ECN
Energy research Centre of the Netherlands

The European Nitrogen Assessment

Summary for policy makers

Lead authors: **Mark A. Sutton and Hans van Grinsven**

Contributing authors: **Gilles Billen, Albert Bleeker, Alexander F. Bouwman, Keith Bull, Jan Willem Erisman, Peringe Grennfelt, Bruna Grizzetti, Clare M. Howard, Oene Oenema, Till Spranger and Wilfried Winiwarter**

Chapter of the book "The European Nitrogen Assessment: Sources, Effects and Policy Perspectives

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Main messages

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 di-nitrogen (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.

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 inter-related, 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.

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 Assessment identifies a package of 7 key actions for overall management of the European nitrogen cycle. These key actions relate to: Agriculture (3 actions), Transport and Industry (1 action), Waste water treatment (1 action) and Societal consumption patterns (2 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.

International cooperation and communication

- Tackling N_r necessitates international cooperation. There are various options to implement multi-lateral 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.

1. 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 di-nitrogen (N_2), it is unreactive and cannot be assimilated by most organisms. By contrast there are many reactive nitrogen (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].[1]

2. With 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 ammonia (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 nitrogen oxides (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].

2. 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 (ENA) 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 (UNECE). 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 multi-lateral environmental agreements, including the Global Partnership on Nutrient Management facilitated by 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].

3. Disruption of the European nitrogen cycle

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 tonnes) 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 SPM.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.

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

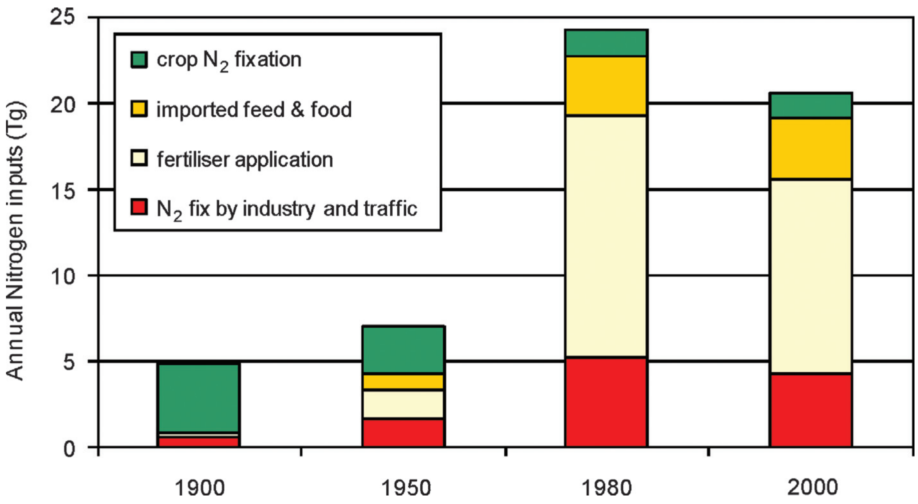

Figure SPM.1 Estimated trend of anthropogenic reactive nitrogen inputs to the European Union (EU-27) [5.1] (1 Tg equals 1 million tonnes).

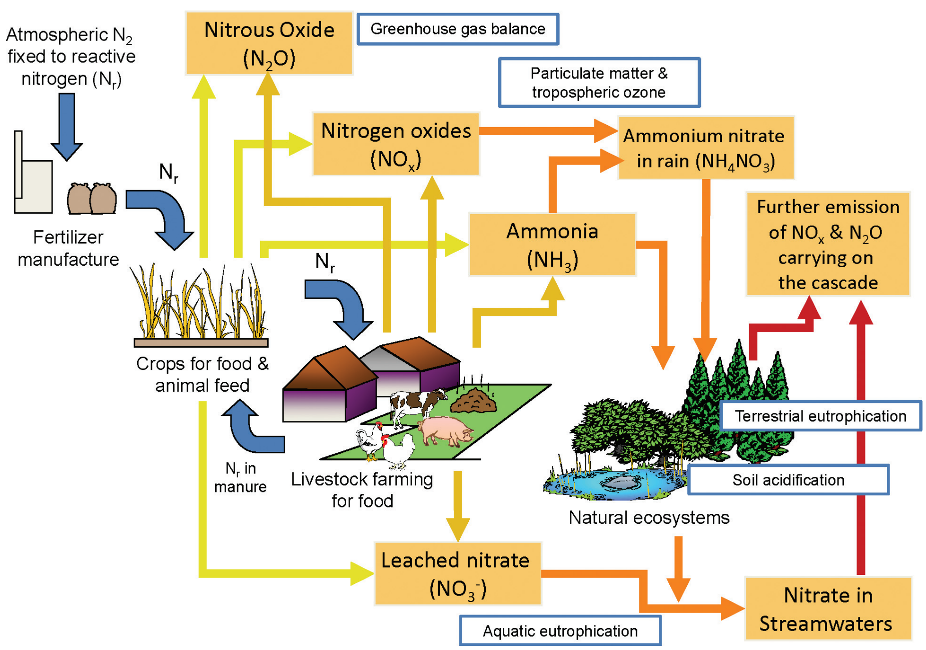

Figure SPM.2 Simplified view of the N-cascade, highlighting the capture of atmospheric di-nitrogen (N_2) to form reactive nitrogen (N_r) by the Haber–Bosch process – the largest source of N_r in Europe. The main pollutant forms of N_r (orange boxes) and five environmental concerns (blue boxes) are summarized. Blue arrows represent intended anthropogenic N_r flows; all the other arrows are unintended flows [1.2]. For fuller description including other N_r sources, see [5.2].

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 SPM.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 from combustion sources, 3.5 Tg per year from food and feed import and 1 Tg per year by crop biological N-fixation (BNF) (Figure SPM.3).

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 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 SPM.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 SPM.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].

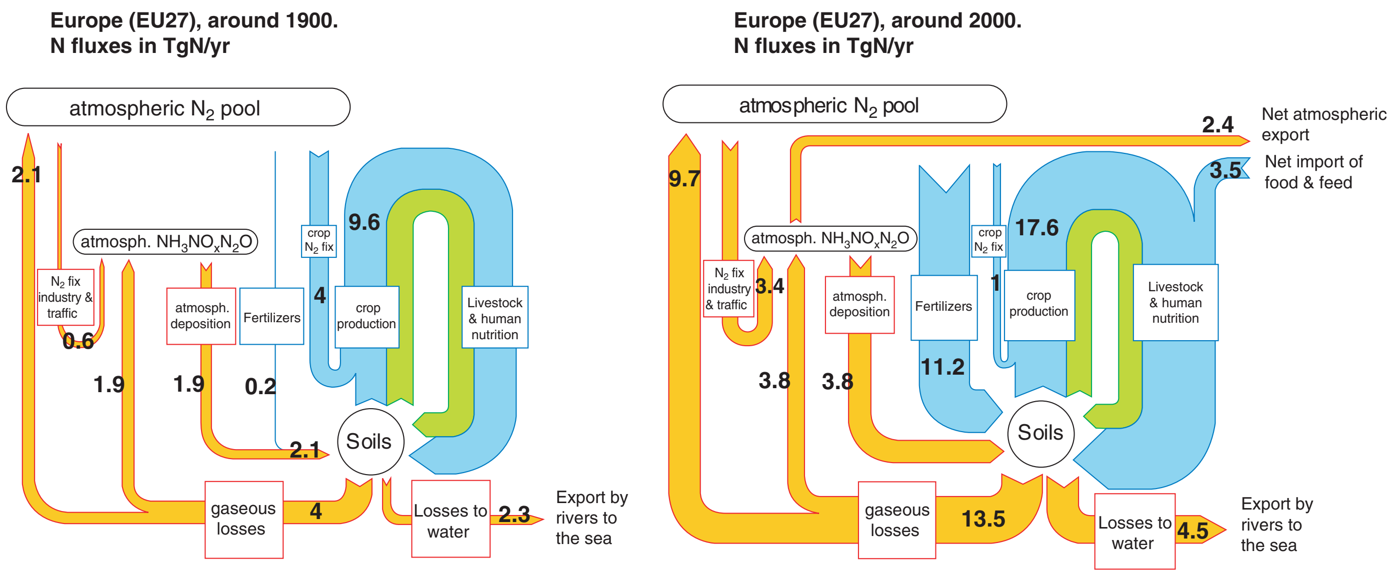

Figure SPM.3 Simplified comparison of the European nitrogen cycle (EU-27) between 1900 and 2000. Blue arrows show intended anthropogenic nitrogen flows; orange arrows show unintended nitrogen flows; green arrows represent the nearly closed nitrogen cycle of natural terrestrial systems [16.4 and 16 supplementary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

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 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 improved perspective on the major drivers and the most effective control options.

19. Figure SPM.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].

21. These major intended alterations in N_r flows cause many additional unintended N_r flows (Figure SPM.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 have 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 byproduct of denitrification.

Achievements and limitations of current policies

23. Peak production of N_r in Europe occurred in the 1980s, which was linked to agricultural over-production and lack of emissions regulations. Since that time, the introduction of policies and other changes affecting agriculture (including the Common Agricultural Policy, Nitrates Directive and the restructuring of Eastern Europe after 1989), as well as stringent emission controls, e.g., for large combustion plants (EC Large Combustion Plants Directive, UNECE Sofia Protocol and Gothenburg Protocol, etc.) and the EURO standards for

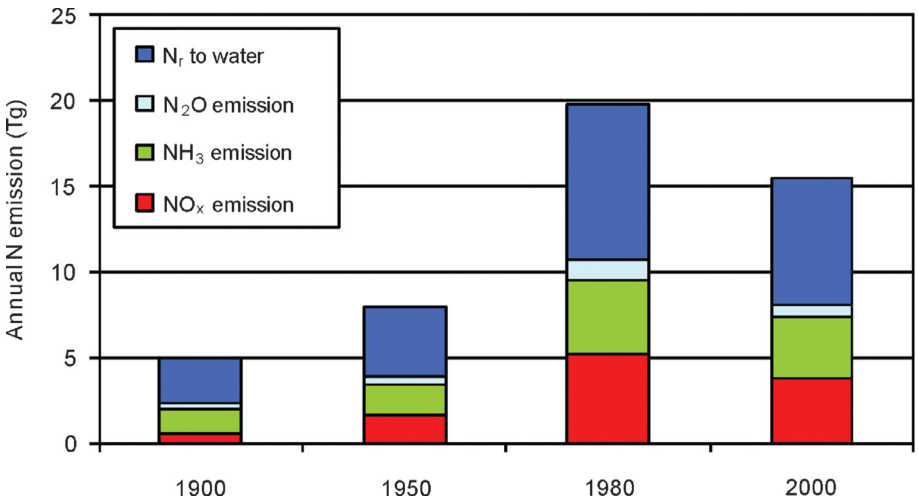

Figure SPM.4 Estimated trends in European reactive nitrogen emissions between 1900 and 2000 (EU-27) [5.1].

road transport vehicles, have led to decreases in the emissions (Figure SPM.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 SPM.1). This small overall reduction is reflected in the trends in NH_3 emissions (Figure SPM.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., Nitrates Directive, Oslo and Paris Commission for the protection of the North East Atlantic, UNECE Gothenburg Protocol and 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 emisssions [9.2].

4. The benefits and efficiency of nitrogen in agriculture

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 tonne per ha of cereal annually. With typical additional inputs from biological nitrogen fixation (BNF), it can produce about 4–6 tonne per ha, and with addition of chemical fertilizer about 8–10 tonne 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 (kg crop production per kg applied 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 SPM.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].

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 liveweight and 5%–40% in the edible weight (Figure SPM.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

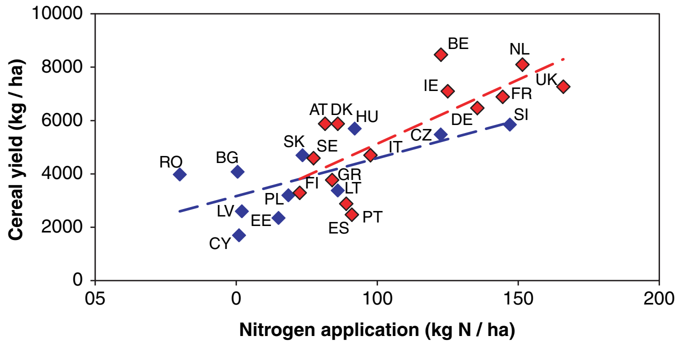

Figure SPM.5 Variation of nitrogen fertilizer use on winter wheat across the European Union (EU 15: blue, EU 12: red) around the year 2000. The variation indicates that there is substantial scope to increase performance and reduce environmental effects [3.2].

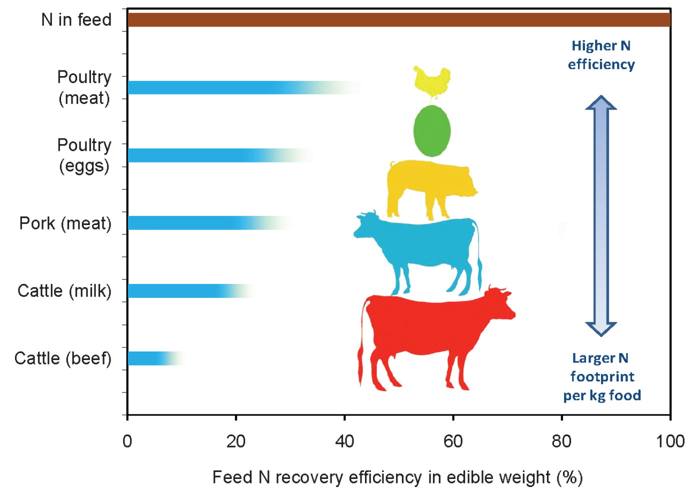

Figure SPM.6 Range of N_r recovery efficiencies in farm animal production in Europe (kg N in edible weight per kg N in animal feed) [3.4, 10.4, 26.3], see also supplementary material for Chapter 3. A higher recovery efficiency is indicative of a smaller nitrogen footprint. Accounting for the full chain 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].

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].

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 SPM.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 SPM.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.

5. 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 SPM.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].

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 mg N_r per litre, above which waterbodies 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 EU-15 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].

Nitrogen as a threat to European air quality

38. Air pollution by nitrogen oxides (NO_x) and ammonia (NH_3) causes formation of secondary particulate matter (PM), while emissions of NO_x also increase levels of nitrogen dioxide

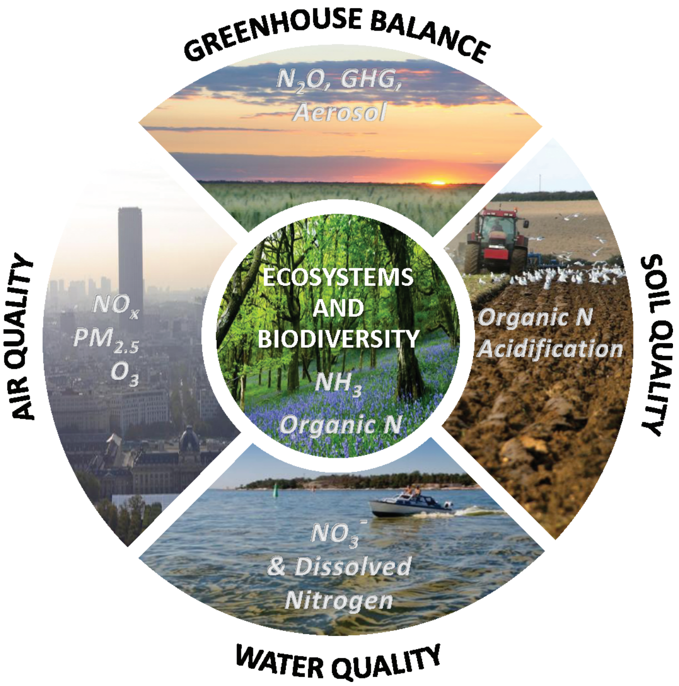

Figure SPM.7 Summary of the five key societal threats of excess reactive nitrogen, drawn in analogy to the 'elements' of classical Greek cosmology. The main chemical forms associated with each threat are shown [5.4]. *Photo sources*: Shutterstock.com and garysmithphotography.co.uk.

(NO_2) and tropospheric ozone (O_3). All of these are causes for respiratory problems and cancers for humans, while ozone causes 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 300–400 thousand 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].

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 nitrous oxide (N_2O) and tropospheric ozone, which are both greenhouse gases. The main cooling effects are atmospheric N_r deposition presently increasing 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 mW per 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 N and C cycles to mitigate greenhouse gas emissions through improved nitrogen use efficiency [19.6].

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].

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 on 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 peatlands 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 is increasingly dominating soil acidification effects over large parts of Europe [20.3, 21.4].

6. The economics of nitrogen in the environment

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 EU-27 (Figure SPM.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].

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].

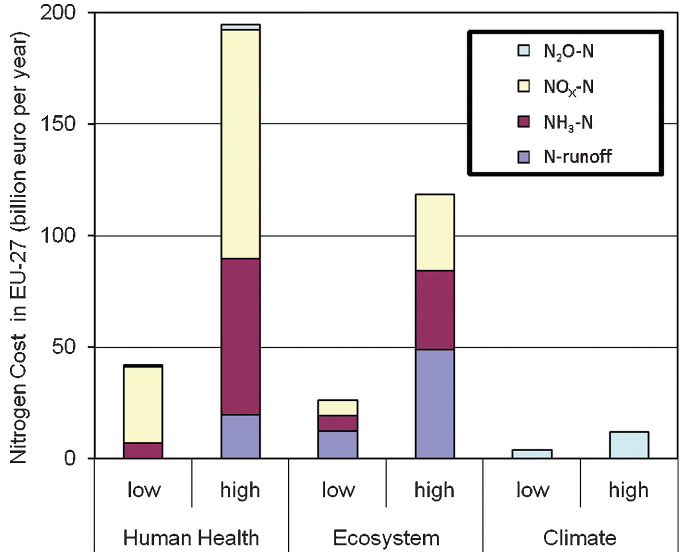

Figure SPM.8 Estimated environmental costs due to reactive nitrogen emissions to air and to water in the EU-27 [22.6].

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 SPM.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 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 SPM.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 emission were to occur.

56. Estimated costs of technical measures to reduce emissions of NO_x, NH_3 and N_2O are available in the IIASA 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.[2]

[2] United Nations Economic Commission for Europe (2010), Options for Revising the 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone: Reactive Nitrogen (ECE/EB.AIR/WG.5/2010/13).

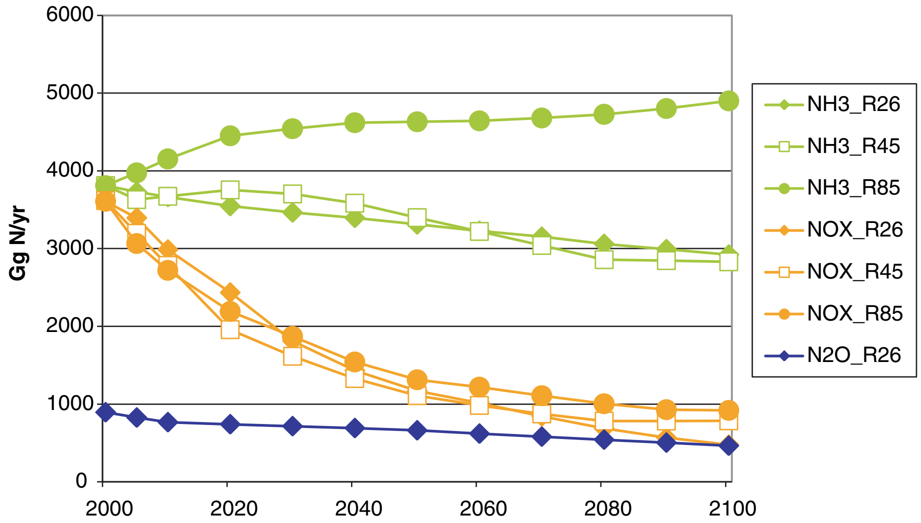

Figure SPM.9 Nitrogen emission scenarios for the EU-27, following the Representative Concentration Pathways (RCP) for three different storylines on radiative forcing. The storyline names indicate the radiative forcing exerted in 2100, between 2.6 (R26), 4.5 (R45) and 8.5 (R85) W per m^2 [24.6].

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 SPM.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].

7. The potential for integrated approaches to manage nitrogen

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 (para. 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.

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].

Waste water treatment

(5) **Recycling nitrogen (and phosphorus) from waste water 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 waste waters, 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 SPM.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.

8. Challenges for society and policy

Nitrogen in multilateral environmental agreements and future research

64. International treaties, such as Multilateral Environmental Agreements (MEAs), 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 MEAs should be further developed, including the Global Partnership on Nutrient Management facilitated by the United Nations Environment Programme, the Task Force on Reactive Nitrogen of the UNECE Convention on Long-range Transboundary Air Pollution and the links with other UNECE Conventions. There is the opportunity for the UNECE Committee on Environmental Policy to develop nitrogen management links between UNECE Conventions, while the European Union 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.

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 life-style and diet having a major role to play [26.3].

69. In Europe, different scenarios and models suggest a strong 75% decline of NO_x, while emissions of NH_3 and N_2O display an uncertain future outlook (Figure SPM.9) [24.6]. The constraints that have so far limited reductions in 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 of European 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 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 foodprints'. 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].