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#### Progress in core activities and implementation of the 2011 workplan

### *European Nitrogen Assessment: Summary for policymakers*

Submitted by the co-Chairs of the Task Force on Reactive Nitrogen

#### *Summary*

The *European Nitrogen Assessment*<sup>1</sup> proposes a package of seven key actions closely linked to the objectives under the Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol) to the Convention on Long-range Transboundary Air Pollution. As the Gothenburg Protocol is currently being revised, at its forty-eighth session, the Convention's Working Group on Strategies and Review invited the co-Chairs of the Task Force on Reactive Nitrogen to submit the Summary for Policymakers of the *European Nitrogen Assessment* to its forty-ninth session, in September 2011, with a view to its being forwarded to the Executive Body in December 2011 as an official document in order to inform the revision of the Gothenburg Protocol (ECE/EB.AIR/WG.5/104, para. 42 (d)). The document is also relevant for the implementation of the Convention's long-term strategy.

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<sup>1</sup> M. A. Sutton, C. M. Howard, J. W. Erisman et al., eds. (Cambridge University Press, 2011). The publication is available from <http://www.nine-esf.org/ENA>.

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## **I. Main messages**

### **A. Too much nitrogen harms the environment and the economy**

- Over the past century humans have caused unprecedented changes to the global nitrogen cycle, converting atmospheric dinitrogen ( $N_2$ ) into many reactive nitrogen ( $N_r$ ) forms, doubling the total fixation of  $N_r$  globally and more than tripling it in Europe.
- The increased use of  $N_r$  as fertilizer allows a growing world population, but has considerable adverse effects on the environment and human health. Five key societal threats of  $N_r$  can be identified: to water quality, air quality, greenhouse balance, ecosystems and biodiversity, and soil quality.
- Cost-benefit analysis highlights how the overall environmental costs of all  $N_r$  losses in Europe (estimated at €70–€320 billion per year at current rates) outweigh the direct economic benefits of  $N_r$  in agriculture. The highest societal costs are associated with loss of air quality and water quality linked to impacts on ecosystems and especially on human health.

### **B. Nitrogen cascade and budgets**

- The different forms of  $N_r$  inter-convert through the environment, so that one atom of  $N_r$  may take part in many environmental effects, until it is immobilized or eventually denitrified back to  $N_2$ . The fate of anthropogenic  $N_r$  can therefore be seen as a cascade of  $N_r$  forms and effects. The cascade highlights how policy responses to different  $N_r$  forms and issues are interrelated, and that a holistic approach is needed, maximizing the abatement synergies and minimizing the trade-offs.
- Nitrogen budgets form the basis for the development and selection of measures to reduce emissions and their effects in all environmental compartments. For instance, the European nitrogen budget highlights the role of livestock in driving the European nitrogen cycle.

### **C. Policies and management**

- Existing policies related to  $N_r$  have been largely established in a fragmented way, separating  $N_r$  forms, media and sectors. Despite the efforts made over many years to reduce  $N_r$  inputs into the environment, most of the  $N_r$ -related environmental quality objectives and environmental action targets have not been achieved to date.
- The five societal threats and N budgets are starting points for a more holistic management of  $N_r$ . The European Nitrogen Assessment identifies a package of seven key actions for overall management of the European nitrogen cycle. These key actions relate to: agriculture (three actions); transport and industry (one action); wastewater treatment (one action); and societal consumption patterns (two actions).
- The key actions provide an integrated package to develop and apply policy instruments. The need for such a package is emphasized by cost-benefit analysis that highlights the role of several  $N_r$  forms, especially nitrogen oxides ( $NO_x$ ), ammonia ( $NH_3$ ) and  $N_r$  loss to water, in addition to nitrous oxide ( $N_2O$ ), in the long term.

## D. International cooperation and communication

- Tackling  $N_r$  necessitates international cooperation. There are various options to implement multilateral environmental agreements; a possible inter-convention agreement on nitrogen needs to be further explored.
- Communication tools for behavioural change should be extended to nitrogen, such as calculating nitrogen “food-prints”. Messages should emphasize the potential health co-benefits of reducing the consumption of animal products to avoid excess above recommended dietary guidelines.

## II. Why nitrogen? Concerns and the need for new solutions

1. Nitrogen is an abundant element on Earth, making up nearly 80% of the Earth’s atmosphere. However, as atmospheric  $N_2$ , it is unreactive and cannot be assimilated by most organisms. By contrast, there are many  $N_r$  forms that are essential for life, but are naturally in very short supply. These include ammonia, nitrates, amino acids, proteins and many other forms. Until the mid-nineteenth century, limited availability of these  $N_r$  compounds in Europe severely constrained both agricultural and industrial productivity [1.1, 2.1].<sup>2</sup>

2. With an increasing population in the late nineteenth century, rates of biological nitrogen fixation were not sufficient for crop needs and Europe became increasingly dependent on limited sources of mined  $N_r$  (guano, saltpetre, coal). At the start of the twentieth century, several industrial processes were developed to fix  $N_2$  into  $N_r$ , the most successful being the Haber-Bosch process to produce  $NH_3$  [1.1, 2.1].

3. Since the 1950s,  $N_r$  production has greatly increased, representing perhaps the greatest single experiment in global geoengineering [1.1]. Europe’s fertilizer needs have been met, as well as its military and industrial needs for  $N_r$  [3.2, 3.5]. In addition, high temperature combustion processes have substantially increased the formation and release of  $NO_x$  [2.4]. While the  $N_r$  shortage of the past has been solved, Europe has stored up a nitrogen inheritance of unexpected environmental effects [1.1].

4. Europe remains a major source region for  $N_r$  production, with many of the environmental impacts being clearly visible and well studied. There is a wealth of evidence on sources, fate and impacts of  $N_r$ . However, the complexity and extent of the interactions mean that scientific understanding has become scattered and focused on individual sectors. A parallel fragmentation can be seen in environmental policies related to nitrogen, which are typically separated by media (air, land, water, etc.), by issue (climate, biodiversity, waste, etc.) and by  $N_r$  form [4.4, 5.3].

5. While this specialization has advanced understanding, European science and policies related to nitrogen have to a significant degree lost sight of the bigger picture. The occurrence of  $N_r$  in many different  $N_r$  forms and media means that each component should not be considered in isolation. A more comprehensive understanding of the nitrogen cycle is therefore needed to minimize the adverse effects of  $N_r$  in the environment, while optimizing food production and energy use [5.3].

<sup>2</sup> References in this summary (e.g., [1.1, 11.1]) refer to chapter and section numbers of the *European Nitrogen Assessment*.

### III. Role and approach of the *European Nitrogen Assessment*

6. A key challenge is to synthesize the science and understanding of nitrogen into a form that is useful to Governments and society. This involves bringing the different  $N_r$  forms, disciplines and stakeholders together.

7. The *European Nitrogen Assessment* was established in response to these needs. It was coordinated by the Nitrogen in Europe (NinE) programme of the European Science Foundation, drawing on underpinning research from across Europe, but especially the NitroEurope Integrated Project co-funded by the European Commission, with input from the COST Action 729. The Assessment provides a European contribution to the International Nitrogen Initiative (INI) [1.3].

8. The lead policy audience for the Assessment is the Geneva Convention on Long-range Transboundary Air Pollution (CLRTAP), established under the auspices of the United Nations Economic Commission for Europe (ECE). Through its Task Force on Reactive Nitrogen, the Convention has formally adopted the Assessment as a contributing activity to its work [1.3].

9. In addition to supporting CLRTAP, the Assessment is targeted to provide scientific and policy support to the European Union and its member States, as well as other multilateral environmental agreements, including the Global Partnership on Nutrient Management facilitated by the United Nations Environment Programme (UNEP) [1.5].

10. Recognizing these needs, the goal of the *European Nitrogen Assessment* was established: *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* [1.4].

11. The Assessment process was conducted through a series of five open scientific workshops between 2007 and 2009. Draft chapters were submitted to internal and external peer review [1.3].

### IV. Disruption of the European nitrogen cycle

#### A. Fertilizers, energy and transport: drivers for increased nitrogen inputs

12. Production of  $N_r$  is a key input for agriculture and industry, and a persistent side effect of combustion for energy and transport. Industrial production in Europe of  $N_r$  in 2008 was about 34 Tg per year (where 1 Tg = 1 million tons), of which 75% is for fertilizer and 25% for chemical industry (production of rubbers, plastics, and use in electronic, metals and oil industry) [3.5]. The trend in mineral fertilizer represents the largest change in overall  $N_r$  inputs to Europe over the past century (figure 1).

13. The combustion of fossil fuels has allowed a substantial increase in industrial production and transportation, reflected in the greatly increased emission of nitrogen oxides, which only over the last 20 years have partly been controlled. By contrast, the total contribution of crop biological nitrogen fixation has decreased significantly.

14. The provision of  $N_r$  from the Haber-Bosch process removed a major limiting factor on society, permitting substantial population growth and improving human welfare. However, accounting for natural sources, humans have more than doubled the supply of  $N_r$  into the environment globally [1.1], and more than tripled this supply in Europe (figure 3 ) [16, supplementary material].

15. As of the year 2000, Europe creates about 19 Tg per year of  $N_r$ , of which 11 Tg per year is from chemical fertilizers, 3.4 Tg per year is from combustion sources, 3.5 Tg per year is from food and feed import and 1 Tg per year is contributed by crop biological nitrogen fixation (BNF) (figure 3).

## B. The nitrogen cascade

16. Human production of  $N_r$  from  $N_2$  causes a cascade of intended and unintended consequences. The intended cascade is that each molecule of  $N_r$  contributes to soil fertility and increased yields of crops, subsequently feeding livestock and humans, allowing the formation of amino acids, proteins and deoxyribonucleic acid (DNA). In a well managed system, the intention is for the  $N_r$  in manures and sewage to be fully recycled back through the agricultural system (blue arrows in figure 2).

17. Reactive nitrogen, is however, extremely mobile, with emissions from agriculture, combustion and industry leading to an unintended cascade of  $N_r$  losses into the natural environment (figure 2). Once released,  $N_r$  cascades through the different media, exchanging between different  $N_r$  forms and contributing to a range of environmental effects, until it is finally denitrified back into  $N_2$ . An important consequence of the cascade is that the environmental impacts of  $N_r$  eventually become independent of the sources, so that nitrogen management requires a holistic approach. This is important, both to minimize “pollution swapping” between different  $N_r$  forms and threats, and to maximize the potential for synergies in mitigation and adaptation strategies [2.6, 5.2].

## C. A new nitrogen budget for Europe

18. One of the tasks addressed in the *European Nitrogen Assessment* has been to construct a comprehensive nitrogen budget for Europe (EU-27<sup>3</sup> for the year 2000), considering each of the major flows in the nitrogen cascade [16.4]. In parallel, the estimates have also been compared with 1900 [16, supplementary material]. By combining all the nitrogen flows, such budgets provide an improved perspective on the major drivers and the most effective control options.

19. Figure 3 summarizes the European nitrogen budget in its simplest form [derived from 16.4]. The budget for 2000 shows that overall human perturbation of the nitrogen cycle is driven primarily by agricultural activities. Although the atmospheric emissions of  $NO_x$  from traffic and industry contribute to many environmental effects, these emissions are dwarfed by the agricultural  $N_r$  flows.

20. It is important to note the magnitude of the European  $N_r$  flow in crop production, which is mainly supported by  $N_r$  fertilizers. The primary use of the  $N_r$  in crops, however, is not directly to feed people: 80% of the  $N_r$  harvest in European crops provides feeds to support livestock (8.7 Tg per year plus 3.1 Tg per year in imported feeds, giving a total of 11.8 Tg per year). By comparison, human consumption of  $N_r$  is much smaller, amounting to only 2 Tg per year in crops and 2.3 Tg per year in animal products. Human use of livestock in Europe, and the consequent need for large amounts of animal feed, is therefore the dominant human driver altering the nitrogen cycle in Europe [16.4].

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<sup>3</sup> The 27 member States of the European Union: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and United Kingdom of Great Britain and Northern Ireland.

21. These major intended alterations in  $N_r$  flows cause many additional unintended  $N_r$  flows (figure 3). Overall,  $NH_3$  from agriculture (3.2 Tg per year) contributes a similar amount to emissions of  $N_r$  to the atmosphere as  $NO_x$  (3.4 Tg per year). Agriculture also accounts for 70% of nitrous oxide ( $N_2O$ ) emissions in Europe, with total  $N_2O$  emissions of 1 Tg per year. The food chain also dominates  $N_r$  losses to ground and surface waters, mainly as nitrates ( $NO_3$ ), with a gross load of 9.7 Tg resulting mainly from losses due to agriculture (60%) and discharges from sewage and water treatment systems (40%) [16.4].

22. The comparison between 1900 and 2000 shows how each of these flows has increased, including denitrification back to  $N_2$ . Denitrification is the largest and most uncertain loss, as it occurs at many different stages during the continuum from soils to freshwaters and coastal seas. Although emissions of  $N_2$  are environmentally benign, they represent a waste of the substantial amounts of energy put into human production of  $N_r$ , thereby contributing indirectly to climate change and air pollution. This is in addition to the impact on climate change of  $N_2O$  formed especially as a by-product of denitrification.

#### **D. Achievements and limitations of current policies**

23. Peak production of  $N_r$  in Europe occurred in the 1980s, which was linked to agricultural overproduction and lack of emissions regulations. Since that time, the introduction of policies and other changes affecting agriculture (including the Common Agricultural Policy, the Nitrates Directive and the restructuring of Eastern Europe after 1989), as well as stringent emission controls, e.g., for large combustion plants (EU Large Combustion Plants Directive, ECE Sofia Protocol concerning the Control of Emissions of Nitrogen Oxides or their Transboundary Fluxes and the Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol), etc.) and the EURO standards for road transport vehicles, have led to decreases in the emissions (figure 4) [4.4].

24. Overall, emissions of combustion  $NO_x$  have reduced by ~30% since 1990, but much greater  $NO_x$  reductions per unit output have been achieved. These have been offset by an increase in traffic and energy consumption. The net emission reduction is therefore a clear example of decoupling, as emissions would have increased by over 30% if no measures had been implemented. The extent of success of the technical measures can be in part attributed to the involvement of a small number of players (e.g., electricity supply industry, vehicle manufacturers) and the fact that the costs of these measures could be easily transferred to consumers [4.5].

25. Agricultural measures have resulted in only a modest reduction in total agricultural  $N_r$  inputs for the EU-27 of ~15% (figure 1). This small overall reduction is reflected in the trends in  $NH_3$  emissions (figure 4). Most of the reductions that have been achieved to date can be attributed to reductions in fertilizer use and livestock numbers, especially in Eastern Europe after 1989. Although management improvements will have contributed to reduced emissions (e.g., nitrate leaching and loss to marine areas), there has as yet been little quantitative achievement of measures to reduce  $N_2O$  and  $NH_3$  emissions from agriculture on a European scale. The fact that current  $N_r$  emission reduction policies in agriculture (e.g., EU Nitrates Directive, OSPAR Commission for the Protection of the Marine Environment of the North-East Atlantic, ECE Gothenburg Protocol and EU National Emissions Ceilings Directive) have only made limited progress can be linked in part to the large number of diverse actors (including many small farms), the diffuse nature of the  $N_r$  emission sources, and the challenge of passing any perceived costs onto consumers [4.5]. As a consequence, agriculture is the sector with the largest remaining emission reduction potential.

26. Several instances of pollution swapping in  $N_r$  control have been observed. These include the introduction of three-way catalysts in vehicles, which increased  $NH_3$  and  $N_2O$  emissions (although overall  $N_r$  emissions were still greatly reduced), and the implementation of the Nitrates Directive, prohibiting wintertime manure spreading, which has led to a new peak in springtime  $NH_3$  emissions [9.2].

## **V. The benefits and efficiency of nitrogen in agriculture**

### **A. Nitrogen fertilizers feed Europe**

27. There is no doubt that human production of  $N_r$  has greatly contributed to the increase in productivity of agricultural land. Without anthropogenic  $N_r$ , a hectare of good agricultural land in Europe, with no other growth limitations, can produce about 2 tons per hectare (ha) of cereal annually. With typical additional inputs from BNF, it can produce about 4–6 tons per ha, and with addition of chemical fertilizer about 8–10 tons per ha. Synthetic  $N_r$  fertilizer has been estimated to sustain nearly 50% of the world's population, and is essential for the EU to be largely self-sufficient in cereals. For pork, poultry and egg production, Europe strongly depends on soybean imports from America [3.1].

28. Agronomic efficiency provides an indicator of the  $N_r$  benefit to the farmer (kilogram (kg) of crop production per kg of applied nitrogen (N)). Typically, fertilizer rates in the eastern EU member States are up to four times lower than in the 15 “old” member States, but agronomic efficiencies are comparable (figure 5). The use of  $N_r$  is profitable as there is a robust financial return of €2–€5 on every euro invested in  $N_r$  fertilizer, depending on the market price of cereals and fertilizer [3.6].

### **B. Grain and meat production considerably differ in their $N_r$ losses to the environment**

29. The nitrogen recovery (kg N taken up by a crop per kg applied N) provides a measure of environmental N loss in crop production. For cereals it varies 30%–60% across Europe, indicating that 40%–70% of the fertilizer  $N_r$  applied is lost to the atmosphere or the hydrosphere [3.2].

30. The nitrogen recovery in animal farming is inherently lower than in crops, with only 10%–50% of  $N_r$  in feed being retained in live weight and 5%–40% in the edible weight (figure 6). Accounting for the additional  $N_r$  losses in feed production, the overall efficiency of  $N_r$  use for meat production is around half these values. For this reason, the full chain of animal protein production generates much more losses to the environment than plant protein production.

31. About one third (7.1 Tg per year in 2000) of the total farm input of  $N_r$  to soil comes from animal manures. This represents about two thirds of the  $N_r$  from animal feeds, while the fraction of  $N_r$  in animal manures that is lost to the environment is typically double that of mineral  $N_r$  fertilizer, highlighting the importance of proper measures to maximize the effectiveness of manure reuse [3.2].

### **C. Variation in nitrogen use efficiency highlights the potential for solutions**

32. The overall efficiency of European agriculture (ratio of N in food produced to the sum of synthetic N fertilizer used plus food and feed imports) is about 30% since 2000 [derived from 16.4, see figure 3]. The wide variety in N application rates and nitrogen use

efficiency across Europe indicates that there is a huge scope to improve resource efficiency and reduce environmental effects (figure 5).

33. In the EU, protein consumption exceeds recommended intake by 70% [26.3] and the share of animal proteins in this total is increasing. Even a minor change in human diet, with less animal protein consumption (or protein from more efficient animals), would significantly affect the European nitrogen cycle.

## **VI. The key societal threats of excess nitrogen**

34. From a longer list of around 20 concerns, the Assessment identifies five key societal threats associated with excess  $N_r$  in the environment: **Water quality**, **Air quality**, **Greenhouse balance**, **Ecosystems and biodiversity**, and **Soil quality**. Together, these threats can be easily remembered by an acronym as the “WAGES” of excess nitrogen, and visualized by analogy to the four “elements” (water, air, fire, earth) and quintessence of classical Greek cosmology (figure 7). These five threats provide a framework that incorporates almost all issues related to the longer list of concerns associated with excess  $N_r$  [5.4].

### **A. Nitrogen as a threat to European water quality**

35. Water pollution by  $N_r$  causes eutrophication and acidification in fresh waters [7.4, 8.8]. Estuaries, their adjacent coastlines and (near) inland seas are also affected by eutrophication from  $N_r$  with inputs to the coastal zone being four times the natural background [13.7]. Biodiversity loss, toxic algal blooms and dead zones (fish kill) are examples of effects [8.8]. Nitrate levels in freshwaters across most of Europe greatly exceed a threshold of 1.5 to 2 milligrams (mg)  $N_r$  per litre, above which water bodies may suffer biodiversity loss [7.5, 17.3].

36. High nitrate concentrations in drinking water are considered dangerous for human health, as they might cause cancers and (albeit rarely) infant methaemoglobinaemia. About 3% of the population in the EU-15<sup>4</sup> is potentially exposed to levels exceeding the standard for drinking water of 50 mg  $NO_3$  per litre (11.2 mg  $N_r$  per litre) and 6% exceeding 25 mg  $NO_3$  per litre [17.3]. This may cause 3% increase of incidence of colon cancer, but nitrate is also considered to be beneficial to cardiovascular health [22.3].

37. Although aquatic eutrophication has decreased to some extent since the 1980s, agreed international policies have not been fully implemented. In addition, increasing nitrate in groundwaters threatens the long-term quality of the resource, due to long residence times in aquifers [7.5, 17.2]. Achieving substantial progress at the European scale requires integration of sectoral policies, reducing overall inputs of  $N_r$  to watersheds [4.5, 13.7, 17.5].

### **B. Nitrogen as a threat to European air quality**

38. Air pollution by  $NO_x$  and  $NH_3$  causes formation of secondary particulate matter (PM), while emissions of  $NO_x$  also increase levels of  $NO_2$  and tropospheric ozone ( $O_3$ ). All of these are causes for respiratory problems and cancers for humans, while ozone causes

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<sup>4</sup> The EU-15 refers to Belgium, Denmark, Germany, Greece, Spain, France, Ireland, Italy, Luxembourg, the Netherlands, Austria, Portugal, Finland, Sweden and the United Kingdom.

damage to crops and other vegetation, as well as to buildings and other cultural heritage [18.2, 18.5].

39. Models estimate that PM contributes to 300,000–400,000 premature deaths annually in Europe, leading to a reduction in life expectancy due to PM of 6–12 months across most of central Europe.  $N_r$  contributes up to 30%–70% of the PM by mass [18.3, 18.5]. However, the individual contributions of  $NO_x$ - and  $N_r$ -containing aerosol to human health effects of air pollution remain uncertain [18.2].

40. Although  $NO_x$  emission decreases have reduced peak  $O_3$  concentrations, background tropospheric  $O_3$  concentrations continue to increase. By comparison to the limited progress in reducing  $NO_x$  emissions, there has been even less success in controlling agricultural  $NH_3$  emissions, which therefore contribute to an increasing share of the European air pollution burden [4.5, 18.6].

### C. Nitrogen as a threat to European greenhouse balance

41. Reactive nitrogen emissions have both warming and cooling effects on climate. The main warming components are increasing concentrations of  $N_2O$  and tropospheric  $O_3$ , which are both greenhouse gases. The main cooling effects are atmospheric  $N_r$  deposition presently increasing carbon dioxide ( $CO_2$ ) removal from the atmosphere by forests, and the formation of  $N_r$  containing aerosol, which scatter light and encourage cloud formation [19].

42. Overall, European  $N_r$  emissions are estimated to have a net cooling effect on climate of –16 megawatts (mW) per square metre ( $m^2$ ), with the uncertainty bounds ranging from substantial cooling to a small net warming (–47 to +15 mW per  $m^2$ ). The largest uncertainties concern the aerosol and  $N_r$  fertilization effects, and the estimation of the European contributions within the global context [19.6]. The estimate of the Intergovernmental Panel on Climate Change (IPCC) for indirect  $N_2O$  emissions from  $N_r$  deposition is considered to be an underestimate by at least a factor of 2 [6.6, 19.6].

43. There are many opportunities for “smart management”, increasing the net cooling effect of  $N_r$  by reducing warming effects at the same time as other threats, e.g., by linking nitrogen and carbon cycles to mitigate greenhouse gas emissions through improved nitrogen use efficiency [19.6].

### D. Nitrogen as a threat to European terrestrial ecosystems and biodiversity

44. Atmospheric  $N_r$  deposition encourages plants favouring high  $N_r$  supply or more acidic conditions to out-compete a larger number of sensitive species, threatening biodiversity across Europe. The most vulnerable habitats are those with species adapted to low nutrient levels or poorly buffered against acidification. In addition to eutrophication, atmospheric  $N_r$  causes direct foliar damage, acidification and increased susceptibility to pathogens [20.3].

45. Although there are uncertainties in the relative effects of atmospheric nitrate ( $NO_3^-$ ) versus ammonium ( $NH_4^+$ ), gaseous ammonia ( $NH_3$ ) can be particularly harmful to vegetation, causing foliar damage especially to lower plants [20.3]. This emphasizes the threat to semi-natural habitats occurring in agricultural landscapes [9.6, 11.5]. While uncertain,  $N_r$  deposition is expected to act synergistically with climate change and ground-level ozone [20.2].

46. Thresholds for atmospheric concentrations and deposition of  $N_r$  components to semi-natural habitats are exceeded across much of Europe, and will continue to be

exceeded under current projections of  $N_r$  emissions. In order to achieve ecosystem recovery, further reductions of  $NH_3$  and  $NO_x$  emissions are needed [20.5]. Due to cumulative effects of  $N_r$  inputs and long time lags, rates of ecosystem recovery are expected to be slow, and in some cases may require active management intervention in the affected habitats [20.5].

## **E. Nitrogen as a threat to European soil quality**

47. Soil integrates many of the other  $N_r$  effects, highlighting their interlinked nature. The major  $N_r$  threats to soil quality are soil acidification, changes in soil organic matter content and loss of soil biodiversity. Soil acidification can occur from the deposition of both oxidized and reduced  $N_r$ , resulting from  $NO_x$  and  $NH_3$  emissions, reducing forest growth and leading to leaching of heavy metals [21.3]. High levels of  $N_r$  deposition to natural peat-lands risk losing carbon stocks through interactions with plant species changes, although this effect is poorly quantified [6.6, 19.4].

48. Addition of  $N_r$  typically has a beneficial effect in agricultural soils, enhancing fertility and soil organic matter [6.4, 21.3]. However,  $N_r$  losses increase, while some soil fungi and N-fixing bacteria are reduced by high N availability. The interactions between  $N_r$  and soil biodiversity, soil fertility and  $N_r$  emissions are not well understood [21.3].

49. European forest soils are projected to become less acidic within a few decades, mainly as a result of reduced  $SO_2$  and  $NO_x$  emissions. Ammonia emissions have only decreased slightly and  $NH_x$  (ammonia plus ammonium) is increasingly dominating soil acidification effects over large parts of Europe [20.3, 21.4].

## **VII. The economics of nitrogen in the Environment**

### **A. Estimated loss of welfare due to nitrogen emissions in Europe**

50. The social costs of the adverse impacts of  $N_r$  in the European environment are estimated. Expressed as € per kg of  $N_r$  emission, the highest values are associated with air pollution effects of  $NO_x$  on human health (€10–€30 per kg), followed by the effects of  $N_r$  loss to water on aquatic ecosystems (€5–€20 per kg) and the effects of  $NH_3$  on human health through particulate matter (€2–€20 per kg). The smallest values are estimated for the effects of nitrates in drinking water on human health (€0–€4 per kg) and the effect of  $N_2O$  on human health by depleting stratospheric ozone (€1–€3 per kg) [22.6].

51. Combining these costs with the total amount of emissions for each main  $N_r$  form, provides a first estimate of the annual  $N_r$ -related damage in the EU-27 (figure 8). The overall costs are estimated at €70–€320 billion per year, of which 75% is related to air pollution effects and 60% to human health. The total damage cost equates to €150–€750 per person, or 1%–4% of the average European income [22.6], and is about twice as high as the present “willingness to pay” to control global warming by carbon emissions trading [22.6].

52. Environmental damage related to  $N_r$  effects from agriculture in the EU-27 was estimated at €20–€150 billion per year. This can be compared with a benefit of N fertilizer for farmers of €10–€100 billion per year, with considerable uncertainty about long-term N benefits for crop yield [22.6].

53. Apart from the uncertainties inherent in valuing the environment, including the use of “willingness to pay” approaches for ecosystem services, the main uncertainties in these estimates concern the relative share of  $N_r$  in PM to human health effects and of  $N_r$  to freshwater eutrophication effects [22.6].

## B. Future European nitrogen mitigation and scenarios

54. Internalizing the environmental costs for N-intensive agriculture in North-Western Europe provides economically optimal annual  $N_r$  application rates that are about 50 kg per ha (30%) lower than the private economic optimum rate for the farmer. This highlights the importance of increasing nitrogen use efficiency and accounting for external effects on the environment in providing N recommendations to farmers [22.6].

55. The results also highlight the small overall cost due to  $N_2O$  emissions compared with  $NO_x$ ,  $NH_3$  emissions and  $N_r$  losses to water (figure 8). Although unit costs of  $N_2O$ , at €6–€18 per kg  $N_r$  emitted, are similar to the other issues,  $N_2O$  emissions are much smaller (para. 21), so that total European damage costs due to  $N_2O$  are much less than from the other  $N_r$  forms. Based on the “willingness to pay” approach and current values, this indicates that the highest policy priority should be put on controlling European  $NO_x$  and  $NH_3$  emissions to air and  $N_r$  losses to water, as compared with the control of  $N_2O$  emissions. It is important to target measures that have maximum synergy, reducing emissions of all  $N_r$  forms and impacts simultaneously. However, where some measures involve limited trade-offs between  $N_r$  (“pollutant swapping”), figure 8 indicates that further control of  $NO_x$ ,  $NH_3$  and  $N_r$  to water would be justified economically even if a proportionate percentage increase in  $N_2O$  emissions were to occur.

56. Estimated costs of technical measures to reduce emissions of  $NO_x$ ,  $NH_3$  and  $N_2O$  are available in the International Institute for Applied Systems Analysis (IIASA) Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model. Based on these estimates, future scenarios up to 2030 compare current reduction plans with maximum feasible reduction and a cost optimization approach. This comparison indicates substantial scope for further reductions in  $NO_x$  and  $NH_3$  emissions, supporting the case for revision of the Gothenburg Protocol [24.6]. Although not assessed here, preliminary indications suggest that costs of  $NH_3$  abatement measures (€ per kg  $N_r$ ) are cheaper than previously estimated, being the subject of ongoing review.<sup>5</sup>

57. Future long-term scenarios emphasize the possibility for major reductions in  $NO_x$  emissions (by 75% or more for 2000 to 2100), due to improved technologies combined with projected decreases in energy use for some scenarios (figure 9). By contrast, the anticipated trends for  $NH_3$  and  $N_2O$  are much less clear. A high  $CO_2$  scenario representing unrestricted development (+8.5  $W/m^2$  radiative forcing) indicates an increase in  $NH_3$  emissions, which does not occur with the more optimistic climate scenarios (+2.6 and +4.5  $W/m^2$  radiative forcing). But even these scenarios highlight a long-term outlook where  $NH_3$  quickly becomes the dominant form of  $N_r$  emission to the atmosphere, and a key challenge for control policies [24.6].

58. The long-term outlook for scenarios of  $N_r$  use and emissions must also consider the possible extent of future renewable energy production. There is potential for substantial synergy in increased forest cover, where the main  $N_r$  input is atmospheric deposition, allowing increased scavenging of air pollutants and a contribution to carbon sequestration [9.4, 19.4]. By contrast, the increased use of fertilizer  $N_r$  to support intensively managed bioenergy and biofuel crops can involve significant trade-offs, requiring that additional  $N_2O$ , other  $N_r$  and  $N_2$  losses be balanced against the carbon benefits (para. 22) [2.4, 24.5].

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<sup>5</sup> See Options for Revising the 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone: Reactive Nitrogen (ECE/EB.AIR/WG.5/2010/13).

## VIII. The potential for integrated approaches to manage nitrogen

### A. A holistic view to managing the nitrogen cascade

59. Given the range of adverse environmental effects in the  $N_r$  cascade, the most attractive mitigation options are those that offer simultaneous reductions of all N pollutants from all emitting sectors and in all environmental compartments.

60. An integrated approach to  $N_r$  management holds the promise of decreasing the risks of inconsistency, inefficiency and pollution swapping. Efforts at integration should recognize the varying level of success in  $N_r$  policies (paras. 23–26) aiming to ensure balance in mitigation efforts between sectors. Integration puts higher demands on interdisciplinarity and consensus building between science, policy and stakeholders [4.6, 23.4].

61. Integrated policies are also justified within sectors, such as agriculture, because of the large number of actors and the connection between sources, sectors and effects [23.4]. The Common Agricultural Policy of the EU provides a potentially powerful incentive to improve sustainability of agricultural production.

### B. Seven key actions for better management of the nitrogen cascade

62. Seven key actions in four sectors provide a basis for further developing integrated approaches to N management [23.5].

#### Agriculture

1. *Improving nitrogen use efficiency in crop production.* This includes improving field management practices, genetic potential and yields per  $N_r$  input, with the potential to reduce losses per unit of produce, thereby minimizing the risk of pollution swapping [3.3, 22.6, 23.5].

2. *Improving nitrogen use efficiency in animal production.* As with crops, this includes management practices and genetic potential, with an emphasis on improving feed conversion efficiency and decreasing maintenance costs, so reducing losses per unit of produce and the extent of pollution swapping [3.4, 10.3, 23.5].

3. *Increasing the fertilizer N equivalence value of animal manure.* Increasing fertilizer equivalence values requires conserving the  $N_r$  in manure during storage and land application (especially reducing  $NH_3$  emissions where much  $N_r$  is lost), while optimizing the rate and time of application to crop demand [3.4, 10.3, 23.5].

#### Transport and Industry

4. *Low-emission combustion and energy-efficient systems.* These include improved technologies for both stationary combustion sources and vehicles, increasing energy efficiency and use of alternative energy sources with less emission, building on current approaches [4.5, 23.5, 24.6].

#### Wastewater treatment

5. *Recycling nitrogen (and phosphorus) from wastewater systems.* Current efforts at water treatment for  $N_r$  in Europe focus on denitrification back to  $N_2$ . While policies have been relatively successful [4.6], this approach represents a waste of the energy used to produce  $N_r$  (para. 22). An ambitious long-term goal should be

to recycle  $N_r$  from wastewaters, utilizing new sewage management technologies [12.3, 23.5].

### **Societal consumption patterns**

6. *Energy and transport saving.* Against the success of technical measures to reduce  $NO_x$  emissions per unit consumption, both vehicle miles and energy use have increased substantially over past decades. Dissuasion of polluting cars and far-distance holidays, and stimulation of energy-saving houses and consumption patterns can greatly contribute to decreasing  $NO_x$  emissions [23.5].

7. *Lowering the human consumption of animal protein.* European consumption of animal protein is above the recommended per capita consumption in many parts of Europe. Lowering the fraction of animal products in diets to the recommended level (and shifting consumption to more N-efficient animal products) will decrease  $N_r$  emissions with human health co-benefits, where current consumption is over the optimum [23.5, 24.5, 26.3].

63. Key Action 4 involves technical measures that are already being combined with public incentives for energy saving and less polluting transport (Key Action 6), linking  $N_r$ , air pollution and climate policies (cf. figure 9). Similarly, each of the Key Actions in the food chain (1–3, 7) offers co-benefits with climate mitigation and the management of other nutrients, including phosphorus. Given the limited success so far in reducing agricultural  $N_r$  emissions, more effort is needed to link the Key Actions, both to learn from the successes and to ensure equitability between sectors.

## **IX. Challenges for society and policy**

### **A. Nitrogen in multilateral environmental agreements and future research**

64. International treaties, such as multilateral environmental agreements, have done much to protect the global environment, promoting intergovernmental action on many environmental issues, but none has targeted nitrogen management policy holistically [4.3, 25.2].

65. A new international treaty targeted explicitly on nitrogen could be a powerful mechanism to bring the different elements of the nitrogen problem together. While a new convention would be complex to negotiate and could compete with existing structures, a joint protocol between existing conventions could be effective and should be explored [25.3, 25.4].

66. New coordinating links on nitrogen management between multilateral environmental agreements should be further developed, including the Global Partnership on Nutrient Management facilitated by UNEP, the Task Force on Reactive Nitrogen of the ECE Convention on Long-range Transboundary Air Pollution and the links with other ECE conventions. There is the opportunity for the ECE Committee on Environmental Policy to develop nitrogen management links between ECE Conventions, while the EU and its member States have important roles to play in harmonization and coordination [25.4].

67. Such coordination actions will require ongoing support from the scientific community, especially given the many remaining uncertainties inherent in developing the long-term vision of a holistic approach. Research programmes should put a higher priority on quantifying the nitrogen links between the traditional domains of disciplines, media and environmental issues, providing data and models that can underpin future negotiations and policies.

## **B. Societal choice, public awareness and behavioural change**

68. European society is facing major choices regarding food and energy security, and environmental threats including climate change, water, soil and air quality and biodiversity loss. These issues are intricately linked to the nitrogen cycle and have a strong global context, with the decisions of European individuals on lifestyle and diet having a major role to play [26.3].

69. In Europe, different scenarios and models suggest a strong 75% decline in  $\text{NO}_x$ , while emissions of  $\text{NH}_3$  and  $\text{N}_2\text{O}$  display an uncertain future outlook (figure 9) [24.6]. The constraints that have so far limited reductions in  $\text{N}_r$  emissions from agriculture include many stakeholders, an open farming system with diffuse losses, the desire to maintain high outputs for European agro-economy and food security, and possible concerns about how to transfer anticipated costs to consumers (para. 25). Changes in agricultural practices to achieve substantial reductions in European  $\text{N}_r$  emissions in the coming decades therefore require awareness and broad support from policy, industry, farmers, retailers and consumers [23.3, 26.3].

70. The comparison between combustion and agricultural  $\text{N}_r$  emissions highlights the need to engage the public. This should emphasize mutual responsibility along the whole food-supply chain, support the basis for transferring any mitigation costs to the consumer, and emphasize that the substantial costs of environmental impacts fully justify taking action [4.5, 23.5, 26.3].

71. At present, public and institutional awareness of the global nitrogen challenge is very low. The comparison with carbon and climate change highlights how the nitrogen story is multifaceted, cutting across all global-change themes. This complexity is a barrier to greater public awareness, pointing to the need to distil easy messages that engage the public [5.4, 26.4].

72. Simple messages for nitrogen include contrasting its huge benefits for society against the environmental threats, and emphasizing the need to extend existing footprinting approaches, for example to calculate “nitrogen food-prints”. Perhaps the strongest message to the public is that there are substantial health benefits to be gained by keeping consumption of animal products within recommended dietary limits. It is an opportunity to improve personal health and protect the environment at the same time [23.5, 24.5, 26.3].

Figure 1  
**Estimated trend of anthropogenic reactive nitrogen inputs to the European Union (EU-27) [5.1]. (1 Tg equals 1 million tons)**

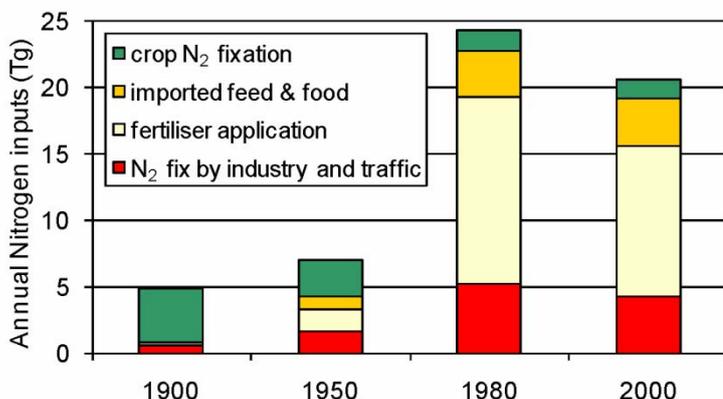


Figure 2  
**Simplified view of the N-cascade, highlighting the capture of atmospheric N<sub>2</sub> to form N<sub>r</sub> by the Haber-Bosch process — the largest source of N<sub>r</sub> in Europe.** The main pollutant forms of N<sub>r</sub> (orange boxes) and five environmental concerns (blue boxes) are summarized. Blue arrows represent intended anthropogenic N<sub>r</sub> flows; all the other arrows are unintended flows [1.2]. For fuller description including other N<sub>r</sub> sources, see [5.2].

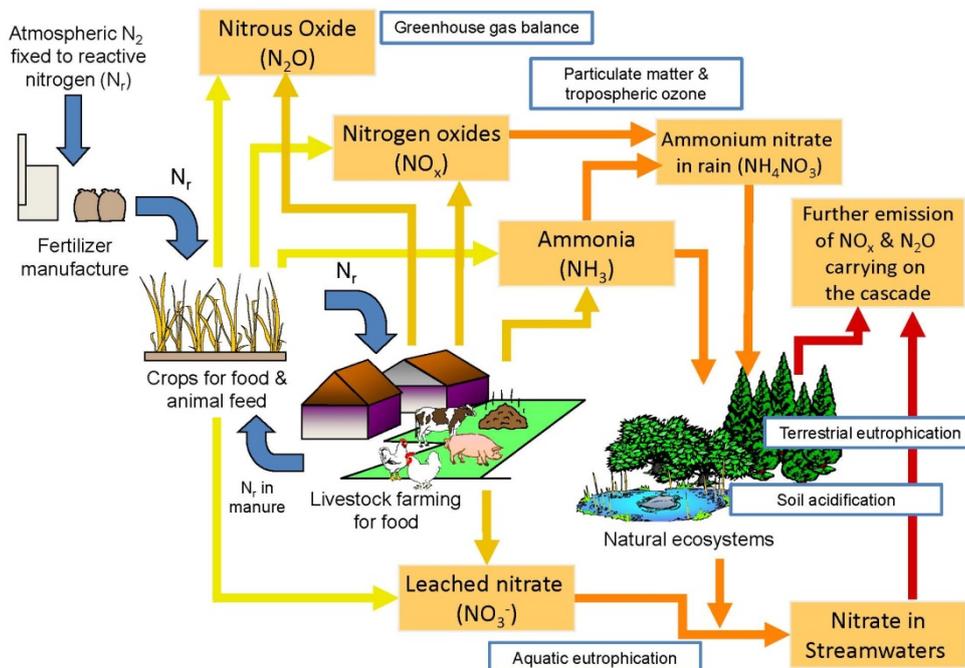


Figure 3  
**Simplified comparison of the European nitrogen cycle (EU-27) between 1900 and 2000.** Blue arrows show intended anthropogenic nitrogen flows; orange arrows show unintended nitrogen flows; green arrows represent the nearly closed nitrogen cycle of natural terrestrial systems [16.4 and 16 supplementary material].

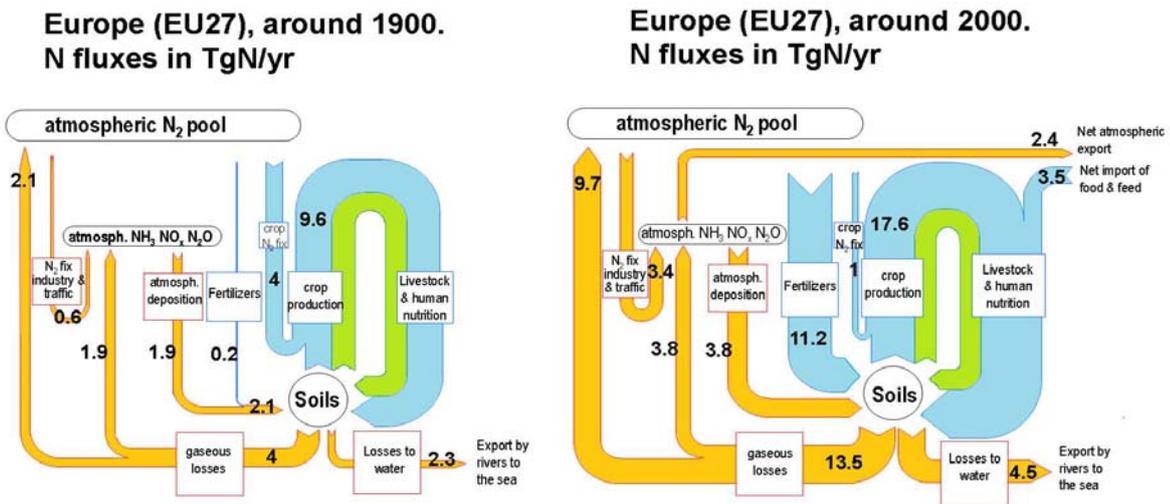


Figure 4  
**Estimated trends in European reactive nitrogen emissions between 1900 and 2000 (EU-27) [5.1].**

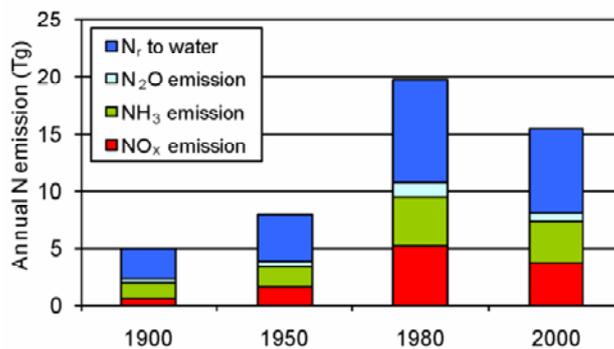
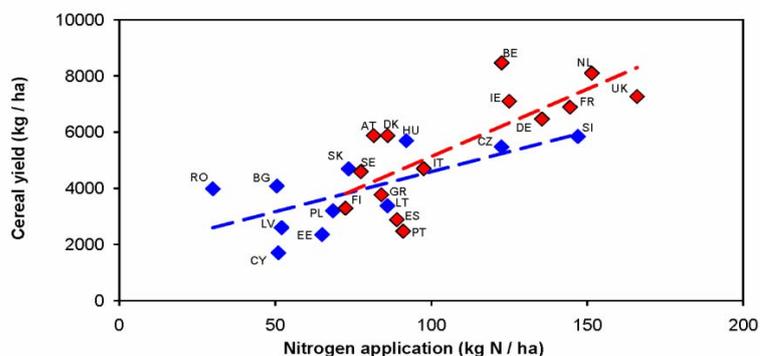


Figure 5

**Variation of nitrogen fertilizer use on winter wheat across the European Union (EU-15: red, EU-12: blue) around the year 2000.** The variation indicates that there is substantial scope to increase performance and reduce environmental effects [3.2].



*Note:* AT = Austria; BE = Belgium; BG = Bulgaria; CY = Cyprus; CZ = Czech Republic; DE = Germany; DK = Denmark; EE = Estonia; ES = Spain; FI = Finland; FR = France; GR = Greece; HU = Hungary; IE = Ireland; IT = Italy; LT = Lithuania; LV = Latvia; NL = Netherlands; PL = Poland; PT = Portugal; RO = Romania; SE = Sweden; SI = Slovenia; SK = Slovakia; and UK = United Kingdom.

Figure 6

**Range of  $N_r$  recovery efficiencies in farm animal production in Europe (kg N in edible weight per kg N in animal feed)** [3.4, 10.4, 26.3], see also supplementary material for chapter 3. A higher recovery efficiency is indicative of a smaller nitrogen footprint. Accounting for the full chain from fertilizer application to  $N_r$  in edible produce, overall nitrogen use efficiency in animal production for the EU-27 is around 15%–17% [3, 10, supplementary material]. While intensive systems tend to have a higher  $N_r$  recovery, they also tend to have larger  $N_r$  losses per ha unless efforts are taken to reduce emissions [10.4].

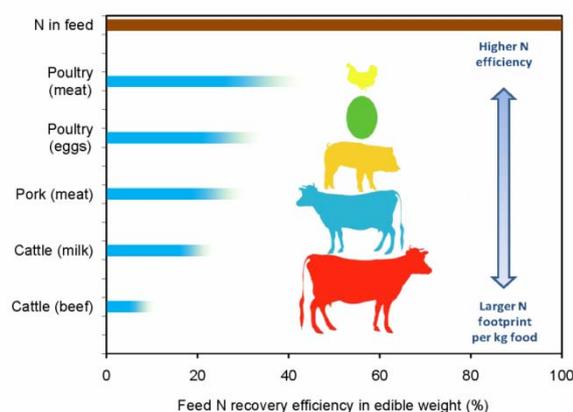


Figure 7

**Summary of the five key societal threats of excess reactive nitrogen, drawn in analogy to the “elements” of classical Greek cosmology.** The main chemical forms associated with each threat are shown [5.4]. *Photo sources:* Shutterstock.com and garysmithphotography.co.uk.

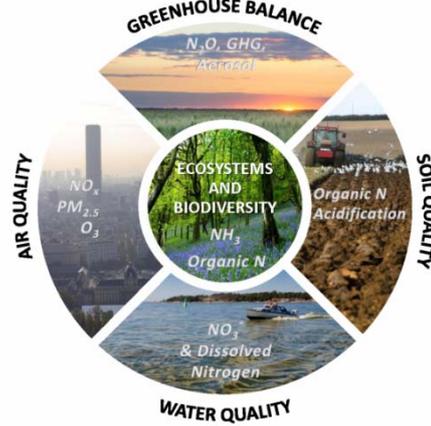


Figure 8

**Estimated environmental costs due to reactive nitrogen emissions to air and to water in the EU-27 [22.6].**

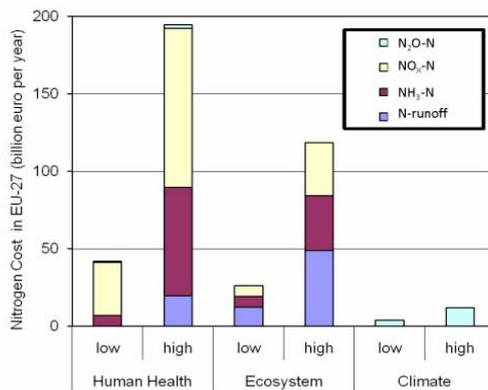


Figure 9  
**Nitrogen emission scenarios for the EU-27, following the Representative Concentration Pathways (RCP) for three different storylines on radiative forcing.** The storyline names indicate the radiative forcing exerted in 2100, between 2.6 (R26), 4.5 (R45) and 8.5 (R85) W per m<sup>2</sup> [24.6].

