Chapter 1

Assessing our nitrogen inheritance

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1.1 A new challenge from a past solution

Human perturbation of the nitrogen cycle represents a major example of global geo-engineering. Historically, the limited availability of reactive nitrogen compounds has provided a key constraint to human activities. Although the element nitrogen is extremely abundant, making up 78% of the Earth's atmosphere, it exists mainly as unreactive di-nitrogen (N_2). By contrast, to be useable by most plants and animals, reactive nitrogen (N_r) forms are needed. These include oxidized and reduced nitrogen compounds, such as nitric acid, ammonia, nitrates, ammonium and organic nitrogen compounds, each of which is normally scarce in the natural environment.

The two main historical needs for reactive nitrogen have been to provide fertilizers to increase food production and as a basis for the manufacture of munitions. Biological nitrogen fixation has always added new reactive nitrogen into the system, but the inputs have been barely sufficient for human needs. As a result, traditional agricultural production was highly dependent on effective recycling of nitrogen in manures.

By the end of the nineteenth century, an increasing human population combined with expanding military needs required that large amounts of extra reactive nitrogen be added into circulation. These demands were met by increased mining of reactive nitrogen deposits, including Chile saltpetre and guano, supplemented by the extraction of reactive nitrogen from coal and peat (Vincent, 1901; Clow and Clow, 1952; Watt, 2003; Sutton *et al.*, 2008). The western world had effectively become a 'fossil nitrogen economy', as both food and military security depended critically on these nitrogen sources (Erisman *et al.*, 2008; Sutton *et al.*, 2009).

Increasing dependence on these fossil nitrogen reserves was, naturally, not sustainable. The 'nitrogen problem' of the time was that many of the mined nitrogen supplies were becoming exhausted, and that these would soon be insufficient to meet the needs of a rapidly growing world population. As Sir William Crookes famously pointed out to the British Association, if sufficient wheat were to be produced to feed the world, new efforts would be urgently needed to find commercially viable ways of fixing atmospheric di-nitrogen into reactive nitrogen (Crookes, 1898; Leigh, 2004). Potentially, the atmosphere represented a nearly inexhaustible supply from which to manufacture reactive nitrogen, limited only by the energy costs of chemical production.

Efforts at industrial nitrogen fixation were intensified, including development of the cyanamide process and the arc process. Both of these were extremely energy expensive. However, by 1908 Fritz Haber in Germany had filed his patent for the direct 'synthesis of ammonia from its elements', in a new process with greatly reduced energy costs (Haber, 1920; Smil, 2001; Leigh, 2004). Following commercial upscaling of Haber's method by Carl Bosch, large-scale chemical production of reactive nitrogen became economic. The 'nitrogen problem' of the early twentieth century rapidly became a thing of the past (Partington, 1925), and by the 1950s, the Haber–Bosch process had replaced fossil reserves as the main source of additional reactive nitrogen.

The scale of the Haber–Bosch achievement cannot be overestimated. It represents perhaps the greatest single experiment in global geo-engineering that humans have ever made, underpinning present day food and military security. By allowing the human population to expand, it can equally be considered as laying the foundation for all other aspects of global change. Thus it is only through synthetic nitrogen fertilizers that humanity has been able to reach 6 billion people, around half of whom would not be alive without it (Erisman *et al.*, 2008). Future projections of the human population depend even more strongly on increasing global production of nitrogen fertilizers.

Together with human-driven increases in crop biological nitrogen fixation, this great effort of geo-engineering has more than doubled the global production of reactive nitrogen compared with pre-industrial levels (Galloway *et al.*, 2008). This extreme change has knock-on effects in other element cycles, both through direct biogeochemical interactions, and because increased nitrogen has allowed the human population to grow, thereby fuelling additional resource use and global change.

It is as a result of this great increase in nitrogen fixation that we now reap our 'nitrogen inheritance'. In learning to produce additional reactive nitrogen, humans have largely failed to manage its implications for the natural environment. Fundamentally, agricultural practices have a low nitrogen-use-efficiency, especially under increasing nitrogen inputs. As a result, losses of reactive nitrogen to the environment

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have increased greatly, including nitrate pollution of water courses and emissions of both ammonia and nitrous oxide to the atmosphere, with impacts on biodiversity and climate change. In parallel with these changes, humanity has found itself releasing reactive nitrogen directly into the atmosphere through high-temperature combustion processes in industry and transport, which convert atmospheric di-nitrogen to nitrogen oxides. These nitrogen compounds are produced unintentionally and react to form ozone and particles in the air we breathe, damaging human health. Even with this brief listing of issues, it is clear that human alteration of the nitrogen cycle is having consequences that could not have been foreseen a century ago.

Just as society has realized the climate implications of fossil fuel combustion, we now appreciate that our nitrogen inheritance is not all good. With reactive nitrogen, humanity has managed to feed the world, but at the same time has created a complex web of impacts occurring through air, land and water that threaten our global environment.

1.2 Challenges for a nitrogen assessment

Research on alteration of the nitrogen cycle is not new. Together with the environmental consequences of excess reactive nitrogen, we also inherit a wealth of scientific literature that covers the wide diversity of nitrogen processes, sources and impacts. Key scientific resources include the assessments brought together by the Scientific Committee on Problems of the Environment (SCOPE) (Söderlund and Svensson, 1976; Blackburn and Sorenson, 1988) and by the Royal Society of London (Stewart and Rosswall, 1982), including a recent assessment of the nitrogen cycle in agriculture (Mosier *et al.*, 2004).

While these studies provide an important foundation, it must be recognized that there has never before been a comprehensive continental-scale assessment covering all the main effects of nitrogen. This may be partly a reflection of the extreme complexity of the nitrogen cycle, with scientific specialization tending to separate the different research communities. It is easy to see, for example, how research into the atmospheric chemistry of oxidized nitrogen species can be sufficient to develop scientific communities that have little awareness of research into carbon-nitrogen interactions in forestry, of the biodiversity implications of nitrogen deposition, or of the consequences of nitrogen-phosphorus interactions for 'dead zones' in coastal waters.

In parallel with the trend toward scientific specialization, environmental policies have gradually begun to address the threats posed by excess reactive nitrogen. Such policy domains have developed in a piecemeal fashion until now, generally focusing on individual threats. With the needs of existing policies feeding research agendas, this has led to further separation of the many nitrogen research communities.

The consequence of these trends is that, in Europe at least, we now inherit a huge scientific expertise on different aspects of the nitrogen problem, together with a disparate set of nitrogen-relevant policies. In principle, there is therefore a huge resource to develop mitigation strategies to the different environmental threats. By contrast, the limited degree of coordination between these activities can mean that they are far from optimal. After the production and release of a new reactive nitrogen molecule, it may be transformed many times, having multiple effects in the environment before eventually being immobilized or denitrified back to di-nitrogen. This idea of a 'nitrogen cascade' including many nitrogen forms and impacts means that substantial interactions can be expected between different policies related to nitrogen (Figure 1.1). In principle, there are serious risks, for example, as measures to reduce nitrogen water pollution

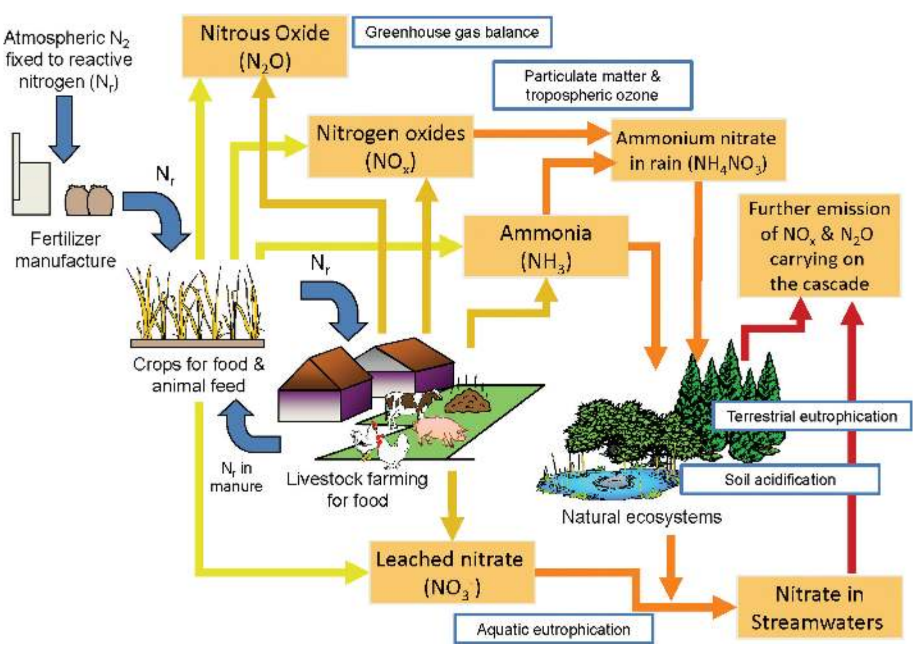

Figure 1.1 Simplified summary of the nitrogen cascade illustrating the example losses, transformation and effects of reactive nitrogen (N_r) fertilizers in the environment. Similar images can be drawn to illustrate the cascade of N_r forms following fossil fuel emissions and crop biological nitrogen fixation.

can increase reactive nitrogen pollution in the air, illustrating the potential for 'pollution swapping'. By contrast, there are also major opportunities to exploit synergies and to identify win–win situations, where several forms of nitrogen pollution are reduced at the same time, while also minimizing other environmental threats.

With these issues in mind, it is clear that the challenges faced by a nitrogen assessment are rather different to the challenges of recent climate assessments. Rather than focusing on a single central question of whether human alteration of the nitrogen cycle is leading to environmental change, the present assessment takes the undoubted evidence of nitrogen impacts as a starting point. The central challenge of the present assessment is to draw together the different aspects of 'nitrogen change' to develop a more coherent understanding of how they fit together. This must be the foundation for identifying options for better nitrogen management, and for explaining the key messages to society. In this respect, the present assessment can be seen as initiating a process of integration and communication between nitrogen scientists of different disciplines, between scientists, industry and policy makers, and finally between scientists and the public at large. There is no doubt that the complexity of nitrogen forms, processing and impacts in the environment hinders public understanding. The scope of this assessment must therefore include considering how the nitrogen challenge facing humanity can be communicated more effectively.

1.3 Approach of the European Nitrogen Assessment

In developing a first continental nitrogen assessment, it is clear that Europe has a key role to play. Given its role in the history of industrial nitrogen fixation, there is a matching responsibility on Europe to consider the full consequences of excess nitrogen in the environment. It is thus appropriate that this assessment coincides with the centenary of Fritz Haber's discovery (Erisman *et al.*, 2008).

In most areas of Europe, there is a surplus of reactive nitrogen, both from agricultural fertilizer inputs and from combustion-based nitrogen oxide emissions. The main focus of the European Nitrogen Assessment (ENA) is therefore on quantifying and managing the environmental impacts. We recognize, by contrast, that, in other parts of the world, a shortage of reactive nitrogen still limits food production. The ENA will thus complement other continental nitrogen assessments, together with which, it will provide a platform to start addressing the wider global picture.

In refining the European Nitrogen Assessment, a close interaction has been developed with key stakeholders, including science communities, policy makers, industry representatives and environmental managers (Figure 1.2). The ENA itself has been developed through a cluster of several European networks, under the lead of the Nitrogen in Europe (NinE) framework research programme of the European Science Foundation (ESF). NinE has worked to integrate scientific understating across nine main interlinked environmental concerns of excess nitrogen, drawing on both national and EU activities (NinE, 2010; Bleeker *et al.*, 2008). Major contributions to the ENA have been provided through the COST 729 Action on 'Managing Nitrogen in the Atmosphere-Biosphere System in Europe', which examines nitrogen impacts and policy interactions including the development of integrated assessment approaches (COST, 2010). In addition, underpinning research, especially on nitrogen-greenhouse gas interactions, has been provided by the NitroEurope Integrated Project (NEU, 2010; Sutton *et al.*, 2007, 2009), funded by the European Commission 6th Framework Programme.

Together, these activities provide key inputs to the International Nitrogen Initiative (INI), a joint project of the Scientific Committee on Problems of the Environment (SCOPE) and the International Geosphere Biosphere Programme (IGBP). The INI is structured around the activities of six regional centres, with the ENA representing a contribution of the INI European Centre. By having a global oversight, the INI provides

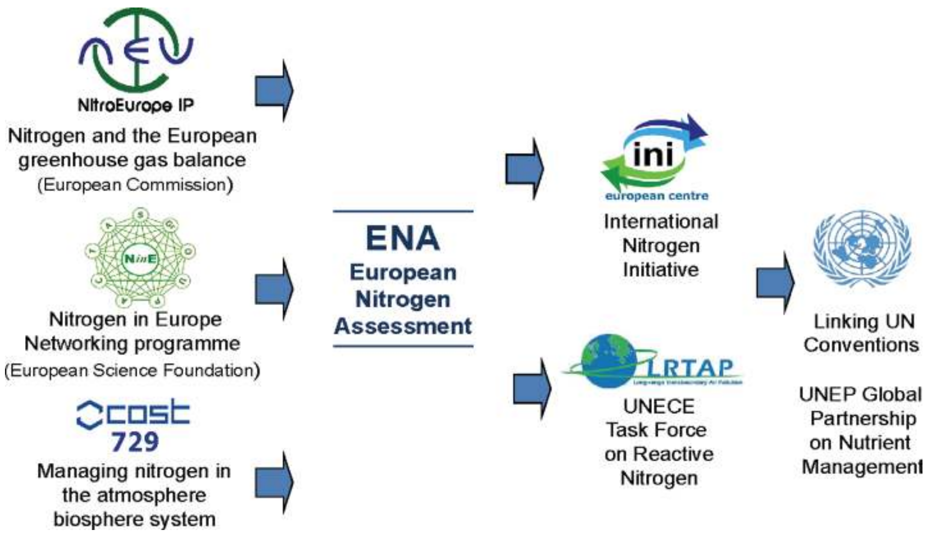

Figure 1.2 The place of the European Nitrogen Assessment in relation to major research networks, integrating activities and policy frameworks.

a coordinating forum with which other continental nitrogen assessments are being developed.

By addressing the linkages between issues, the ENA is specifically designed to support the work of several international conventions. These include:

- the Convention on Long-range Transboundary Air Pollution (CLRTAP) of the United Nations Economic Commission for Europe (UNECE),
- the UN Framework Convention on Climate Change (FCCC),
- the UN Convention on Biological Diversity (CBD),
- the Helsinki Convention on the Protection and Use of Transboundary Watercourses and International Lakes (Water Convention) of the UNECE,
- the UNECE Espoo Convention on Environmental Impact Assessment in a Transboundary Context (TEIA Convention),
- the Marine Conventions for the North Atlantic and North Sea, Baltic Sea and Mediterrean Seas: respectively, the Oslo and Paris Commission (OSPARCOM), the Helsinki Commission (HELCOM) and the Barcelona Convention.

Given the scale of activity in each of these different conventions, coupled with the substantial legislative programme of the European Union, the challenge of communication between conventions is substantial. The CLRTAP has a long-standing experience of developing multi-pollutant multi-effect strategies, such as in the Gothenburg Protocol. At the same time, many of the environmental effects of reactive nitrogen are connected to long-range transport in the atmosphere. Recognizing this challenge, in 2007 the CLRTAP established the Task Force on Reactive Nitrogen (TFRN) (UNECE, 2007). This Task Force works to investigate the linkages between nitrogen issues across the CLRTAP and encourage communication of the nitrogen-related interactions between conventions, as a base to develop more effective mitigation strategies. Considering the obvious affinities, the TFRN adopted the European Nitrogen Assessment into its work plan, thereby providing an important bridge to policy makers in the CLRTAP and the other international conventions.

The European Nitrogen Assessment process represents a four year effort over 2007 to 2011. The outline structure and objectives of the ENA were initially developed through a workshop with key stakeholders in Schaagen, the Netherlands, in January 2007, being refined through subsequent meetings linked to NinE, COST 729, NitroEurope and the CLRTAP. Based on the structure established, the ENA process was developed as a series of five main workshops taking place through 2008–2009, linked to five main sections of the assessment.

For each of the workshops, background documents were invited as a basis to inform working group discussions, from which draft chapters of the ENA were prepared. Following successive tuning between different parts of the assessment, revised chapters were reviewed within the wider ENA team. Finally, each of the chapters was subjected to international peer review prior to publication.

1.4 Overall goal and structure of the European Nitrogen Assessment

Based on the developments described above, the overall goal of the European Nitrogen Assessment was established as being *to review current scientific understanding of nitrogen sources, impacts and interactions across Europe, taking account of current policies and the economic costs and benefits, as a basis to inform the development of future policies at local to global scales*.

In taking this approach, it was recognized that the ENA required the involvement of a wide variety of actors, focused especially in bringing together scientists of different disciplines, together with economists and experts in policy development. Given the magnitude of this challenge, the ENA was developed to establish a process of gradual integration between communities.

The following main workshops were held as the basis for the matching parts of this assessment.

I Nitrogen in Europe: the present position. The focus of this part is to take stock of the current nitrogen challenges faced by Europe. The scene is set by considering both the European environmental threats in the global context (Chapter 2; Erisman *et al*., 2011) and the significant benefits of reactive nitrogen production (Chapter 3; Jensen *et al*., 2011). The multiplicity of current European policies relevant to nitrogen in the environment is then reviewed (Chapter 4; Oenema *et al*., 2011a), followed by a reflection of the developing approach taken by the ENA to link different science and policy areas more closely (Chapter 5; Sutton *et al*., 2011).

II Nitrogen processing in the biosphere. The aim of this part is to review recent progress in scientific understanding of the nitrogen cycle and to highlight the major uncertainties. The focus on processes deliberately emphasizes the fundamental interactions between the many forms of nitrogen as these occur in different environmental compartments. Recognizing the specialized nature of the nitrogen research communities, this part makes a first step toward integration by including consideration of all different nitrogen forms into each chapter, while retaining the distinctive expertise of research communities on terrestrial ecosystems (Chapter 6; Butterbach-Bahl *et al*., 2011a), freshwater aquatic ecosystems (Chapter 7; Durand *et al*., 2011), coastal and marine ecosystems (Chapter 8; Voβ *et al*., 2011) and, finally, nitrogen processing in the atmosphere (Chapter 9; Hertel *et al*., 2011).

III Nitrogen flows and fate at multiple spatial scales. The next step of integration, as addressed in this section, is to scale up nitrogen processes through the range of different spatial domains. For this part of the assessment, science communities were increasingly linked between environmental compartments in order to assess the key interdisciplinary concerns in managing the fate of nitrogen in the environment. The section starts with consideration of nitrogen management at the farm scale, considering the variation in typical nitrogen flows across Europe (Chapter 10; Jarvis *et al*., 2011). The assessment then increases in scale to consider how adjacent sources and sinks of nitrogen interact within rural landscapes (Chapter 11; Cellier *et al*., 2011) and urban landscapes, with a focus on example cities (Chapter 12; Svirejeva-Hopkins *et al*., 2011). The regional scale transport of reactive nitrogen is then addressed, contrasting the transfers through regional scale watersheds into coastal marine areas (Chapter 13; Billen *et al*., 2011) to the atmospheric transport and deposition of reactive nitrogen (Chapter 14; Simpson *et al*., 2011). The approach of developing nitrogen budgets provides a means to consider how different components of the nitrogen cycle fit together (Chapter 15; De Vries *et al*., 2011), followed by the integrated picture of nitrogen fluxes across Europe (Chapter 16; Leip *et al*., 2011).

IV Managing nitrogen in relation to key societal threats. Given the multi-dimensional complexity of reactive nitrogen forms and impacts on the environment, significant effort was given to distilling out the key threats, as discussed in Chapter 5 (Sutton *et al*., 2011). The idea was to identify a short list of key threats, to which the main concerns of nitrogen could be linked, as a means of visualizing the problem and encouraging more effective communication. The resulting chapters in this section review the consequences of nitrogen in Europe for five key threats: water quality (Chapter 17; Grizzetti *et al*., 2011), air quality (Chapter 18; Moldanová *et al*., 2011), greenhouse balance (Chapter 19; Butterbach-Bahl *et al*., 2011b), terrestrial ecosystems and biodiversity (Chapter 20; Dise *et al*., 2011) and soil quality (Chapter 21; Velthof *et al*., 2011). Each of the chapters aims to give evidence of how the threat has developed over time, to highlight the future prospects and to indicate the focus of current mitigation approaches.

V European nitrogen policies and future challenges. The final part of the assessment brings together the key threats to consider how nitrogen might be managed more effectively in the future. The first challenge is to see how different nitrogen threats may be inter-related, including assessment of the costs and benefits of different nitrogen forms in the environment (Chapter 22; Brink *et al*., 2011). Together with preceding material, this provides a basis to review the options for integrated approaches to manage nitrogen in the environment (Chapter 23; Oenema *et al*., 2011b). Linked future nitrogen scenarios are then addressed, bringing together each of the main nitrogen threats (Chapter 24; Winiwarter *et al*., 2011). Two last chapters explore how the developing messages for reactive nitrogen can be communicated. The first considers how to develop coordination between different European policies and international conventions in which nitrogen plays an important role (Chapter 25; Bull *et al*., 2011). The second considers how the scientific perspective can be distilled to communicate the nitrogen challenge to society at large (Chapter 26; Reay *et al*., 2011).

In reviewing the overall product, it is clear that the ENA has contributed substantially to bringing the different research, policy and other stakeholder communities together. In this respect the ENA should be considered as much an ongoing process, as it is a book. The present volume thus represents a milestone along the road, rather than a final destination.

The nitrogen story provides a clear example of the great benefits of global geo-engineering. At the same time it provides a warning, demonstrating the complexity and extent of the unanticipated environmental effects. While even more reactive nitrogen will be needed in future, we should aim to pass on an inheritance that allows for a more-sustainable management of this precious resource.

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Excerpt
More Information

Part I Nitrogen in Europe: the present position

Chapter

2

The European nitrogen problem in a global perspective

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Executive summary

Nature of the problem

- Reactive nitrogen has both positive and negative effects on ecosystems and human health. Reactive nitrogen is formed through the use of fossil fuels releasing large amounts of nitrogen oxides into the atmosphere and through the production of ammonia by the Haber–Bosch process and using it in agriculture to increase our food, feed and fuel production. While the use of nitrogen as a fertilizer and chemical product has brought enormous benefits, losses of fertilizer nitrogen and combustion nitrogen to the environment lead to many side effects on human health, ecosystem health, biodiversity and climate.

Approaches

- The European nitrogen problem is placed in a global perspective, showing the European nitrogen fixation, transport and environmental impacts compared with different regions of the globe.

Key findings/state of knowledge

- Humans, largely through agriculture, but also through burning of fossil fuels, have had a huge impact on the nitrogen budget of the Earth. Europe is one of the leading producers of reactive nitrogen, but it is also the first region in the world where the issue was recognized and in some parts of Europe the reactive nitrogen losses to the environment started to decrease. Europe is a nitrogen hotspot in the world with high nitrogen export through rivers to the coast, NO_x and particulate matter concentrations and 10% of the global N_2O emissions.
- The consequences of nitrogen losses in Europe are visible and are on the average more pronounced than in the rest of the world. Nitrogen contributes to all environmental effects to some extent.
- There is a clear policy on reducing nitrogen oxide emissions that led to reductions by implementation of end of pipe technology. Europe is ahead compared to the rest of the world with NO_x policies.
- Fertilizer production and use decreased in Europe in the early 1990s, in particular, due to the economic recession in the Eastern part of Europe. Currently, the fertilizer use in Europe is about 12 Mton, which is 4 Mton lower than in the 1980s, but increasing again. The nitrogen use efficiency of nitrogen in the EU, defined as the net output of N in products divided by the net input is about 36%. This is lower than the world average (50%) as fertilization rates in Europe are much higher.

Major uncertainties/challenges

- More quantification of the effects is needed to establish cause–effect relationships. Most is known about the exceedances of critical limits, but more quantitative results are needed on impacts, including biodiversity loss, ground water pollution and eutrophication of ecosystems; eutrophication of open waters and coastal areas resulting in algal blooms and fish kills; increased levels of NO_x and aerosols in the atmosphere resulting in human health impacts and climate change; and the increased emissions of the greenhouse gas nitrous oxide resulting in climate change. The effects of nitrogen affecting the other biogeochemical cycles such as carbon and phosphorus need to be quantified on different scales.
- The complexity of multi-pollutant–multiple-effect interactions is a major hurdle to improving public awareness.

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2.1 Introduction

Nature and its biodiversity could only exist because of the availability, even if limited, of reactive nitrogen (N_r) in the system, which is defined as all nitrogen compounds except for N_2. This reactive nitrogen was provided by limited natural sources such as lightning, biomass burning and biological nitrogen fixation. Because of the limited availability, nature became very effective in conserving and re-using reactive nitrogen compounds. Nitrogen, together with other nutrients and water, is the limiting factor for the production of food. Mankind has sought for different ways to increase the crop production necessary for food to sustain a growing population. This has led to the development of synthetic fertilizer production based on the Haber–Bosch process (Smil, 2001; Erisman *et al.*, 2008). This additional availability of reactive nitrogen has led to increased crop production and to the intensification of agriculture. The large increase in population is due to intensification and extension of agricultural land, but also due to the availability of fertilizers. A recent estimate of the current human population supported by synthetic fertilizer is 48%, 100 years after the invention of the synthesis of ammonia from its elements (Erisman *et al.*, 2008; Figure 2.1).

To maximize crop production, the availability of cheap fertilizer in the industrialized world led to excessive use of nitrogen, resulting in a large nitrogen surplus and increased nitrogen losses. As the use of fossil fuel in the industrial revolution expanded, fertilizer production increased similarly (see Figure 2.1). The industrial revolution was accelerated by the combustion of fossil fuels producing heat and power, but also polluting gases, such as carbon dioxide, sulphur dioxide and nitrogen oxides. The use of fossil fuels led at the same time to an increase in the production of fertilizer through the Haber–Bosch process, and to a replacement of manpower by machines increasing the productivity and yield per hectare, further accelerating excess nitrogen. Furthermore, the availability of fossil fuels made globalization possible, transporting food, feed, goods and products all over the world, and depleting nutrients in one area and concentrating nutrients in another area, e.g. in intensive livestock production (Galloway *et al.*, 2008). These leakages from agriculture, industry and transport, in their turn, have led to a cascade of N through the global environment causing a number of different environmental effects: loss of biodiversity, eutrophication of waters and soils, drinking water pollution, acidification, greenhouse gas emissions, human health risks through exposure to oxidized nitrogen (NO_x), ozone (O_3) and particulates, and destruction of the ozone layer.

Europe has benefited to a large extent from the increase in nitrogen, both economically as well as socially (see Jensen *et al.*, 2011, Chapter 3 this volume). Agriculture has contributed to a large extent to GDP development and, apart from some poorer areas in Europe, hunger is no longer a key issue. The situation has, however, developed into overuse of nitrogen in agriculture as a straightforward 'cheap' insurance against low yields with all the concomitant negative side effects. Therefore the focus is to deal with the unwanted downside: optimizing use while minimizing adverse effects.

This chapter of the European Nitrogen Assessment (ENA) provides an overview of the European nitrogen problem in a global perspective. The chapter reviews existing knowledge, bringing different studies together to assess the European nitrogen situation relative to different priorities in other areas in the world. The specific processes and effects are addressed in more detail in the following chapters in this book. This chapter starts with an introduction on reactive nitrogen formation in nature, agriculture and through fossil fuel combustion. Then the nitrogen fluxes are described, including the losses to air and water, followed by a section describing the negative effects of nitrogen in Europe in a global perspective.

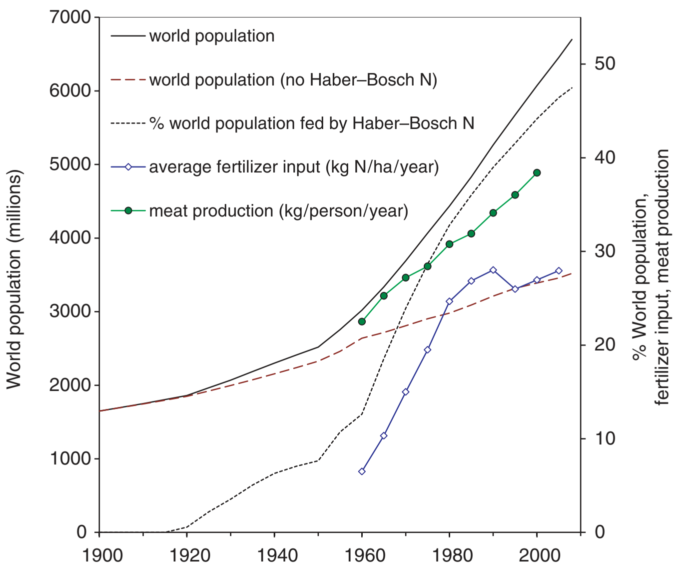

Figure 2.1 Trends in human population and nitrogen use throughout the twentieth century (Erisman *et al.*, 2008). Of the total world population (solid line), an estimate is made of the number of people that could be sustained without reactive nitrogen from the Haber–Bosch process (dashed line), also expressed as a percentage of the global population (short dashed line). The recorded increase in average fertilizer use per hectare of agricultural land (blue symbols) and the increase in per capita meat production (green symbols) are also shown.

2.2 Reactive nitrogen

Reactive nitrogen, N_r, is defined here as all other nitrogen forms in our system apart from N_2. This includes oxidized nitrogen, mainly NO, NO_2, NO_3; reduced forms of nitrogen: NH_4^+, NH_3 and organic nitrogen: proteins, amines, etc., with different states of oxidation (Table 2.1)

Natural sources of the formation of N_r include volcanoes, biological nitrogen fixation in natural soils and lightning (Figure 2.2, Box 2.1) (Smil, 2001; Reid *et al.*, 2005; Schlesinger, 2009; Sutton *et al.*, 2008 and Hertel *et al.*, 2011 (Chapter 9 this volume), Simpson *et al.*, 2011 (Chapter 14 this volume), where details are provided) and weathering of rocks (Holloway and Dahlgren, 2002). Senescence of plants, wildlife and forest fires are natural processes that result in the re-distribution of N_r in the biosphere. Most of the abiotic natural sources of N_r are in oxidized forms, although wildlife and volcanos also emit reduced forms (Galloway *et al.*, 2003; Schlesinger, 2009). In Europe natural sources of N_r are estimated to create annually 2–3 Mton N_r (van Egmond *et al.*, 2002; Galloway *et al.*, 2004). Anthropogenic activities enhancing the formation of N_r include cultivated Biological Nitrogen Fixation (BNF) in agriculture, N_2 fixation through the Haber–Bosch process, the burning of fossil fuels and forest fires (Figure 2.2).

Table 2.1 Examples of nitrogen components and their oxidation state

Oxidation state	Example	Component name
Reduced forms		
−3	NH_3	Ammonia
−2	NH_2NH_2	Hydrazine
−1	HNNH	Diimide
0, non-reactive	N_2	Di-nitrogen
Oxidized forms		
+1		
+2	NO	Nitrogen oxide
+3	HNO_2	Nitrous acid
+4	NO_2	Nitrogen dioxide
+5	HNO_3	Nitric acid

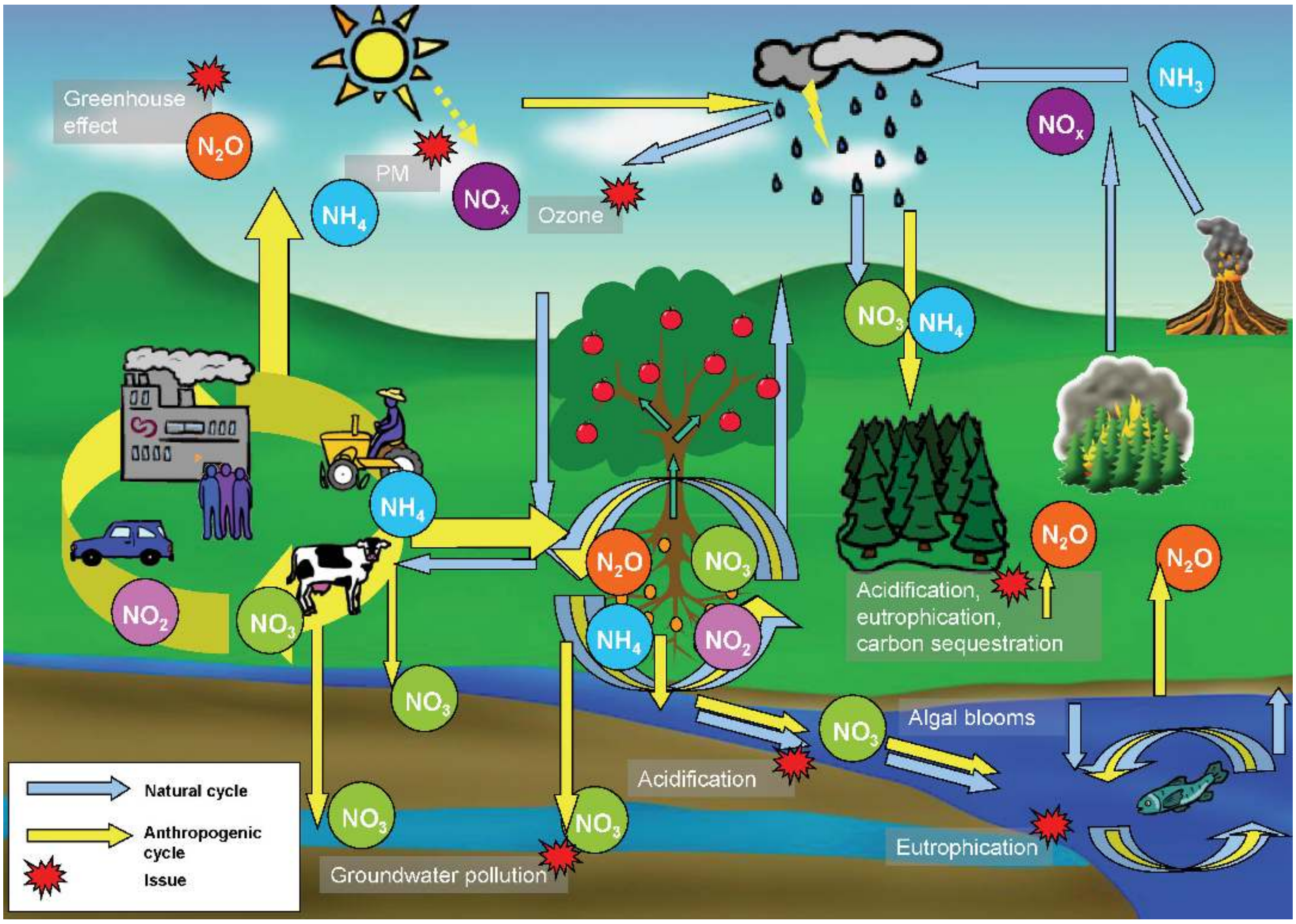

Figure 2.2 The N_r cycle and the main fluxes (picture by Anne-Christine LeGall).