROUNDWATER AND SURFACE WATER

Increased indirect nitrogen demand due to growing human population with shifting consumption patterns

The growing human population along with an increased preference for animal-based protein created the need for increased agricultural productivity. The 20th century solution to this situation was to both convert large amounts of natural ecosystems into farmland and to dramatically increase fertilizer application to intensify production. The old on-farm nutrient cycle was irrevocably altered.

Higher production led to steeper increases of N_r losses to the environment. This is especially true for the production of animal proteins. With an average NUE of 8%, a staggering 92% of the N_r used in producing meat and dairy is lost, whereas the efficiency of plant-based food is about 20% (Bouwman et al., 2013; Galloway and Cowling, 2002). The NUE of animal protein production is lower because N_r is lost at two different stages. The first loss occurs while producing the feed for the animals. The second loss occurs while the animals are raised and fed, as most of the N in their feed is lost in manure. Even if perfect recirculation of N_r from manure were possible, the additional need for N_r will always reduce the resulting NUE in agriculture due to the inevitable losses of N_r during the period of plant growth. A global decrease in demand for animal proteins could significantly reduce excess use of N_r.

IN THE PRODUCTION OF MEAT AND DAIRY, 92% OF THE REACTIVE NITROGEN IS LOST TO THE ENVIRONMENT

Fossil fuel combustion and dependence of agriculture on fossil fuels

Combustion of fossil fuels is another important driver for the disruption of the N-cycle. NO_x is generated at high temperatures in combustion processes mainly from the oxidation of N_2. Road transport and public power generation are by far the largest contributors to the emissions, each contributing 20 % to 25 % of total NO_x emissions. Industrial production and shipping each contribute 10% to 15%. The remainder of the sources comprise aviation, biomass and agricultural burning, emissions from forest and agricultural soil, waste incineration and lightning (Hertel et al. 2014).

Fossil fuels, especially natural gas, are the main resources required for fertilizer production which - in turn - is the main source of agricultural N_r use and loss. About 1.5% of current global energy use is dedicated to the production of fertilizers (IFA, 2009).

Fossil fuels also power machinery and enable the transportation of food, products and resources across the globe. N_r from fossil fuels contributes to greenhouse gas emissions and therewith climate change.

N_r FROM FOSSIL FUELS CONTRIBUTES TO GREENHOUSE GAS EMISSIONS AND THEREWITH CLIMATE CHANGE

What the future brings: scenarios project increases in reactive nitrogen production

A growing population and the anticipated intensification of agriculture will most certainly boost N_r use and exacerbate the problems associated with the environmental consequences of N_r emissions. The magnitude of these effects will depend on the pathway that humanity chooses to take in the next decades.

Winiwarter et al. (2013) estimated industrial N fixation through the end of the 21st century using the same drivers that underlie the climate change scenarios developed by IPCC (2013). These scenarios were extended with estimates of population growth, consumption of animal protein, agricultural intensification and additional biofuel production. The researchers arrived at N_r fixation rates for agricultural use that range from slightly less to almost twice the fixation rate of the year 2000. Future anthropogenic N fixation for production of explosives, plastics and from fossil fuel combustion will remain considerably less than N fixation related to agriculture. Other published work on N fixation towards 2100 indicate that the high estimates are rather conservative (e.g. Erisman et al. 2008).

Even the most optimistic scenario predicts no real decline in the industrial N fixation rate. The scenario using the lowest fossil carbon in Winiwarter et al. (2013) is potentially the largest contributor to nitrogen pollution. This is due to the huge amounts of biofuels required and the fertilizer needed to produce them. This scenario shows the tension and potential trade-offs between different environmental challenges, requiring a holistic approach in fundamentally greening humanity's impact on the planet (Erisman et al., 2008).

A GROWING POPULATION AND THE ANTICIPATED INTENSIFICATION OF AGRICULTURE WILL MOST CERTAINLY BOOST N_r USE

THE TENSION BETWEEN DIFFERENT ENVIRONMENTAL CHALLENGES, REQUIRE A HOLISTIC APPROACH IN FUNDAMENTALLY GREENING HUMANITY'S IMPACT ON THE PLANET

A boy swims in the algae-filled coastline of Qingdao, Shandong province, China.

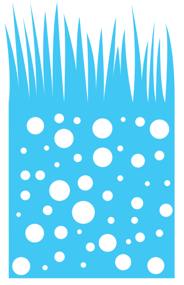
FINDING A BALANCE: SOLUTIONS TO REDUCE GLOBAL NITROGEN IMPACTS

Compared to climate change and biodiversity loss the nitrogen issue is relatively neglected - in spite of the fact that it is now one of the most pressing issues on the planet. We depend on N_r as an important resource for agriculture production, and hence our daily food. But agriculture and consumption patterns are also the main driver for disruption of the N-cycle and the consequent impacts on our natural environment. The challenge lies in finding an appropriate balance in using and reducing the amount of human produced N_r. This will require a tremendous global effort, especially in the light of a growing world population, increased consumption per capita and a change to diets with more animal proteins.

Holistic integrated approach needed to prevent trade-offs

Efforts to reduce the use of reactive nitrogen need to be holistic and integrated to reduce the risk of unwanted trade-offs between the interlinked concerns of global warming, land use change, biodiversity loss, ocean acidification and other environmental themes. For instance, a shift from fossil fuels to sustainable renewable energy will on the one hand reduce reactive nitrogen load as fossil fuel combustion is an important N_r source. On the other hand, this shift might induce increased demand for biomass to produce energy, leading to the use of more N-fertilizer to increase biomass production. Many climate change mitigation policies imply a competition with land use for other purposes such as food versus fuel crops. The same trade-offs are apparent when developing strategies for feeding a growing world population: intensification of production through the use of N-fertilizer might boost productivity, but also affects the resilience of the agro-ecosystem and generates N_r losses to the environment.

INTENSIFICATION OF PRODUCTION THROUGH THE USE OF N-FERTILIZER MIGHT BOOST PRODUCTIVITY, BUT ALSO AFFECTS THE RESILIENCE OF THE AGRO-ECOSYSTEM AND GENERATES N_r LOSSES TO THE ENVIRONMENT



Global problems, regional solutions

Like other issues of global concern, the N_r problem is complex because of the many actors, interactions and effects. General solutions are challenging because N_r creates benefits and costs on multiple scales, from local to global, and there are innumerable interconnections between the scales.

Options to reduce reactive nitrogen

The most effective mitigation options are those that reduce demand for N_r or that keep emissions from entering the larger biogeochemical system. The most important general approaches to date are:

1. Improving the efficiency of nitrogen use in agriculture

a. Substitute N-fertilizer by natural alternatives such as biological fixation, e.g. by using leguminous crops in rotation, better use of soil N and better recycling of N (closing the nutrient cycles at different scales)

b. Close the nutrient cycle and preventing loss of nutrients in the production system, e.g., by balanced nutrients per crop, producing animal feed where the manure is produced, and/or by improving soil quality.

c. Adopt agro-ecology principles. Agro-ecology principles focus on the optimization of productivity (instead of maximisation) and farming practices in accordance with the characteristics of the ecosystem, e.g., by improving resilience of the farm by making use of natural processes, strengthening functional biodiversity (such as soil quality) and protecting the ecosystem services that the farm depends on. Soil biodiversity can contribute to increased resistance to droughts and floods and can increase nutrient efficiencies.

2. Improving nitrogen use efficiency in the food chain

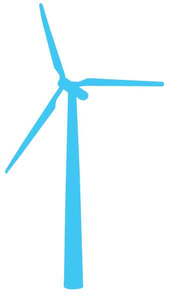
a. Reducing waste throughout the food chain could also considerably reduce demand for agricultural goods per person and would therefore reduce N_r pollution (Grizzetti et al. 2013). The FAO estimated that one-third of food produced for human consumption is lost or wasted globally, which amounts to about 1.3 billion tons per year. Food is lost or wasted throughout the supply chain, from initial agricultural production down to final household consumption.

b. Promote healthy diets, low in animal protein. In many developed countries, individuals eat more food in general and especially more animal products than is necessary for a healthy balanced diet. Even in some developing countries per capita consumption of animal products is fast increasing to levels that are less healthy and environmentally unsustainable. Where animal protein consumption is high, there is a need to encourage options for those who choose to reduce the consumption of animal products. Reducing per capita meat consumption has the potential to offer significant health benefits, improve nutrient use efficiency, reduce overall production costs and reduce environmental pollution. In some regions of the world, however, increased nutrient availability is needed to improve diets.

3. Reducing fossil fuel combustion

a. Replace fossil fuel use with sustainable renewable alternatives such as solar and wind technologies.

b. Ensure that fossil fuel replacements in the form of biomass are not inducing an increased demand for N_r. The use of biomass as an alternative energy source would not be an appropriate choice because it would require even more fertilizer (Erisman et al. 2008).



4. Stimulating the removal of nitrogen from the cascade

Reactive N_r can be converted back into its inactive N_2 form via a process called denitrification. Removal can occur in wetlands for denitrification or in wastewater treatment plants. Nitrogen is removed in waste water treatment plants through the biological oxidation of N_r from ammonia to nitrate (nitrification), followed by denitrification, the reduction of nitrate to N_2 gas. N_2 is released to the atmosphere and thus removed from the water.

Although most of the issues highlighted in this section are global in scale, they affect specific locations very differently. For instance, over-fertilization causes severe environmental problems in some parts of the world, while in other regions people suffer from a serious lack of N-fertilizer. Nutrient-limited regions include much of Africa (Sanchez, 2002; Stoorvogel et al., 1993), where 80% of countries still face N scarcity (Liu et al., 2010), as well large areas of Latin America and South East Asia (MacDonald et al., 2011). Consequently, local and regional perspectives are of vital importance for understanding the differing nature and priority of the issues. A regional context is also important for the design of solutions. Varying cultural, social and economic factors must be considered to ensure sound policy implementation.

THE MAIN TARGET SHOULD BE TO OPTIMIZE LOCAL TO GLOBAL FOOD AND ENERGY PRODUCTION AND CONSUMPTION WITH THE LOWEST POSSIBLE ENVIRONMENTAL CONSEQUENCES

In intensive agricultural areas the increase in nitrogen use efficiency can be very effective in the short term to limit losses of N_r, which means the reduction of inputs and using them more efficient. In areas with very low N_r inputs where there is a need for higher inputs to increase yield, closing the nutrient cycles is of major importance to optimise the use on N_r efficiency in the whole system. The same holds for the difference in scale: globally the closing of nutrient cycles has highest priority, whereas on the local scale other priorities might be set, such as limiting the emissions that contribute to local nitrogen deposition. The main target should be to optimize local to global food and energy production and consumption with the lowest possible environmental consequences.

Existing policies to reduce N_r pollution

There is little policy development directed toward excess N_r in the global system. However, in Europe and the US there are successful policies that have led to the reduction of NO_x emissions - through the air quality standards for O_3 and NO_2 in the US and through UN-ECE NO_x and Gothenburg protocols in Europe. Successful technologies are the three-way catalysts in car exhausts, the Selective (Non) Catalytic Converter systems in industry and energy production. NO_x emissions were reduced by 40% in 2009 relative to 1990 in 27 member states of the European Union (EEA, 2012).

Concerning NH_3, the Gothenburg protocol (national NO_x and NH_3 emission ceilings) has led to 14% reductions in Europe (EEA, 2012). At the national level, two countries have implemented NH_3 abatement measures and reduced emissions: Denmark has achieved a 40% reduction and the Netherlands has achieved a 70% reduction (EEA, 2012) in NH_3. Abatement technologies encouraged in these policies include low- emission animal housing systems, coverage of manure storage facilities, and application of slurry injection technologies. Furthermore, total N inputs in agriculture were decreased by reducing N in feed and by reducing mineral fertilizer application.

Nature conservation: towards an integrated landscape approach

From a nature conservation perspective, it is essential to harness the will of individuals, governmental bodies and industries across sectors to reduce the N emissions released from human activities. Target setting of critical loads of N_r to maintain healthy ecosystems and biodiversity is one step toward forming practical policy development (e.g. Bobbink et al., 2010). The goal should be to lower the level of N_r in the system to the point where original vegetation composition and abundance could be restored.

Management options for removing N from unbalanced systems should depend upon the circumstances. Restoration might include the removal of N enriched top soils in heathland systems to recreate N-poor systems with species-rich heathlands (Power et al., 2001). In order to restore eutrophic freshwater systems or coastal zones, nitrogen management for restoration is also possible (e.g. Chislock, et al. 2013). Systems where the biodiversity problem results from short-term increase in N_r concentrations (e.g. surface waters without a large sediment 'bank' of N_r) might be restorable by turning off the N_r tap. Systems with long-term N load issues (e.g. most long-term N_r-impacted terrestrial ecosystems) will be more difficult to treat. There are areas where the N_r load is high and the ecological communities have shifted so much that it's not financially feasible to restore the 'pre-industrial' state. This should trigger a political discussion to what extent we are prepared to live with new, more N_r-enriched, ecological communities.

In many parts of the world; nature, agriculture and other land uses are closely intertwined. In these landscapes, nature conservation, agriculture and N management should be managed as an interconnected system, where each function is preserved and optimally used. Thus promoting an integrated landscape approach where maintaining the resilience of ecosystems and preserving biodiversity can benefit nature and agricultural production. Agro-ecology can be a beneficial tool for managing such mosaic landscapes.

AN INTEGRATED LANDSCAPE APPROACH WHERE MAINTAINING THE RESILIENCE OF ECOSYSTEMS AND PRESERVING BIODIVERSITY CAN BENEFIT NATURE AND AGRICULTURAL PRODUCTION

Raising public awareness about the N issue

Over the past decade, the public has learned a lot about climate change and the effects of greenhouse gas emissions on global warming. Humanity's enormous effect on the global N_r cycle is far less known. The task ahead to reduce impacts is perhaps more daunting than reducing GHG emissions, as we are facing a clear paradox: N is vital to human survival, yet its use negatively affects both people and ecosystems. There is a pressing need to raise awareness among citizens, politicians, nature conservationists, industry and farmers about the positive and negative aspects of N and the challenge to strike a balance between human and ecological needs. Nitrogen footprints can provide more specific information and solutions regarding N-related problems. Personal and/or institutional N footprint calculators raise awareness and connect consumers with the N_r lost to the environment as a result of their activities (see figure 7).

WE ARE FACING A CLEAR PARADOX: N IS VITAL TO HUMAN SURVIVAL, YET ITS USE NEGATIVELY AFFECTS BOTH PEOPLE AND ECOSYSTEMS

Tools to raise awareness about nitrogen

A personal footprint model for N is available at www.N-print.org (Leach et al., 2012). This model asks users questions about their resource consumption in terms of food and energy. Based on these answers, the tool then scales the user's footprint from the country average.

N-Calculators for consumers and for entire countries are available for the US, the UK, Germany, and the Netherlands (Figure 7; adapted from Leach et al. 2012, Stevens et al. 2014). Since food and energy production practices are relatively similar among developed countries, the creation of additional versions for other developed countries would be relatively straightforward.

The general N-Calculator framework is available as a baseline and includes default emissions and losses to calculate the N flows using global databases (FAO, etc.). While calibrated for developed countries at present, the basic N-Calculator could be used elsewhere if country/area specific data and models become available.

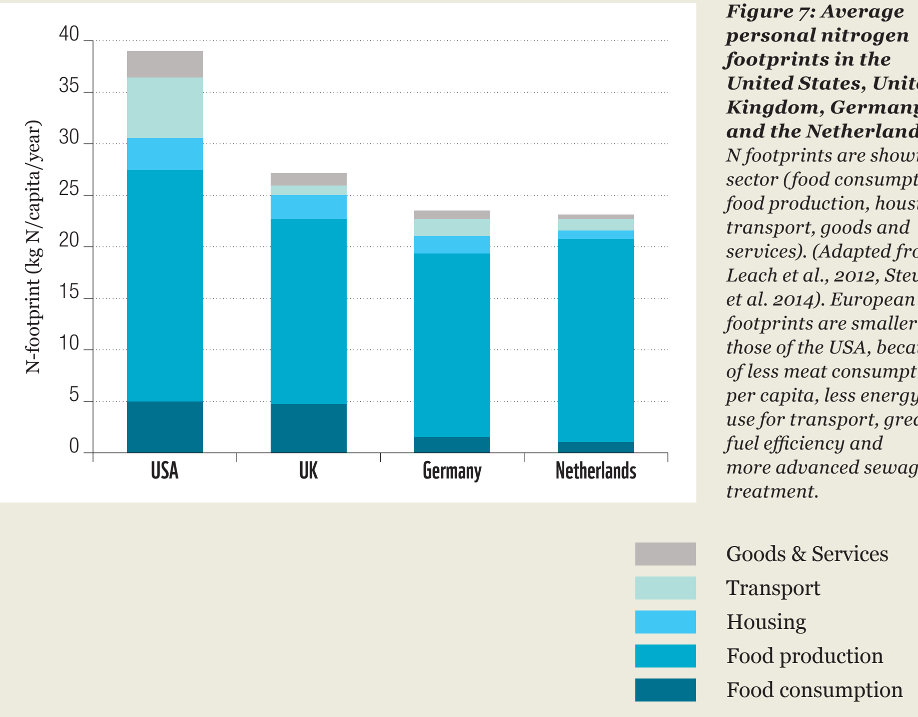


Figure 7: Average personal nitrogen footprints in the United States, United Kingdom, Germany, and the Netherlands. *N footprints are shown by sector (food consumption, food production, housing, transport, goods and services). (Adapted from Leach et al., 2012, Stevens et al. 2014). European footprints are smaller than those of the USA, because of less meat consumption per capita, less energy use for transport, greater fuel efficiency and more advanced sewage treatment.*

CONCLUSIONS

Nitrogen is vital to human life and all other living organisms. The widespread use of artificial N-fertilizers has greatly increased agricultural productivity, keeping pace with the growth of the human population. But also resulting in substantial losses of N_r to the environment and biosphere. The on-going demand for more food and the steady increase of animal proteins in diets is boosting fertilizer and land use even further, leading to increased release of N_r to the biosphere. At the same time, the burning of fossil fuels has also significantly increased reactive nitrogen oxide emissions to the atmosphere.

IMMEDIATE ACTION IS NEEDED TO REDUCE THE USE OF REACTIVE NITROGEN AND TO BETTER MANAGE NITROGEN LOSSES IN ORDER TO LIMIT ITS CASCADING EFFECT

Human activities now convert more nitrogen from the atmosphere into reactive forms than all of the Earth's terrestrial processes combined. In many places, this has led to detrimental consequences. Nitrogen has been identified as a major driver of terrestrial biodiversity loss, and many other, often interlinked, thresholds for human and ecosystem health have been exceeded due to reactive nitrogen pollution, including those for drinking water quality (nitrates), air quality (smog, particulate matter, ground-level ozone), eutrophication of freshwater and coastal ecosystems (dead zones), climate change and stratospheric ozone depletion. Each of these environmental effects can be magnified by the 'nitrogen cascade' whereby a single atom of reactive nitrogen can trigger a sequence of negative environmental impacts through time and space.

On the planetary scale the threshold for nitrogen has been estimated to be exceeded by a factor 2. This means that for nitrogen, the safe operating space of humanity with respect to the earth system has been well transgressed. Immediate action is therefore needed to reduce the use of reactive nitrogen and to better manage nitrogen losses in order to limit its cascading effects.

Potential actions to improve nitrogen management are optimizing food production and consumption, and reducing the use of fossil fuels, while limiting nitrogen impacts. The most effective and integrated solutions comprise increasing nitrogen use efficiency in agriculture, reducing waste in the food chain, promoting diets with less animal protein in developed countries, and a shift from fossil fuels to sustainable renewable energy sources such as solar and wind energy.

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APPENDIX:
EXPLANATION OF TERMS AND LIST OF ABBREVIATIONS

Abbreviation; chemical formula	Explanation
NH_3	Ammonia, reduced form of nitrogen, can be emitted from manure and produced through the Haber-Bosch process. Basis for chemical industry and fertilizer
N_2	Atmospheric di-nitrogen, unreactive form of nitrogen. 78% of the atmosphere consists of N_2
NO_x	Nitrogen oxides, Oxidized form of nitrogen emitted to the atmosphere through combustion processes
N_2O	Nitrous oxide, third most important greenhouse gas
NO_3	Nitrate
NUE	Nitrogen Use Efficiency
N_r	Reactive Nitrogen: all reactive forms of nitrogen, such as oxidized forms (NO_x, N_2O, NO_3, HNO_3, etc.), reduced forms (NH_3, NH_4 and amines) and organic forms
GPNM	Global Partnership on Nutrient Management
Eutrophication	Excessive nutrients in a lake or other body of water, usually caused by runoff of nutrients from the land, which causes a dense growth of plant life; the decomposition of the plants depletes the supply of oxygen, leading to the death of animal life
IFA	International Fertilizer Industry Association
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IPNI	International Plant Nutrition Institute
NUE	Nutrient Use Efficiency
Tg	Tera (10^{12}) gram
SDGs	Sustainable Development Goals
UNEP	United Nations Environment Programme

Front cover photograph:
A satellite image of a phytoplankton bloom stretching across the Barents Sea off the coast of mainland Europe's most northern point, Cape Nordkinn. These microscopic marine organisms that drift on or near the surface of oceans and seas have been called 'the grass of the sea' because they are the foundation of the oceanic food chain. Phytoplankton are able to convert inorganic compounds such as water, nitrogen and carbon into complex organic materials. With their ability to 'digest' these compounds, they are credited with removing as much carbon dioxide from the atmosphere as their plant 'cousins' on land - therefore having a profound influence on climate. © ESA

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