Chapter 5

The challenge to integrate nitrogen science and policies: the European Nitrogen Assessment approach

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Executive summary

Nature of the problem

- Anthropogenic releases of reactive nitrogen (N_r) can disturb natural systems and affect human health and welfare in many different ways. Scientific and policy views of the nitrogen cycle have typically addressed these problems from separate perspectives, looking in each case at only part of the overall issue.
- Given the multi-faceted nature of the nitrogen cycle, it is a major challenge to develop a more-integrated understanding of how different areas of nitrogen science and policies fit together.

Approaches

- Observations from the first part of the European Nitrogen Assessment (ENA Part I) are summarized, considering the distinctive character of N_r in Europe, the benefits and threats, and the current policies. Approaches to developing the following parts of the Assessment are discussed with an emphasis on how to draw out the key issues.

Key findings

- Recognizing the multi-pollutant, multi-phase complexity of the nitrogen cycle, it is concluded that it is essential to focus on a limited set of priority issues to allow effective communication between nitrogen scientists and policy makers.
- A pathway is developed for prioritization of the key environmental concerns of excess N_r. Starting with around twenty environmental effects, the list is reduced down, first to nine main concerns, and then to five key societal threats.
- The five key threats of excess N_r in Europe are identified as: Water quality, Air quality, Greenhouse gas balance, Ecosystems and biodiversity, and Soil quality. These headings – which are easily remembered by the acronym 'WAGES' – provide a basis for summarizing societal concern about excess N_r in later chapters of the Assessment.
- The selection of five key threats represents a conscious balancing of complexity and simplification. The division also lends itself to developing communication models, as illustrated by its analogy to the classical cosmology of Empedocles and Aristotle.

Major challenges

- Ongoing efforts must focus on linking scientific communities between nitrogen form (N_2O, NH_3, NO_x, NO_3^-, etc.), environmental compartment (air, water, plant, soil, etc.), and spatial scale (farm, landscape, region, continent, etc.), tracing the N_r cascade from the main source sectors, especially agriculture and combustion.
- For policy makers, major infrastructural constraints limit the connection of different threats and media (climate, air pollution, water pollution, etc.) through spatial scales (local, regional, global policies). Political positions often require a deliberate separation between issues, making it harder to negotiate joined-up approaches.
- Ongoing efforts are needed to simplify further the nitrogen story. Multiple communication models should be used, matching the needs of different audiences.

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Recommendations

- Ongoing research at the scale of nitrogen processes (ENA Part II) is essential as this provides the foundation for developing mechanistic understanding.
- Additional efforts are needed to quantify nitrogen flows through different spatial scales (ENA Part III). A new emphasis on rural and urban landscapes provides an important link between the plot and regional scales, while nitrogen budgeting should be further developed as an integration tool identifying the main N_r pathways.
- The key societal threats of excess N_r (ENA Part IV) are not equally well quantified. While understanding of the water and air threat is rather mature, the threat of N_r on greenhouse gas balance is still at the stage of early quantification. Further efforts are needed to quantify fully the impacts of all the threats.
- The first multi-pollutant approaches to N_r cost–benefit analysis, future scenarios and integrated N_r management (ENA Part V) should be further developed to underpin the development of integrated abatement strategies.
- Efforts at communicating N_r to policy makers should highlight how integrated N_r management can help meet multiple environmental targets. For the general public, efforts should emphasize the responsibility we all have to manage our own nitrogen footprint.

5.1 Introduction

As introduced in Chapter 1, the European Nitrogen Assessment (ENA) has been structured in five parts, each of which deals with a different stage of the ENA process (Sutton *et al.*, 2011, Chapter 1 this volume). The previous chapters in Part I provide the background upon which we here develop the vision and approach for the rest of the Assessment.

It is thus clear from the continental context explained in Chapter 2, that, compared with many other parts of the world, Europe is characterized by an excess of reactive nitrogen (N_r) leading to many environmental problems (Erisman *et al.*, 2011, Chapter 2 this volume). This is true equally of the N_r which is deliberately produced for food production, as for the N_r that is produced inadvertently through high temperature combustion processes. This concern about excess N_r provides a central theme running through the Assessment, which may be contrasted with some other parts of the world (such as parts of Africa and South America) where there is still a societal shortage of N_r.

Based on the analysis of Chapter 3 (Jensen *et al.*, 2011, this volume), it is equally evident that there are huge societal benefits associated with fixing atmospheric N_2 into N_r. The focus of Jensen *et al.* is on adding up the benefits of deliberate N_2 fixation in fertilizer production and biological nitrogen fixation, which are together essential for healthy functioning of the European economy. If the most obvious benefit is the supply of N_r-containing fertilizers to agriculture, it is equally obvious that modern society would not be possible without the concomitant production of N_r explosives (essential for all mining activity in the world), many plastics (such as nylon) and a huge diversity of other N_r-containing chemicals. By contrast, we must exclude formation of N_r due to the combustion of fossil fuels from the list of benefits, since the N_r produced is immediately lost to the environment, while control efforts (such as catalytic converters) focus on its chemical denitrification back to N_2, rather than capture and use of the N_r produced.

In economic terms, it is obvious that a better management of nitrogen has substantial benefits. The aim to improve nitrogen use efficiency means that less N_r fertilizers are needed, potentially saving costs and the energy-use associated with their production (Jensen *et al.*, 2011). However, it is equally clear that N_r as a commodity is currently rather cheap, its price being largely set by the fuel costs associated with its production in the Haber–Bosch process. As a result, no policies appear to have been needed in recent decades to ensure adequate supply of N_r in Europe.

Against this, it is clear from the analysis of Oenema *et al.* (2011a, Chapter 4 this volume) that there has been a plethora of different government policies related to the release of different N_r forms into the environment. As N_r is emitted, its conversion into many different chemical forms and accumulation of stocks in each of air, land and water, makes it obvious that several environmental effects should be expected. One of the clear conclusions of Oenema *et al.* (2011a) is that policies designed to address these environmental effects have in most cases been conducted separately according to N_r form and environmental media in which the pollution form occurs (e.g., freshwater pollution, urban air pollution, marine pollution). There is thus a lack of a joined-up view of how N_r is being lost into the environment and how holistic approaches may be implemented to manage the nitrogen cycle.

Based on Chapter 4, it appears that one of the most problematic sectors for managing N_r threats on the environment is agriculture. Oenema *et al.* (2011a) explain how policies to reduce atmospheric emissions from large combustion sources, such as power stations, and from vehicles have been relatively successful. By focusing on a few key actors (e.g., large power generating companies, vehicle manufacturers), with a clear ability to transfer any costs to consumers, it has been possible to achieve a high take-up of technical measures. The challenges in those sectors have been the offsetting of reductions, achieved through technical mitigation measures, by increased consumption patterns (e.g., increased vehicle miles per person), as well as by some chemical trade-offs (e.g., catalytic converters increasing N_2O and NH_3 emissions).

By comparison, the challenges to control N_r loss from agriculture have been rather harder. In this sector, N_r emissions are generated by many independent actors (individual farmers), operating a high diversity of processes, in a rather open system (i.e., open to air, soil and water). The sector, especially with the smaller operators, is frequently characterized by conservatism, reflected in a caution to take up new technical approaches, particularly if there is uncertainty on how any perceived costs might be transferred to consumers.

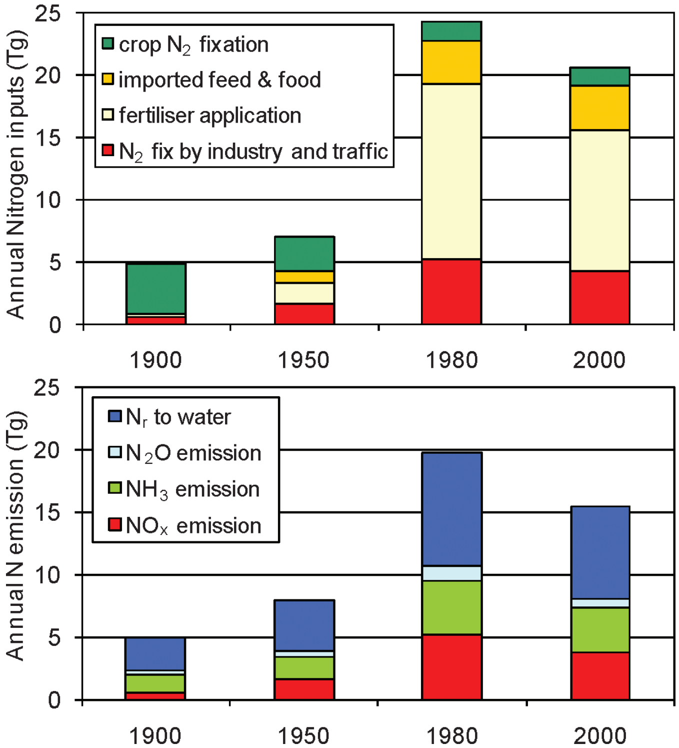

Figure 5.1 Temporal changes in annual reactive nitrogen (N_r) inputs to Europe (EU-27) and the emissions to the environment. Top panel: crop biological nitrogen fixation, N in imported feed and food, land application of mineral fertilizers (mainly from N fixation by the Haber–Bosch process) and N fixed in industry and traffic combustion processes. Bottom panel: leaching and run-off to water, especially as nitrate, emission to air as ammonia (NH_3) mainly from agriculture, emission to air as nitrogen oxides (NO_x) mainly from industry and traffic. Inferred from Leip *et al.* (2011, Chapter 16 this volume) and Bouwman *et al.* (2011).

Such differences between sectors are clearly reflected in the trends of N_r pollution to air and water as summarized by Oenema *et al.* (2011a), with only modest reductions in the agricultural emissions. If these effects of recent policies over the last two decades are put into historical context, it is clear that European use and emissions of N_r from all sources are still greatly in excess of natural rates. The massive increase in fertilizer and manure use in Europe since 1860 is shown in Chapter 2 by Erisman *et al.* (2011). This can be compared with the amounts N_r inputs through N fixation (crops and NO_x formation) mineral fertilizer application feed and food imports, and the consequent emissions of N_r through leaching and run-off, and as ammonia (NH_3) and nitrogen oxides (NO_x) emission to air (Figure 5.1). Overall, there has been a major up-regulating of the European nitrogen cycle by human activities. Recent policies over the last two decades have made some progress in reducing both inputs and emissions, but represent only the first step in developing optimized strategies for N_r management.

The message that emerges is that there is a huge diversity of N_r pollutant forms, including NO_x, nitrous oxide (N_2O), NH_3, NO_3^-, leading to many secondary pollutants (including many organic nitrogen forms in water and in air), and an even longer list of environmental effects. The problem of N_r in the environment provides a degree of complexity that few scientists are able cover in full, that policy makers have so far tackled in piecemeal fashion, and that is far too complex to be easily explained to the general public.

In this chapter, we reflect on these challenges to develop the basis for subsequent Parts II–V of the *European Nitrogen Assessment*. We outline a vision for integration both across nitrogen science domains and across policy domains, as well as the links between the two. In particular, we focus on how to communicate the issues in a way that balances complexity with an easily understandable list of priority concerns.

5.2 Integrating nitrogen science

5.2.1 Linking nitrogen forms, processes and scales

The complexity and many facets of the nitrogen cycle are clearly reflected in the structure and relationships of the scientific communities that have developed to study it. This is illustrated in Figure 5.2, for the research area of atmosphere–biosphere exchange of N_r and interacting compounds. In this area, in recent decades, the degree of specialization has become such that the individual compounds have become the focus for whole research communities, and with the main focus of integration being between components listed in the vertical in Figure 5.1. Examples are recent major collaborations, such as the GRAMINAE project, which focused on the exchange of ammonia, also considering interactions with nitric acid and inorganic aerosol dynamics (Sutton *et al.*, 2001, 2009a), and the GREENGRASS project, which investigated the integration between N_2O, CH_4 and CO_2 exchange processes with European grasslands (Soussana *et al.*, 2007). At a similar scale, the NOFRETETE project addressed the dynamics of N_2O and NO fluxes with European forest soils (Pilegaard *et al.*, 2006). Given the different measurement tools relevant for each of these chemical species and diverse set of biogeochemical processes (e.g., plant processes, soil processes, atmospheric chemistry interactions), it therefore becomes a major challenge to integrate our understanding of all of the different components listed in Figure 5.2. Such integration efforts have become an important focus in recent years, such as within the NitroEurope and ACCENT research communities (Sutton *et al.*, 2007; Fowler *et al.*, 2009), which have started to develop the links across the whole suite of pollutant forms shown in Figure 5.2.

It is evident, however, that these efforts are part of addressing an even larger challenge to integrate communities, not just between N_r forms, but between environmental media and spatial contexts. At present, there is still only limited connection between many N_r research communities, such as between interests in stratospheric chemistry, biosphere–atmosphere exchange, freshwater and marine pollution. In aquatic research for instance, the community dealing with nitrate groundwater contamination is rather distinct from that concerned with nitrogen river fluxes causing coastal zone eutrophication. A similar tension is repeated across many domains within the nitrogen cycle, as the tendency to specialization of recent decades is reflected by the need to assess the wider perspective.

From the perspective of environmental management, it is clear that much more linkage between science communities

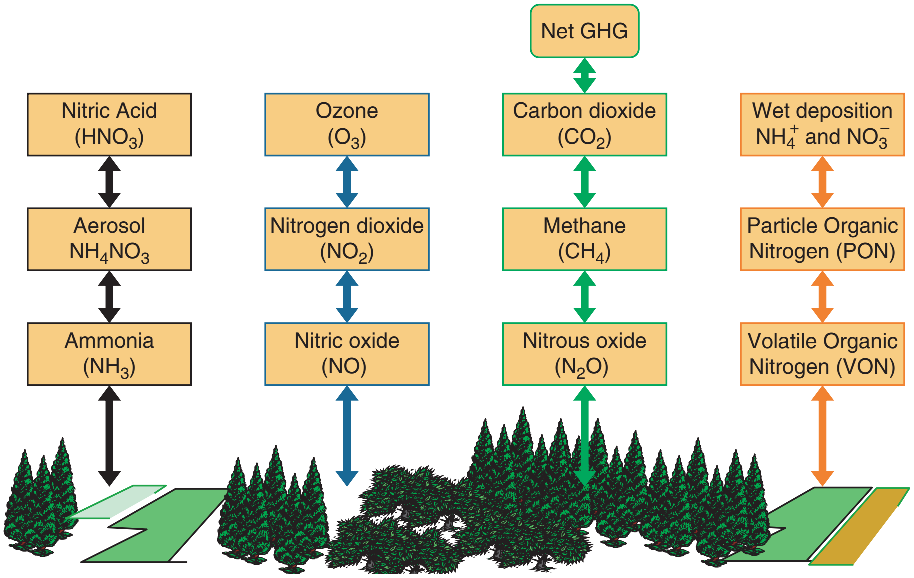

Figure 5.2 Specialization in N_r and greenhouse gas fluxes over recent decades has led to separation of research communities on biosphere–atmosphere exchange according to chemical compound. The vertical arrows indicate first stages of emerging integration, while the vertical blocks indicate a stronger separation between research communities.

across the N cycle is needed (Galloway *et al.*, 2008; Sutton *et al.*, 2009b). This is essential to deal with issues of trade off's between different N_r forms and linked biogeochemical cycles. Such management issues apply over different temporal and spatial scales. For example, ways need to be understood of how N_r migrates through individual natural or agricultural ecosystems, and subsequently moves from one ecosystem type to another, either through human transfers (such as agricultural products) or by dispersion through water courses and the atmosphere.

With the centre of gravity of recent European nitrogen research tending toward individual N_r forms at a series of different scales, the question that arises is how fast and how far should a greater level of integration be developed. Here it must be recognized that the process of scientific integration is a slow one, and that an effort such as the European Nitrogen Assessment represents only the first steps on the path toward integration.

It is with this in mind that the following group of chapters (Part II) retain a current focus on the point and process scale reflecting the expertise of the current scientific communities (Butterbach-Bahl *et al.*, 2011a; Durand *et al.*, 2011; Voß *et al.*, 2011; Hertel *et al.*, 2011, Chapters 6–9 this volume). The 'integration target' for these chapters is to ensure that all the N_r forms and their major interactions are considered, focusing on what we know about N_r processing in each of these systems, as well as the major knowledge gaps. While the complexity of these systems will always make it hard to take a fully integrated approach at the process level, such a focus is nevertheless essential as the foundation for understanding the component mechanisms underlying the system.

In developing the ENA though a series of workshops as explained in Chapter 1 (Sutton *et al.*, 2011, this volume), the degree of integration achieved in Part II of the Assessment, provided the basis to develop the subsequent stages. Hence Part III of the Assessment develops the next steps of integration, in examining the nitrogen cycle of Europe through successive spatial scales.

5.2.2 Integrating through the nitrogen cascade

A useful concept in upscaling nitrogen processes that has informed recent research is the 'nitrogen cascade' (Galloway *et al.*, 2003). In the classical concept of the nitrogen cycle, the emphasis is on recycling between atmospheric di-nitrogen (N_2) and the many N_r forms. In a natural system, the nitrogen cycle is seen as being in balance, as nitrogen fixation from N_2 to N_r is ultimately matched by denitrification returning N_r to N_2. Under anthropogenic modification, the amounts of N_r in circulation are increased in multiple directions.

The concept of the nitrogen cascade emphasizes a rather different view of the same system under human influence. Substantial energy is needed to fix nitrogen from N_2 into N_r forms, be it fuels needed for industrial production of ammonia or the photosynthetic energy needed for biological nitrogen fixation. The fixation process therefore raises nitrogen from a low to a high energy state, providing a starting point for the subsequent cascade. The important point of the cascade is that, as this energy is gradually dissipated, the N_r converts between a multiplicity of different forms, with different environmental consequences at every stage. Each molecule of N_r can therefore be expected to be involved in several environmental effects before it is finally denitrified back to unreactive N_2.

The complexity of the nitrogen cascade means that any graphical description is necessarily a simplification. An extremely simplified version is shown in Chapter 1 (Sutton *et al.*, 2011), illustrating the cascade of fertilizer N_r produced by the Haber–Bosch process. This can be compared with Figure 5.3, which provides a more complete – but still very simplified – summary of the cascade, accounting for each of the main anthropogenic influences on nitrogen fixation.

For simplicity, the only numbers shown in Figure 5.3 are the amounts of N_2 fixed to N_r by human activities, comparing global estimates (Galloway *et al.*, 2008; Erisman *et al.*, 2011) with European estimates, as developed in Chapter 16 for the EU-27 by Leip *et al.* (2011, this volume). At both Global and European

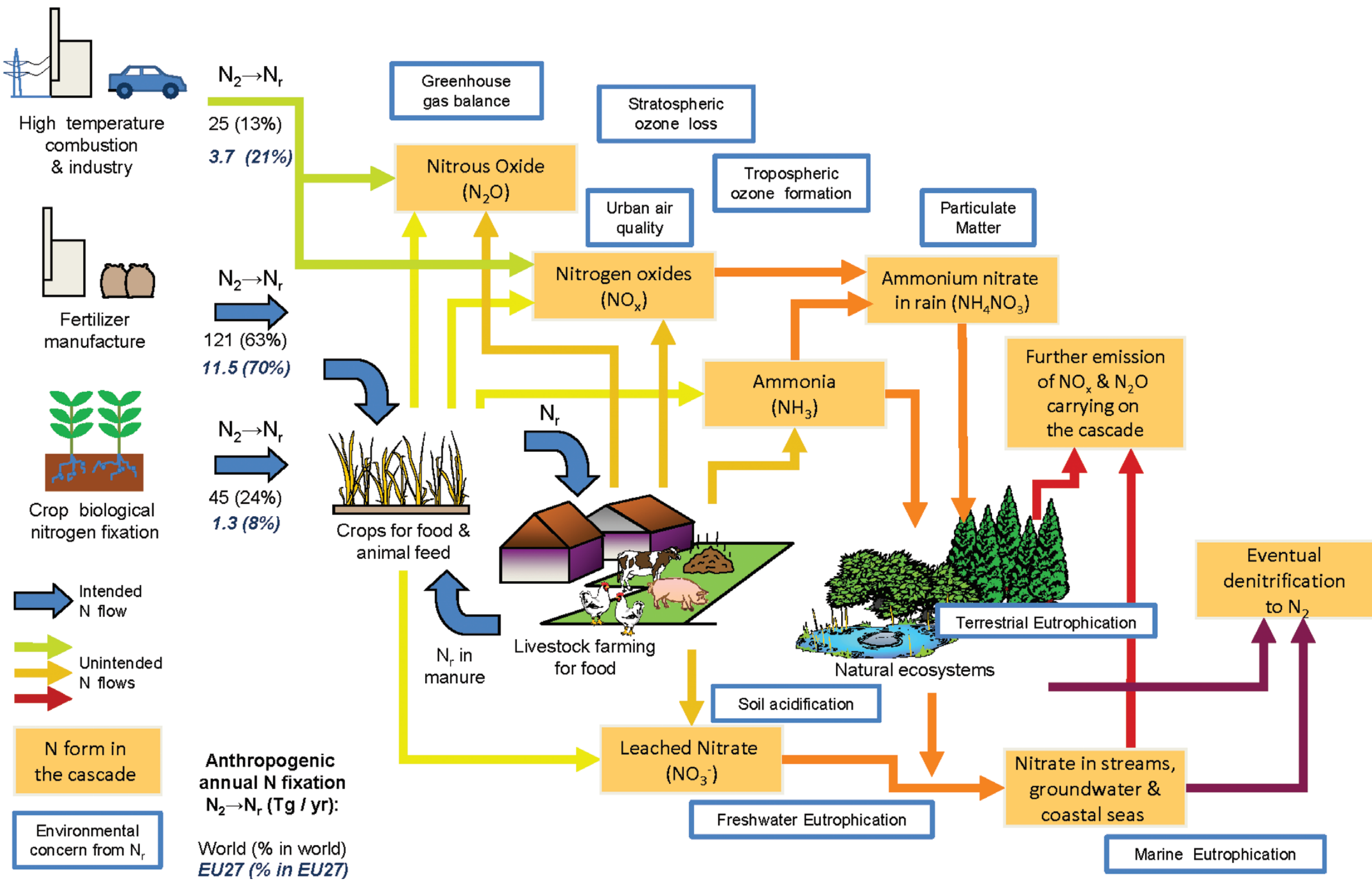

Figure 5.3 Simplified view of the nitrogen cascade, highlighting the major anthropogenic sources of reactive nitrogen (N_r) from atmospheric di-nitrogen (N_2), the main pollutant forms of N_r (orange boxes) and nine main environmental concerns (boxes outlined with blue). Estimates of N fixation for the world (Tg /yr for 2005, in black; Galloway *et al.*, 2008) are compared with estimates for Europe (Tg /yr for 2000, in blue italic; Leip *et al.*, 2011, Chapter 16 this volume). Energy is needed to fix N_2 to N_r, which is gradually dissipated through the cascade with eventual denitrification back to N_2. Blue arrows represent intended anthropogenic N_r flows; all the other arrows are unintended flows.

levels, industrial production is by far the largest source of new N_r. Industrial production accounts for 63% and 70%, of total anthropogenic nitrogen fixation at Global and European scales, respectively, of which use of the Haber–Bosch process to make fertilizers is the largest component. Compared with the global average, Europe has a higher contribution of N_r production from combustion processes (power generation, transport, other industry) (13%, 21%, respectively), reflecting the fact that Europe is an industrialized region with a high intensity of energy use and motorized transport. By contrast, compared with the global average, Europe has a smaller contribution from crop biological nitrogen fixation (24%, 8%, respectively), owing to the high use of mineral fertilizers in Europe. It is clear from the magnitude of these numbers that understanding the pathways and fate of industrially produced nitrogen fertilizers must be a priority for Europe. Secondly, the N_r formed from high temperature combustion is of particular interest as it represents a completely unintended production of N_r.

As can be seen from Figure 5.3, each of the forms of N_r produced can be inter-converted, having several environmental effects, before eventually being denitrified to N_2 at the end of the cascade. For the purpose of this summarized view, nine main environmental concerns are shown in Figure 5.3, as further discussed in Section 5.4.

It must be acknowledged that, to date, the nitrogen cascade represents a purely conceptual framework. So far, models have yet to be constructed that fully trace the pathway of anthropogenically fixed N_r though all forms and stages, showing how many times on average each N_r atom contributes to different environmental effects. The cascade concept nevertheless provides a stimulus for integrating N_r research at different spatial scales, as well as for identifying control points (Erisman *et al.*, 2001; Galloway *et al.*, 2008; see Section 5.5).

Based on the need to track N_r through the different environmental compartments and impacts in the cascade, Part III of the Assessment emphasizes the building up of understanding between the different scales. Each of the chapters in Part III necessarily addresses the lateral flows of N_r, including, as relevant, those by direct human transfers (movement of fertilizer, manure, feed and food), by atmospheric transport and by water flow in catchments. Figure 5.4 illustrates the conceptual upscaling of Part III, putting into context the following parts of the assessment. The components scale up from the farm level (Jarvis *et al.*, 2011, Chapter 10 this volume) to complete multimedia N_r integration across Europe (de Vries *et al.*, 2011; Leip *et al.*, 2011, Chapters 15 and 16 this volume).

Traditionally, much effort has been put into addressing regional scale transfers in watersheds and in the atmosphere,

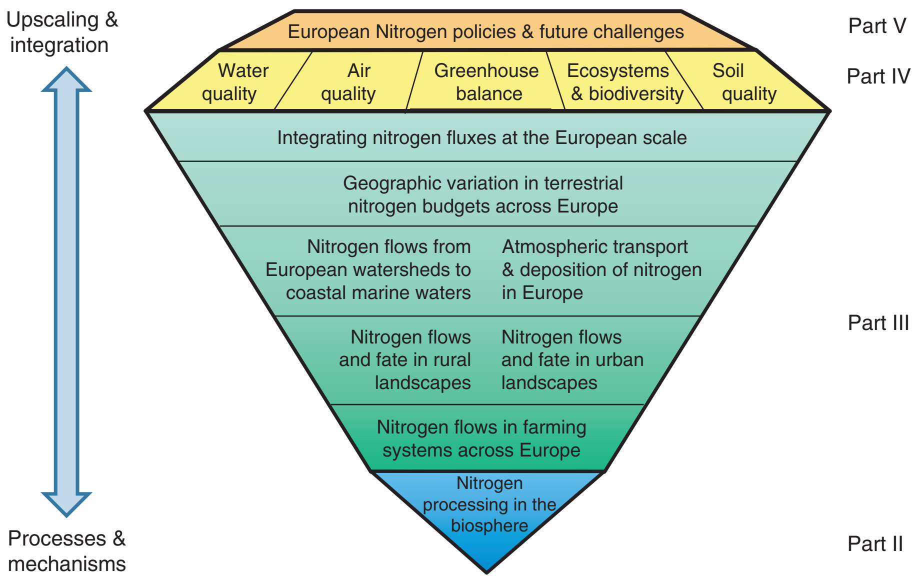

Figure 5.4 Main structure of the following parts of the *European Nitrogen Assessment*, highlighting the upscaling elements addressed in Part III and the five key societal threats of excess nitrogen addressed in Part IV.

and these scales are addressed by the chapters of Billen *et al.* (2011, Chapter 13 this volume) and Simpson *et al.* (2011, Chapter 14 this volume). Much is known at these scales, which represent relatively mature, though still challenging, areas of research. As complex areas, there remain many unknowns, including tracing the fate of nitrogen through compartments and the chemical exchanges between inorganic and the many organic N_r forms. Nevertheless, by comparison, full assessment of the nitrogen cascade at the landscape scale has been much less studied compared with regional N_r transfers in either air or water. A full view of the N_r cascade in landscapes integrates spatially explicit transfers between source and sink landscape elements (e.g., farms, fields, roads, forests, mountains) and between each of the air, land and water compartments. The landscape scale is particularly important as it is the linking scale between the plot and region, being the scale in which many local decisions on N_r management take place. Two chapters address these new scales of integration, contrasting N_r flows in rural and urban landscapes (Cellier *et al.*, 2011; Svirejeva-Hopkins *et al.*, 2011, Chapters 11 and 12 this volume).

If the integration of nitrogen science across N_r forms and spatial scales already represents a complex challenge, it cannot be forgotten that nitrogen also interacts with many other biogeochemical cycles. Given the complexity and resources, it is important to limit the scope of this assessment to focus on the nitrogen interactions, rather than assess all biogeochemical cycles simultaneously. In order to optimize the scientific effort, the approach taken here centres on the interactions between nitrogen forms, while not forgetting the main links with other element cycles where these occur. These main links tend to be different according to the environmental compartment being considered. In atmospheric chemistry, the main biogeochemical links are with sulphur chemistry and organic carbon chemistry (e.g., in aerosol and photochemical oxidant transformation processes, Hertel *et al.*, 2011; Simpson *et al.*, 2011). In terrestrial ecosystems, key relationships exist between nitrogen supply, turnover of organic matter and net carbon storage, both through influences on primary production and decomposition (Butterbach-Bahl *et al.*, 2011a) and with phosphorus through the use of manures in agriculture (Jarvis *et al.*, 2011). Finally, in freshwater and marine systems, the relationships between nitrogen and phosphorus are especially important, as well as interactions with silica (Durand *et al.*, 2011; Billen *et al.*, 2011). The Assessment thus addresses the interactions with key other element cycles according to the priorities in the different environmental compartments.

5.3 The challenge to integrate nitrogen policies

Similar to the scientific perspective, Oenema *et al.* (2011a, Chapter 4 this volume) explain how current environmental policies in Europe have taken a rather fragmented approach to the nitrogen cycle. The reasons for this appear to relate both to this historical separation between the supporting scientific communities, and the fact that such policies have been driven by perceived environmental problems in different contexts. This is equally reflective of the way in which policy portfolios are typically separated in government departments (e.g., between water and air, between urban and rural, between agriculture and nature, etc.). It can even be the case that political positions require a deliberate separation between issues, making it harder to negotiate joined-up approaches. An example here is the desire of some parties to the UN Framework Convention on Climate Change to ensure that climate related policy issues are not addressed in other conventions. This makes it challenging to address multi-effect interactions in international conventions, which is compounded by the fact that the relevant multi-lateral environmental agreements are made up of different memberships (e.g., UN, UN-ECE, EU-27, etc.).

In response to the present position, there is a strong case to be considered for developing more joined-up, integrated approaches to managing nitrogen in the environment (see also Section 5.5 in relation to Part V of the Assessment). Aside from the procedural difficulties, a key challenge that emerges is to find the optimum level of integration. For example a balance should be identified between the simplicity of single-issue approaches, versus the inefficiencies that occur as a result of not considering the major interactions. Put in another way, it must be recognized that joined-up approaches take longer to develop and the advantages (in optimization, improved delivery, synergies, avoidance of trade-offs, etc.) must be shown to outweigh the risk of additional complexity (Oenema *et al.*, 2011b; Bull *et al.*, 2011, Chapters 23 and 25 this volume). In particular, the benefits of integration must be shown to be achievable in order to address the potential concern that the complexity of integration becomes an excuse for inaction. However, an integrated approach can also lead to simpler policies if integration is used to weigh and prioritize the many N-issues.

In this context, it is extremely important to identify the priority issues that should be integrated. If a short list of key issues can be established, this would provide a foundation on which to identify an achievable level of integration, at least between the key issues. The short-list can then inform the discussion on to what extent specific multi-sector, multi-issue policies on nitrogen are needed, or to what extent existing policies should be further developed to be nitrogen aware, what may be called 'nitrogen proofing'.

5.4 Distilling complexity to integrate and communicate nitrogen

It is not surprising that something as multi-faceted as the nitrogen cascade should be associated with an extremely large number of environmental concerns. As explained above, establishing a short-list of priority issues is therefore important as a basis for informing the integration of environmental and other policies. At the same time, such a short-list is needed in order to communicate the nitrogen problem more effectively to the general public.

The Nitrogen in Europe (N*in*E) networking programme (funded by the European Science Foundation), in its aims to link together for the first time the environmental problems related to N_r, established a short list of priorities. The identification of the priorities was carried out in two stages. Starting with a list of around 20 environmental issues related to nitrogen, N*in*E agreed a list of 9 major environmental concerns, as a basis for communication of its efforts to link issues across the nitrogen cycle. The outcome is clearly expressed in the N*in*E logo, including the mnemonic acronym 'ACT AS GROUP' (Figure 5.5). While this first listing of nine concerns was useful to illustrate the challenge faced by the N*in*E network, it was recognized it needed further simplification to allow effective communication to a wider audience.

In the second stage of simplification, the full list of around 20 environmental concerns was ranked by a group of European experts as a contribution of the activities N*in*E, NitroEurope and COST Action 729 to an expert workshop under the Convention on Long-range Transboundary Air Pollution (Saltsjöbaden-3, Gothenburg, April 2007), with the short-list being tested through further consultation with experts and other stakeholders during the COST Action 729 Workshop on integrated assessment modelling for nitrogen (Laxenburg, November 2007). The full lists of nitrogen effects, as developed in this process (Erisman *et al.*, 2007) are shown in Tables 5.1 to 5.3.

In estimating scores of the 'relevance and link to nitrogen', the experts used a scale of 1 (highest relevance) to 5 (unimportant). This prioritization combined consideration of the relevance of the issue to society and the extent to which nitrogen contributed to that issue.

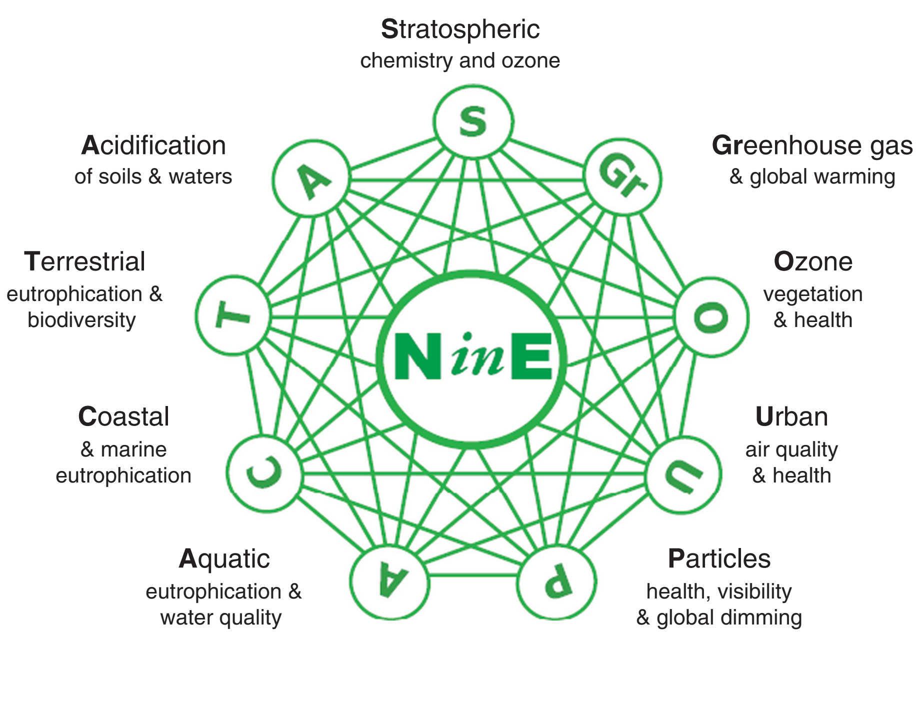

Figure 5.5 Graphical representation of the main nitrogen concerns addressed by the Nitrogen in Europe (N*in*E) networking programme of the European Science Foundation. The nine environmental concerns together provide the mnemonic 'ACT AS GROUP'.

Table 5.1 Summary of the direct effects of excess nitrogen on humans in relation to currently used indicators, the current existence of limit values (legally binding and/or broadly established for scientific assessment) in Europe, and the link to the nitrogen cascade. The relevance and link to N provides a prioritization estimated by an expert group for international action to mitigate the effects of excess nitrogen (based on Erisman *et al.*, 2007)

Direct effects on humans	Indicators	Limit?	Link to N cascade	Relevance and link to N
Respiratory disease in people caused by exposure to high concentrations of:				
– ozone	O_3 conc. values including SOMO35	Yes	NO_x emission	3
– other photochemical oxidants	Organic NO_3, PAN	No	NO_x emissions	5
– fine particulate aerosol	PM_{10}, $PM_{2.5}$	Yes	NH_3, NO_x emissions	1
– direct toxicity of NO_2	NO_2	Yes	NO_x emissions	2
Nitrate contamination of drinking water	NO_3 conc $_{(aq.)}$	Yes	NO_3 leaching	2
Increase allergenic pollen production, and several parasitic and infectious human diseases	—	No	N fertilizer and N deposition	5
Blooms of toxic algae and decreased swimmability of in-shore water bodies	Chlorophyll A $NO_{3\ (aq.)}$	No	Run-off, N deposition	1

Relevance and link to nitrogen qualitatively incorporates the societal priority of the issue and the N contribution to that issue: (1) highest relevance, (2) high relevance, (3) significant relevance, (4) some relevance, (5) unimportant.
Indicators: SOMO35: sum of ozone concentration above 35 parts per billion in air; PAN, peroxyacetyl nitrate; PM_{10}, $PM_{2.5}$: particulate matter in air having a median diameter larger than 10 μm and 2.5 μm, respectively.

Table 5.2 Summary of the effects of excess nitrogen on ecosystems in relation to currently used indicators, the current existence of limit values (legally binding and/or broadly established for scientific assessment) in Europe and the link to the nitrogen cascade. The relevance and link to N provides a prioritization for future international action to mitigate the effects of excess nitrogen (based on Erisman *et al.*, 2007)

Direct effects on ecosystems	Indicators	Limit?	Link to N cascade	Relevance and link to N
Ozone damage to crops, forests, and natural ecosystems	O_3 flux, AOT40	Yes	NO_x emission	2
Acidification effects on forests, soils, ground waters, and aquatic ecosystems	Critical loads	Yes	N deposition	2
Eutrophication of freshwaters, lakes (incl. Biodiversity)	BOD, $NO_{3\ (aq)}$ Critical loads	Yes No	Run-off, N deposition	3
Eutrophication of coastal ecosystems inducing hypoxia (incl. Biodiversity)	BOD, $NO_{3\ (aq)}$ Critical loads	Yes No	Run-off, N deposition	1
Nitrogen saturation of soils (incl. effects on GHG balance)	Critical loads	Yes	N deposition	1
Biodiversity impacts on terrestrial ecosystems (incl. Pests and diseases)	Critical loads, critical level (NH_3 in air)	Yes	N deposition	1

Relevance and link to nitrogen qualitatively incorporates the societal priority of the issue and the N contribution to that issue: (1) highest relevance, (2) high relevance, (3) significant relevance, (4) some relevance, (5) unimportant.
Indicators: AOT40: accumulated ozone concentration above a threshold of 40 parts per billion in air; BOD: biological oxygen demand in water.

Tables 5.1–5.3, show that the following issues were given the highest scores:

(1) Respiratory disease caused by fine particulate matter in the atmosphere.
(2) Blooms of toxic algae and decreased swimmability of in-shore water bodies.
(3) Eutrophication of coastal ecosystems inducing hypoxia (incl. their biodiversity).
(4) Nitrogen saturation of soils (incl. effects on GHG balance).
(5) Biodiversity impacts on terrestrial ecosystems (including pests and diseases).
(6) Global climate warming induced by excess nitrogen.
(7) Regional climate cooling induced by aerosol.

Table 5.3 Summary of the effects of excess N on other societal values in relation to currently used indicators, the current existence of limit values (legally binding and/or broadly established for scientific assessment) in Europe, and the link to the nitrogen cascade. The relevance and link to N provide a prioritization for future international action to mitigate the effects of excess nitrogen (based on Erisman *et al.*, 2007)

Effects on other societal values	Indicators	Limit?	Link to N cascade	Relevance and link to N
Odour problems associated with animal agriculture	NH_3 concentration	No	NH_3 emission	5 (in Europe)
Effects on monuments and engineering materials	Precipitation acidity, O_3, PM_{10}, $PM_{2.5}$ concentrations	Yes	NO_x, NH_3	3
Regional hazes that decrease visibility at scenic vistas and airports	$PM_{2.5}$	No	NO_x, NH_3	4 (for Europe)
Depletion of stratospheric ozone	NO_x, N_2O concentrations	No	NO_x, N_2O	3
Global climate warming induced by excess nitrogen	N_2O, CH_4, CO_2 concentrations	No	N_2O (direct & indirect sources), CH_4, CO_2	1
Regional climate cooling induced by aerosol	$PM_{2.5}$ concentration	No	NO_x, NH_3	1

Relevance and link to nitrogen qualitatively incorporates the societal priority of the issue and the N contribution to that issue: (1) highest relevance, (2) high relevance, (3) significant relevance, (4) some relevance, (5) unimportant.
Indicators: PM_{10}, $PM_{2.5}$: particulate matter in air having a median diameter larger than 10 μm and 2.5 μm, respectively.

Based on these and recognizing some overlap, a group of five key societal threats of nitrogen was identified:

- Air quality (including respiratory disease concerns), especially as affected by NO_x, O_3 and particulate matter.
- Water quality (including ecosystems and human health concerns).
- Greenhouse balance (including effects on trace gases and atmospheric aerosol).
- Ecosystems and biodiversity (including pests and diseases), especially as affected by atmospheric N_r deposition.
- Soils quality (including effects on nitrogen saturation and acidification).

In regard of the last threat, feedback from stakeholders at the Laxenburg workshop, strongly argued for the inclusion of soils, given the need to include soil acidification and to consider soils as an integrator of different pressures.

Subsequent reflection of these five key societal threats of excess nitrogen has shown several interesting features. Firstly, with these headings, many of the other environmental concerns become automatically incorporated into the overall framework. For example, the air quality threat of N_r includes both ozone and particulate matter, while the soils threat includes acidification and alteration of soil organic matter storage. Secondly, this subdivision into five threats has allowed analysis of the negative effects caused by nitrogen together with some potential benefits. This is the case for the effect of nitrogen on greenhouse balance, where warming effects due to N_r (e.g., nitrous oxide, ozone) are at least partly offset by several cooling effects (e.g., aerosol, carbon sequestration).

In addition to highlighting the key issues for policy makers, the key societal threats also lend themselves to developing wider communication approaches. The selection of five issues highlights the complexity of the nitrogen problem (i.e. it is multi-issue), while focusing on a list which is sufficiently short to remember. The threats can, for example, be considered as the WAGES of excess nitrogen, being a mnemonic for the five key threats to: Water, Air, Greenhouse balance, Ecosystems and Soils.

Somewhat more surprising is the observation that this list of five threats also falls neatly into another ancient communication framework. The Greek philosopher Empedocles is famous for having presented the fundamental components of matter as four 'elements': water, air, fire and earth (Wright, 1995), to which Aristotle subsequently added aether as the quintessence, or fifth element (*de Caelo* I.2, Guthrie, 1986; Wilderg, 1988). Figure 5.6 illustrates the analogy between these elements of the Greek cosmos and the five key threats of excess nitrogen. In this model of nitrogen in the environmental macrocosm, the allocation of water, air and soil is straightforward, while greenhouse balance is linked to fire, with ecosystems and biodiversity, placed as the quintessence. Figure 5.6 also shows how it is possible to apply the system to highlight the key N_r forms for each threat. Such an assignment is naturally open to much debate, and must be considered loosely. However, any such controversy should not hinder the use of this model to communicate nitrogen issues, just as the longstanding debate in identifying Empedocles' elements (Wright, 1995) did not prevent – or even encouraged – acceptance of his approach.

Part IV of the ENA considers each of these five societal threats of excess nitrogen in turn, water quality (Grizzetti *et al.*, 2011, Chapter 17), air quality (Moldanová *et al.*, 2011, Chapter 18), greenhouse balance (Butterbach-Bahl *et al.*, 2011b, Chapter 19), ecosystems and biodiversity (Dise *et al.*, 2011, Chapter 20) and soil quality (Velthof *et al.*, 2011, Chapter 21). A deliberately sectoral approach is taken in each of these chapters, providing the basis to show the key issues that need to be linked in developing more integrated approaches. As far as possible, trends in N_r threats over time and across Europe are explored to show how the problem has arisen and to highlight the outlook in the light of existing policies.

Although these five chapters were initially developed in parallel using a common framework, it quickly became apparent that different approaches were needed according to each

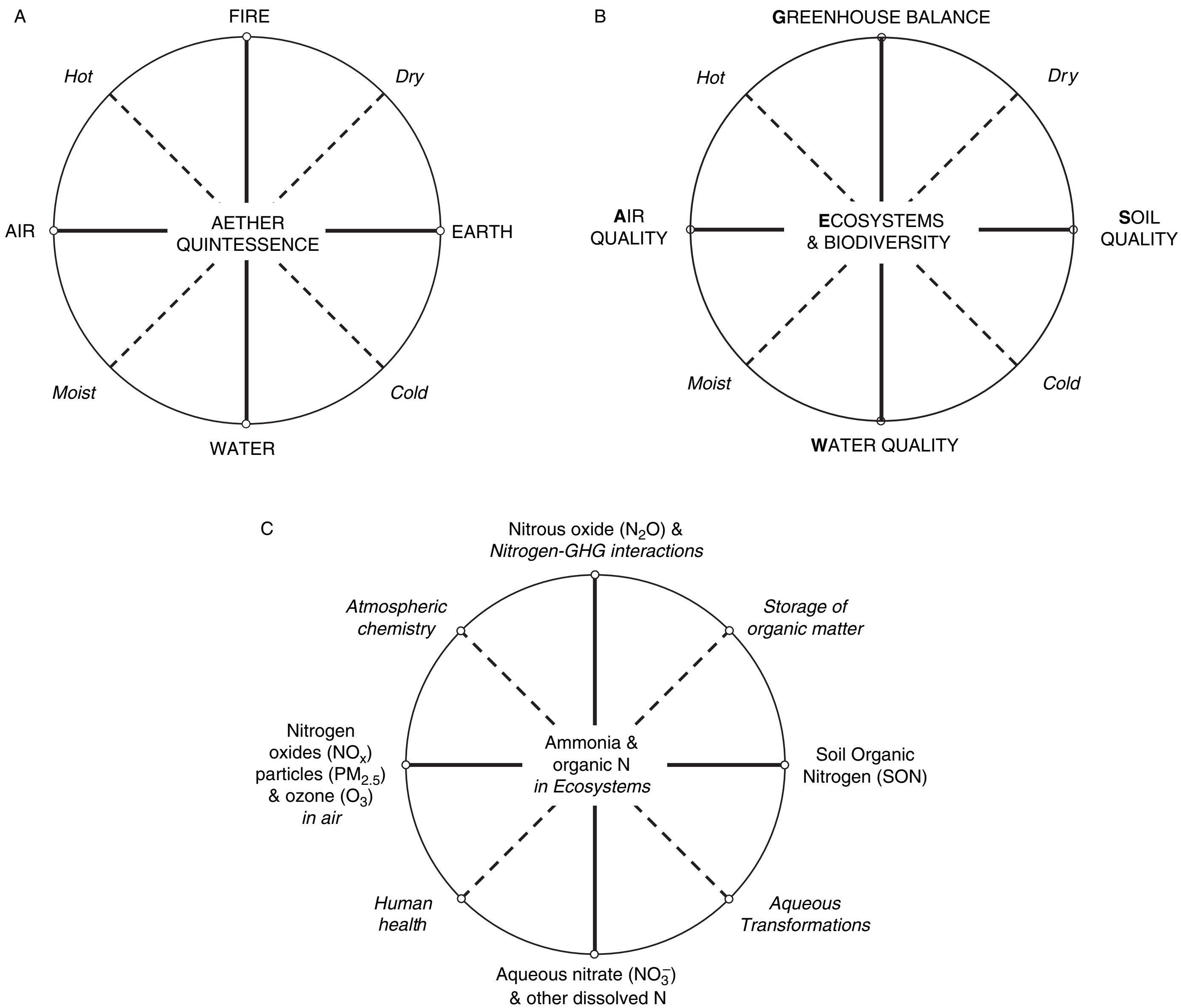

Figure 5.6 Analogy of nitrogen concerns in the environment to the Empedoclean–Aristotelian framework of the macrocosm: (A) visualization of Empedocles' elements, indicating their common properties, together with aether, the Aristotelian 'quintessence'; (B) the five key societal threats of reactive nitrogen visualized in macrocosmic framework; (C) key chemical forms and issues typifying each of the key societal threats. In each model, the diagonals represent shared properties of the adjacent elements.

issue. Thus some of the key threats like water quality and air quality represent mature areas, where data on spatial patterns and trends are well established. By contrast, the threat of N_r on greenhouse gas balance represents a much less well developed research and policy area. In this case, the chapter provides a first examination, drawing together the evidence needed to guide assessment of the net effects and the future policy development.

The use of these five threats was also tested as a communication tool by the N*in*E programme in collaboration with the BBC 'Green Room' (N*in*E, 2008; Sutton, 2008). In exploring the idea of the 'NitroNet', the web of interlinked challenges related to nitrogen, members of the public visiting the web-site were asked in the 'NitroNet Poll' how they would rate the different societal threats, on a scale of 1 to 5, from unimportant to important. The results, summarized in Figure 5.7, show that, while there were some significant differences between mean scores, members of the public had a wide range of views over which problems were the priority. The clear message was that all the issues need to be addressed. Feedback also showed that while some respondents accepted the challenge to prioritize between issues, others rejected the whole idea, considering that it is impossible to set such priorities. Whatever view one takes, the very debate on the validity of such a comparison again serves its main purpose of encouraging people to start thinking about how to manage the multiple threats of excess nitrogen.

An important communication tool is the use of visual images. For example, a further simplification of the Greek cosmological analogy (Figure 5.6) provides the basis to summarize visually the five key societal threats of excess nitrogen (Figure 5.8). Of the five threats, it is notable that the two that scored highest in

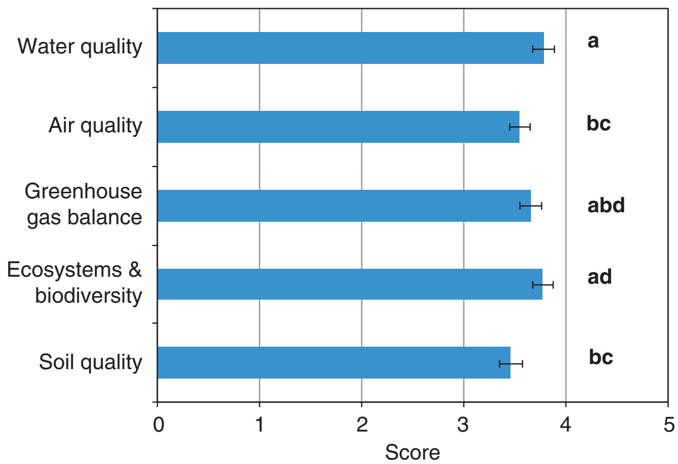

Figure 5.7 Outcome of scores from members of the public regarding the relative priorities between the five key societal threats of excess nitrogen, from the NitroNet Poll of N*in*E (2008) in cooperation with the BBC 'Green Room'. Members of the public were asked to allocate a score for each issue ranging from 1 (low priority) to 5 (high priority). The error bars are standard errors (n = 175), with the different letters (a to d) indicating significant differences (P = 0.05) based on paired t-tests (a shared letter indicates no significant difference between bars).

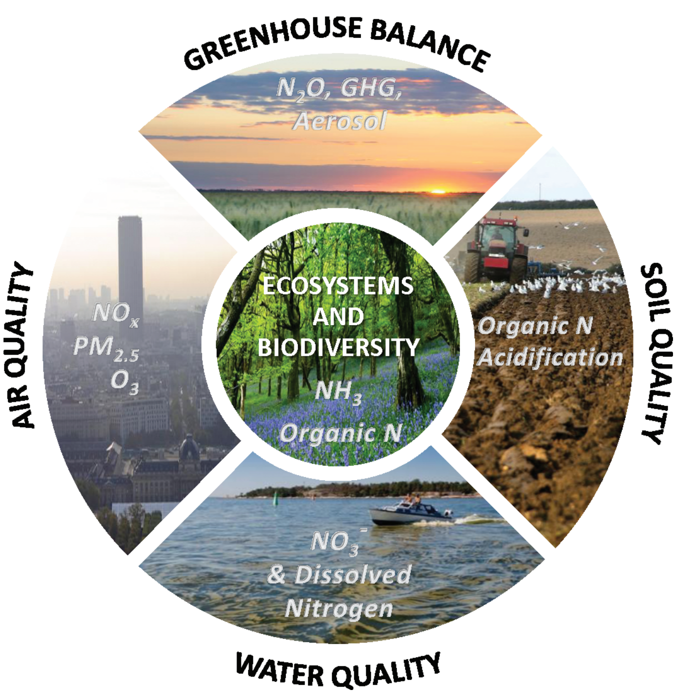

Figure 5.8 Summary of the five key societal threats of excess reactive nitrogen, with the visualization based on the analogy presented in Figure 5.6. *Photo sources*: Shutterstock.com and garysmithphotography.co.uk.

the NitroNet Poll – Water quality, and Ecosystems and biodiversity – are also highly amenable to visual images. To illustrate this, Figure 5.9 shows two examples of the effects of excess reactive nitrogen in the environment. The first (top) shows some of the consequences of high levels of atmospheric ammonia deposition on the epiphyte flora of birch woodland in the United Kingdom. On the left, at a clean site, the birch trunk shows a rich diversity of lichens and bryophytes. On the right, at a site near an intensively managed livestock farm, the natural flora has been completely eradicated, being replaced by a thick algal slime. Of course there are many stages between the conditions shown by these two photographs, but the comparison powerfully demonstrates the way in which reactive nitrogen supply is having major effects on terrestrial biodiversity. The second (lower) image shows the results of nutrient enrichment in coastal marine waters. Again, excess reactive nitrogen encourages algal growth, forming harmful 'blooms' which reduce oxygen availability and threaten fish and other species populations. Such algal blooms can have negative effects on bathing water quality, reducing water visibility and causing high levels of foam, as shown here, resulting from released gelatinous substances.

5.5 Integrating European nitrogen policies and future challenges

The analysis of key societal threats in Part IV of the Assessment provides the platform to develop more integrated science and policy approaches. With the main issues clearly identified, Part V of the Assessment brings these threats together and relates them to the benefits of N_r for food security and industrial production. As the same time, such approaches can be informed by the development of more integrated approaches, such as the establishment of comprehensive nitrogen budgets and maps for Europe (de Vries *et al*., 2011; Leip *et al*., 2011). Three chapters in Part V address different elements of integration followed by two chapters on how to communicate the outcomes with policy makers and the general public.

It is evident that the simple comparison of the 'NitroNet Poll' (Figure 5.7) represents only a first step, and it is a major challenge to develop more rigorous approaches to bring together the nitrogen issues and set priorities. In fact, the NitroNet Poll captures significant differences of opinion, as the respondents were answering based on a wide mix of perspectives and degrees of knowledge. In developing a more formal approach to compare the issues, economic methods may be used. In the subsequent assessment, Chapter 22 applies economic approaches to assess the environmental costs and societal benefits of reactive nitrogen in Europe (Brink *et al*., 2011, Chapter 22 this volume). Using willingness-to-pay approaches, the authors estimate societal damage costs as euro per kg N_r emission for each of N_r to water, NH_3 to air, NO_x to air and N_2O to air. The quantified uncertainty bounds estimated by Brink *et al*. highlight the major challenges of such an approach. Nevertheless, they provide a foundation for discussion with policy makers, showing the substantial financial benefits of mitigating N_r emissions.

The different elements of managing N_r are brought together by Oenema *et al*. (2011b, Chapter 23 this volume). Based on the foregoing contributions, they analyze what it means to develop 'integrated approaches' to nitrogen management. They examine several dimensions of integration, linking scales, issues, stakeholders etc. Based on these reflections, they identify a package of key actions that together provide an integrated perspective for overall management of anthropogenic N_r emissions and their effects. Such a short list builds on the key actions previously identified by Galloway *et al*. (2008) and warrants further consideration as a foundation for developing future European

Figure 5.9 Visual illustrations of the effect of excess nitrogen on the natural environment. Top: effect of atmospheric ammonia on epiphyte biodiversity in birch woodland in the UK: left, clean conditions showing a rich array of lichens and bryophytes (photo: Ian Leith); right, replacement of the natural epiphyte flora under high ammonia by a thick algal slime (photo: Mark Sutton). Bottom: nitrogen input into coastal seas in excess over silica, can cause severe algal blooms, in this case with *Phaeocystis globosa*, leading to a build up of gelatinous foam on a Dutch beach (photo: Gilles Billen).

policies. While some of the key actions are already being implemented in existing policies, it is equally clear that most of them require much more attention.

In developing future perspectives, it is vital to have a clear idea on the trajectories of N_r emissions and effects that can be expected. This places an important role on scenario development, considering both future economic development and current plans for N_r mitigation. Such a first assessment for the major N_r emissions in Europe is brought together by Winiwarter *et al.* (2011, Chapter 24 this volume). A major achievement is the combination of both short- and medium-term scenarios, though further efforts will be needed to develop scenarios of integrated packages for N_r management, including the long-term (e.g., 2100).

In developing the European Nitrogen Assessment, it has become clear how nitrogen issues cut across all global change threats. At the same time, the connected nature of the nitrogen cycle has clearly not been fully addressed by policy makers or recognized by the general public. A key task for the Assessment must therefore be to consider how better to communicate the nitrogen issues to these audiences.

Bull *et al.* (2011, Chapter 25 this volume) address the issue of how to communicate the N_r challenge with policy makers, highlighting the possibilities for more effective coordination between multi-lateral environmental agreements. They demonstrate the complexity of the international landscape for nitrogen, involving agreements between many different sets of national parties (e.g., UN, UN-ECE, EU, other groupings). The key challenge they raise is to develop mechanisms that ensure joined up approaches to nitrogen management, linking all of the key societal threats. They assess the possibility and relative merits different options, ranging from coordination actions, 'nitrogen proofing' existing policies, to the establishment of an international convention on nitrogen. An intermediate option is to develop the basis for a multi-media protocol on nitrogen, drawing on the work of the existing international conventions. The analysis of Bull *et al.* (2011) reflects the tension to ensure streamlined approaches that avoid substantial additional burden on the current conventions, while maximizing the synergies. In particular, it remains a challenge to develop a framework that develops sufficient 'gravity' to ensure that the different N_r related problems are drawn together.

Finally, Reay *et al.* (2011, Chapter 26 this volume) address the issue of how to communicate the European nitrogen challenge to the general public. They highlight how insufficient recognition has been given to the different barriers to optimizing future human use of nitrogen and its environmental consequences. They assess these barriers and relate them to the key societal levers, drawing on experience from the societal and policy challenge to manage climate change. In particular, they highlight the role of societal choice both in raising awareness of the nitrogen challenge, and in making a significant contribution towards meeting mitigation targets. Patterns of societal consumption – one of the seven key actions listed by Oenema *et al.* (2011b, Chapter 23 this volume) – are identified as a key focus relevant for the nitrogen cycle, especially related to diets, food choice and food waste. Based on the dominance of the food chain in the nitrogen cascade (Figure 5.3), human food choices have major effects on the overall amounts of N_r processed and lost to the environment. Reay *et al.* (2011) discuss how a 'segmented strategy' can be used to reach different stakeholders, including the use of proven communication tools, with involvement of the social sciences.

5.6 Conclusions

A key emerging feature of the European Nitrogen Assesment (ENA) is the challenge to develop holistic approaches that integrate across science disciplines, across policy domains and build the links between the science and policy communities. Until now the multi-media, multi-impact nature of the nitrogen cycle has been much broader than the individual science communities, and several steps are needed to provide the basis to address the whole.

This chapter reflects at the end of Part I of the ENA on how to develop subsequent parts of the Assessment. Based on the particular characteristics of the European nitrogen problem, on the major benefits of reactive nitrogen to the European economy and on the many existing policies that address parts of the nitrogen cycle, it is evident that Europe has a long history and experience of actively managing its nitrogen cycle. At the same time, it is clear that the complexity of the system has hindered the development of a broad perspective that would aim to optimize European nitrogen management. The need for such a perspective is fully justified by the multiple, non-linear interacting impacts illustrated by the nitrogen cascade.

In seeking to optimize future European nitrogen management, the first steps must be to agree on the scientific foundations. For this reason, the following parts of the ENA focus on our understanding of nitrogen processes (Part II) and how these can be upscaled from the farm to the European level (Part III).

The next step must be to establish the basis for prioritization of the key issues, which is necessary to set the framework for judging the optimum level of integration. Given the complexity of integration, the components need to be kept as simple as possible to be understandable and implementable in policy. Without such an issue building, the complexity of nitrogen management risks becoming seen in policy circles as an excuse for inaction.

Based on these reflections, this chapter reports a distillation of the many different nitrogen threats facing society. In a first cut, the Nitrogen in Europe (N*in*E) programme identified a network of nine main concerns of excess N_r. Such a grouping is well fitted to the scientific community, emphasizing the need to cooperate between media and disciplines. However, it was concluded that this listing remains too complicated to be the basis for developing integrated approaches with policy makers or to communicate the issues with society.

The chapter therefore describes a second distillation, into five key societal threats of excess nitrogen. This listing of five key threats was derived from a prioritization and clustering of around twenty environmental concerns, with the number five reflecting a deliberate balancing between complexity and simplification.

The five key societal threats: Water quality, Air quality, Greenhouse gas balance, Ecosystems and biodiversity, and Soil quality turn out to be well suited to developing communication models. In mnemonic form these threats can be seen as the 'WAGES of excess nitrogen', and be easily illustrated by analogy to each of the 'elements' of classical Greek philosophy.

Part IV of the Assessment analyzes each of the five key threats, clearly highlighting the main reasons why society should be concerned about excess N_r in the European environment. The initial aim was to ensure that these five chapters were closely streamlined in approach, highlighting the magnitude, spatial distribution, temporal trends and current efforts to manage each issue. However, it quickly became clear that the knowledge base for the five threats is very different, with the result that the greenhouse gas and soils threat chapters focus much more on problem quantification, while the water, air, and ecosystems chapters are able to provide more detail on trends and patterns.

Finally, the key societal threats provide the basis to inform the development of more holistic approaches to nitrogen management in Part V of the Assessment. A first examination of the costs of N_r pollution on the European environment and the benefits of N_r mitigation is conducted, scenarios of future N_r use and pollution are brought together, and integrated approaches to N_r management are developed. In particular, a package of seven key actions is identified, which would together provide the basis for integrated management of the European N_r resource, minimizing the environmental threats.

These messages provide the foundation for further communication and application by policy makers and by society at large. Here major challenges remain.

In the context of policy development, it is evident that more holistic approaches are needed, but much more work is needed by policy makers to agree the optimum degree of policy integration, and the right framework within which it should be conducted. There are major opportunities for closer working between existing multi-lateral environmental agreements in Europe, such as the different conventions of the UN-ECE and across EU policy domains. Such action needs to develop sufficient 'gravity' to pull together the key nitrogen concerns, while being sufficiently streamlined in order to have a chance of making effective progress.

The bottom line of Section V of the Assessment is the challenge to involve European citizens in recognizing and taking action on nitrogen. Major efforts still need to be devoted to simplifying the nitrogen story to make it understandable to the general public, developing the key messages. One of the key hooks identified is the importance of personal food choice to the whole nitrogen cascade. This illustrates the need for future efforts to quantify the impacts and mitigation potential, as well as to quantify the co-benefits of eating patterns that are both healthy for the individual and for the environment.

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Supplementary materials

Supplementary materials (as referenced in the chapter) are available online through both Cambridge University Press: www.cambridge.org/ena and the Nitrogen in Europe website: www.nine-esf.org/ena.

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