

Managing the European Nitrogen Problem

A proposed strategy for integration of European Research
on the multiple effects of reactive nitrogen



This document has been prepared by the co-chairs of the UNECE/CLRTAP Task Force on Reactive Nitrogen (TFRN) in collaboration with the chairs of the Nitrogen in Europe (NinE) programme of the European Science Foundation, the chairs of COST Action 729, the Scientific Steering and External Advisory Groups of the EU NitroEurope Integrated Project and the European Centre of the International Nitrogen Initiative (INI).

Report authors: M.A. Sutton, O. Oenema, J.W. Erisman, P. Grennfelt, C. Beier, G. Billen, A. Bleeker, C. Britton, K. Butterbach-Bahl, P. Cellier, H. van Grinsven, B. Grizzetti, E. Nemitz, S. Reis, U. Skiba, M. Voss, W. de Vries and S. Zechmeister-Boltenstern.



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- Globally, reactive nitrogen (Nr)¹ production has more than doubled during the last century as a result of human activity. The additional Nr has been essential to increase both global food production and the fraction of animal products in human diets. Use of Nr is thus of central importance for world food security. At the same time, the acceleration of Nr production, combined with a low efficiency of Nr use, has led to a complex web of environmental impacts (*paras 5-10*).
- The natural nitrogen cycle is generally tuned to operate with Nr in short supply. Under these conditions Nr is recycled tightly within ecosystems. However, when Nr is supplied in excess, it is easily lost to the wider environment, generating a cascade of different Nr forms and effects, before eventually being denitrified to di-nitrogen (N₂).
- The web of adverse Nr impacts crosses all environmental spheres, with major consequences for the functioning of ecosystems, leading to effects on greenhouse balance, air quality and atmospheric chemistry, biodiversity, soil quality and water quality in both freshwater and marine systems (*paras. 11-14*).
- Understanding the cause - effect relationships and developing options to minimize the adverse effects represent major challenges for the European Research Area. Although progress is being made in understanding the individual Nr threats, it is becoming increasingly clear that a holistic research strategy is needed (*paras. 15-18*). Such a **'full nitrogen approach'** is important because of the many synergies and antagonisms: fixing one form of Nr pollution often creates another.

Globally, reactive nitrogen (Nr) production has more than doubled during the last century as a result of human activity

¹ The term reactive nitrogen (Nr) represents all biologically active, photochemically reactive, and radiatively active N compounds in the atmosphere and biosphere, including inorganic reduced N compounds (e.g., NH₃, NH₄⁺), inorganic oxidized N compounds (e.g., NO_x, HNO₃, N₂O, NO₃), and organic N compounds (e.g., urea, amines, proteins).





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- The need for an integrated response to Nr is now beginning to be recognized internationally (*paras. 19-32*).
 - UNEP has identified problems related to Nr as an emerging global environmental issue and recently established the Global Partnership on Nutrient Management (GPNM).
 - The UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP) has recently established the Task Force on Reactive Nitrogen (TFRN) to make the links between the different airborne and other Nr threats.
 - The Nitrogen in Europe (NinE) programme of the European Science Foundation has initiated the European Nitrogen Assessment (ENA), analyzing the current status of science and policy frameworks, and prioritizing the future challenges.
- These moves are in line with the emerging request for integrated approaches in European Union Directives and the international conventions (Framework Convention on Climate Change, CLRTAP, Convention on Biological Diversity, Marine Conventions etc.).
- The fundamental importance, cross-cutting implications and complexity of the Nr problem, combined with the emerging needs of international policy development, requires a major directed research effort on the European nitrogen problem.
- The research should be targeted to underpin the needs of EU legislation and the international conventions, with an emphasis to understand the linkages. This will allow Europe to develop integrated strategies that balance the different benefits and threats of excess Nr and which may serve as a guiding model for other regions of the world.
- A European cross-programme research activity on Nr must be a priority for the EU Seventh Framework Programme (FP7). This should focus on drawing together European expertise on the different Nr threats, benefits and their management. It is proposed to implement this through a cluster of Collaborative Projects that would support the development of more integrated solutions to the nitrogen problem (*paras. 33-38*).
- As a focus for discussion among the EU Member States and other parties to the relevant international conventions, we here outline a cluster of seven collaborative projects that link the key threats to greenhouse balance, atmospheric chemistry, biodiversity, water quality and soil quality, with the development of integrated approaches for sustainable Nr management while bearing in mind the challenges of future food and energy security.

- Each of the major nitrogen threats and mitigation options should be considered, with the cluster supported by coordination measures to maximize synergies (*paras. 39-47*):

- **Project Concept 1: Integrating the biospheric and atmospheric effects of nitrogen on global radiative balance.** (In support of FCCC and CLRTAP.) (Large collaborative project: €8M, 2011-2014.)
- **Project Concept 2: Developing new approaches to quantify and minimize the impacts of atmospheric nitrogen deposition on European habitats.** (In support of CBD, CLRTAP, Habitats Directive, Water Framework Directive and EU policies on soils and eutrophication). (Medium-sized collaborative project €5M, 2011-2014.)
- **Project Concept 3: Quantifying the multiple roles of atmospheric chemistry on European impacts of reactive nitrogen.** (In support of the CLRTAP, FCCC and CBD.) (Large collaborative project: €6M, 2012-2015.)
- **Project Concept 4: Integrating the role of nitrogen in catchment, coastal and marine eutrophication.** (In support of Nitrates Directive, WFD, Water and Marine Conventions.) (Large collaborative project: €8M, 2012-2015.)
- **Project Concept 5: Integrating the consequences of EU and international policies on nitrogen-related impacts in European landscapes as a basis to develop locally optimized solutions.** (In support of FCCC, CLRTAP, CBD, WFD, CAP and EU policies on soils and eutrophication.) (Large collaborative project ca. €9M, 2013-2016.)
- **Project Concept 6: Understanding nitrogen flows and emissions in the food production and consumption chain of Europe.** (In support of FCCC, CLRTAP, CBD, WFD, CAP and EU policies on soils and eutrophication.) (Large collaborative project ca. €5M, 2012-2015.)
- **Project Concept 7: Managing the European nitrogen cycle to increase nitrogen use efficiency by 50%.** (In support of FCCC, CLRTAP, CBD, WFD, CAP and EU policies on soils and eutrophication.) (Large collaborative project ca. €8M, 2013-2016.)

- The overall outcome of such a cross-cutting programme should be an improved understanding of how different parts of the nitrogen cycle fit together, together with the consideration of key mitigation options, thereby underpinning the development of future European and international nitrogen management strategies.
- The aim of this document is to stimulate debate among European Member States, other parties to the international conventions and the scientific community. Feedback is requested on six key questions to help tune the research strategy (*paras. 1-4*).



Photograph - Shutterstock

Nitrogen threatens the biodiversity of many European habitats, leading to losses of sensitive species such as the insectivorous plant sundew

The aim of this document is to stimulate debate among European Member States, other parties to the international conventions and the scientific community

FOSTERING DEBATE ON THE FUTURE NITROGEN RESEARCH NEEDS

1. This document provides a starting point for discussion among EU Member States and other parties to the international conventions on the priorities for future research into the multiple effects of reactive nitrogen in the environment.
 2. In particular, we invite your comments on the following questions:
 - a. Do you agree that a more joined-up approach to European nitrogen research is needed and will have benefits for future policy development?
 - b. Do you consider that the proposal made in this document is appropriately ambitious and yet outlines an achievable level of communication and integration between scientific communities?
 - c. What are your views on the relative priorities between the five key societal threats of excess nitrogen (global radiative balance, air quality, water quality, biodiversity and soil quality) and the need to balance these against the societal benefits, especially for global food and energy security?
 - d. How much should the programme give particular attention to the challenges related to managing Nr in the food chain as the largest global source of Nr, compared with other sources such as energy production, industry and transport?
 - e. To what extent should the programme address the global scale, given the importance of EU policies for global Nr use and the associated threats, and the potential for Europe to provide a guiding model for other regions worldwide?
 - f. Are there other key scientific or policy issues related to nitrogen that are currently missing or poorly represented in the present document?
3. This document is being distributed to scientists, policy-makers and other stakeholders. We encourage you to circulate it to relevant officials responsible for European and national research programming. It is most important that you give them your views. In addition, we encourage you to send written comments to the Office of the UNECE/CLRTAP Task Force on Reactive Nitrogen (TFRN):
email: tfrn@ceh.ac.uk
www.clrtap-tfrn.org/european-research-strategy
 4. Responses received at the TFRN Office before **17:00 on 01 October 2009** will be synthesized to develop the next stage of the nitrogen research strategy. Comments received after this date will be useful for further refinement as the strategy develops.

Ammonia flux measurement instrumentation at a NitroEurope fieldsite

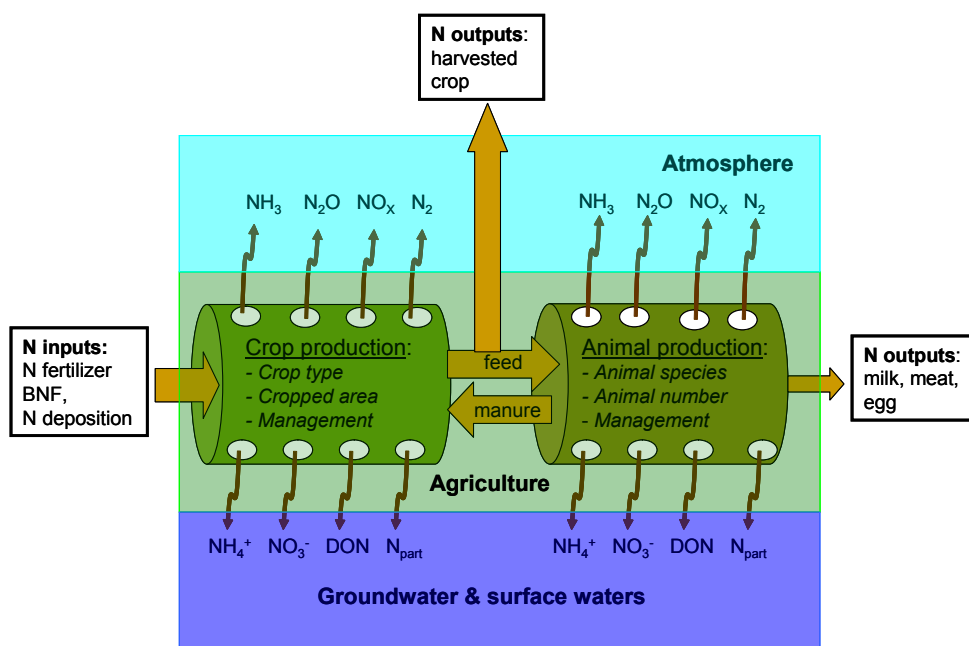


5. Excess reactive nitrogen represents a major environmental threat that is only now beginning to be fully appreciated. At a global level, humans have more than doubled the production and cycling of reactive nitrogen, leading to a plethora of impacts that interact across all global spheres: atmosphere, biosphere, hydrosphere and geosphere.
6. Nitrogen occurs in many different forms and these have different functions, reactivity and mobility. The most abundant form of nitrogen on earth is the least reactive species: di-nitrogen (N_2). Reactive nitrogen (Nr) represents all biologically active, photochemically reactive and radiatively active N compounds, including inorganic reduced forms of N (e.g., NH_3 , NH_4^+), inorganic oxidized forms (e.g., NO_x , HNO_3 , N_2O , NO_3^-) and organic compounds (e.g., urea, amines, proteins).
7. In natural systems the supply of reactive nitrogen forms is limited. The main natural sources of Nr are bacteria that are able to fix N_2 from the air, either in symbiosis with (leguminous) plants or as free-living bacteria in soil.
8. Compared with the natural sources, human activities have massively increased the rate of global nitrogen fixation. Intentional Nr fixation includes the manufacture of fertilizers and other nitrogen compounds, while unintentional fixation includes NO_x emissions to the atmosphere from fossil fuel and biomass combustion.
9. Currently, the largest source of new Nr is the synthesis of ammonia (NH_3) through the Haber-Bosch process. The main Nr product is synthetic fertilizer, which supplies food to support around 50% of the human population. In parallel, there has been a substantial increase in biological N-fixation from expanding areas of leguminous crops (e.g., soybean, peas and clover). Reactive nitrogen is thus of fundamental importance to global food security.
10. Much of the new anthropogenic Nr produced has a low efficiency of use. For example, NO_x is a by-product of combustion processes, which is lost to the atmosphere without being used. The global food chain has a mean N use efficiency of 14% for plant products and 4% for animal products (meat, dairy, egg). The remainder is dissipated into the environment, mainly in the forms of NH_3 , N_2O and N_2 to air, and in the forms of NO_3^- and NH_4^+ to groundwater and surface waters.



11. The increased Nr production and losses have contributed to a substantial enrichment of the environment with Nr in Europe and many other parts of the world. Excess Nr in the environment represents a major threat to human health and the biosphere. Furthermore, one molecule of nitrogen can, in principle, contribute in time to several effects – the so-called ‘nitrogen cascade’ effect. The consequences of excess Nr cut across all major global change issues:
- **Modification of the global greenhouse gas budget**, e.g., nitrous oxide (N₂O), methane (CH₄) and carbon dioxide (CO₂) fluxes, relevant to the FCCC and new EU climate targets.²
 - **Adverse effects on terrestrial ecosystems and their biodiversity**, with a loss of the most sensitive species and habitats, especially relevant to European commitments under Natura 2000, TSAP, CBD and CLRTAP.
 - **Formation of atmospheric particulate matter**, especially as ammonium, nitrates and many organic nitrogen forms (e.g., PM₁₀, PM_{2.5}), with consequences for human health, visibility and global radiative balance, relevant, for example, to the TSAP, CLRTAP and the FCCC.
 - **Formation of nitrogen oxides and tropospheric ozone**, and loss of stratospheric ozone, with consequences for human health, agricultural production and forest growth and global radiative balance, relevant, for example, to the CLRTAP, FCCC and TSAP.
 - **Effects on water quality in freshwater systems**, leading to changes in biodiversity and drinking water quality, relevant, for example, to the Nitrates Directive, Urban Waste Water Directive, Water Framework Directive and CLRTAP.
 - **Effects on water quality in marine systems**, both through atmospheric deposition and riverine inputs of Nr, leading to oceanic algal blooms, anoxia in coastal systems, associated with die-offs of benthic animals, adverse effects on fish stocks, and problems for bathing water quality, relevant, for example, to the Bathing Water Directive and Marine Conventions (HELCOM, OSPAR, Barcelona Convention).
- **Effects on soil quality**, especially through soil acidification, nutrient imbalances, and changes in biodiversity, linking to soil carbon stocks, relevant to the EU Soil Thematic Strategy, the CLRTAP and the FCCC.
12. Until now, specialist scientists and policy-makers have largely considered these different facets of increased Nr in Europe as separated issues. What is missing is an integrated approach, both in relation to the assessment of the biogeochemical and ecological interactions, and in relation to emissions abatement strategies. Society needs to find ways to balance the benefits of Nr use against the interacting web of adverse environmental effects. This is essential if Europe is to optimize its ‘nitrogen economy’ over the next decades.
13. At the same time, it is recognized that the great complexity of the nitrogen cycle clearly hinders public recognition and understanding of the Nr problem. New ways to distil this complexity must be found as a basis to improve public understanding.
14. *Combining the above mentioned issues we can identify a major ‘Nitrogen Challenge’: to develop and communicate a scientifically sound strategy to manage Europe’s nitrogen cycle, maximizing the net economic and societal benefits of Nr use while minimizing the overall environmental burden of Nr.*

² The following acronyms are used: FCCC: United Nations Framework Convention on Climate Change; CLRTAP: United Nations Economic Commission for Europe Convention on Long-range Transboundary Air Pollution; CBD, United Nations Convention on Biological Diversity; TSAP, Thematic Strategy on Air Pollution; WFD, Water Framework Directive; HELCOM, Helsinki Commission, Baltic Marine Environment Protection Commission; OSPAR, Oslo and Paris Commission for the Protection of the Marine Environment of the North East Atlantic; Barcelona Convention, for the Protection of the Marine Environment and the Coastal Region of the Mediterranean.



Oenema et al., 2009

Agriculture is a major user of reactive nitrogen (Nr) with many loss pathways occurring in both crop and animal production systems. This graphic visualizes each system as a 'leaky pipe' with many holes through which Nr can be lost. Because of the many pathways, closing one leak can simply increase another. Mitigation strategies must therefore develop a holistic view, which also requires understanding of the links with other source sectors (transport, energy etc) and biospheric compartments (forest, semi-natural land, open oceans etc).

15. Addressing this challenge urgently needs the application of new scientific tools to direct and integrate the European scientific effort. At the same time, improved links need to be forged between the different nitrogen-related policy areas and stakeholders. Specifically, the future research effort needs to:
- *understand the key biogeochemical processes* of the nitrogen cycle, providing a holistic understanding of the interacting environmental threats and benefits,
 - *measure the pools and fluxes* of nitrogen across Europe and through time, to provide a baseline position and understand the consequences of existing policies,
 - *quantify the interactions* and relationships between different Nr compounds, fluxes and issues, scaling up to landscape, regional and European scales, as a basis to identify the synergies and antagonisms in current and future policies,
 - *develop effective measures for increasing nitrogen use efficiency* so as to minimize Nr input needed to allow maximum utilization of resources, especially in European farming systems,
 - *develop integrated management strategies* that increase recycling of Nr, decrease leakages of Nr, and manage denitrification to N_2 ,
 - *communicate between experts on different environmental media* (air, land, water) and between analysts in the different policy areas, in order to develop a more integrated approach to mitigating Europe's nitrogen problem,
 - *understand the effects of human dietary choices and consumption patterns* on Nr use and emissions to the environment,
 - *explore better ways of comparing and balancing* the different environmental impacts of Nr, providing a foundation to inform high level decision-makers,
 - *distil the complexity of nitrogen into easily understandable messages* for the wider European public, thereby raising awareness and the motivation for solid actions.



Photograph - Shutterstock

16. These different aspects of the 'Nitrogen Challenge' set the perspective needed for the European research agenda over the next decade.
17. It should be noted that Europe is now in a strong position to develop an integrated approach to nitrogen management, and is providing international leadership on this issue. In particular, the foundations are being developed through the NitroEurope Integrated Project, the Nitrogen in Europe (NinE) programme of ESF, the COST Action 729, the European Centre of the International Nitrogen Initiative (INI) and the newly established Task Force on Reactive Nitrogen under the CLRTAP³.
18. In the following sections, we summarize current European research activities dealing with nitrogen and show how these are starting to develop the necessary integration. We then develop the strategy needed to address the research needs under FP7. *Overall, the aim is for a more joined-up delivery of nitrogen-related research in FP7, which is able to meet the needs of EC policy development and the relevant international conventions.*

³NitroEurope IP: "The nitrogen cycle and its influence on the European greenhouse gas balance" (www.nitroeuropa.eu) (Framework Programme 6); Nitrogen in Europe (NinE): a Research Networking Programme of the European Science Foundation, ESF (<http://www.nine-esf.org/>); COST: European Cooperation in the Field of Scientific and Technical Research; COST 729: Assessing and Managing Nitrogen Fluxes in the Atmosphere Biosphere System in Europe (<http://cost729.ceh.ac.uk/>); European Centre of the INI (<http://www.ini-europe.org/>). The Task Force on Reactive Nitrogen (TFRN) is a new body reporting to the Working Group on Strategies and Review (WGSR) of the CLRTAP (www.uncece.org/env/lrtap/).

19. The multiple benefits and threats related to reactive nitrogen make it essential that European research should contribute the understanding to underpin future policy development. The Appendix to this document gives a summary of current projects that link to different nitrogen-related policy areas. However, in many cases the researchers have only a limited connection with the policy issues. There is great potential for improved policy awareness to focus such detailed studies more effectively in relation to the key unknowns.
20. Reactive nitrogen is relevant for many international conventions and European directives as listed in Box 1. The wide range and large number of these policy instruments highlight the huge challenge faced in developing a more integrated approach to managing nitrogen in Europe. In particular, much better tools and communication are needed to link the different environmental threats, their assessment and the development of integrated policy responses.
21. In several of the conventions and directives listed, the links to other problems are already explicitly recognized. For example, in the Strategies of OSPAR, the links are explicitly stated with existing Community legislation relevant to nitrogen (www.ospar.org, Sections I.3, II. 5). However, the linkages between many directives and international conventions could be further optimized.
22. Under the UNECE Convention on Long-range Transboundary Air Pollution, there is already substantial experience in linking the multiple effects of different air pollutants. The Gothenburg Protocol represents a key example, as it links each of acidification, eutrophication and ground level ozone.
23. During ongoing review of the CLRTAP in 2007 (e.g., <http://asta.ivl.se/Saltsjobaden3>) it was concluded that there are multiple impacts of nitrogen on transboundary air pollution, with substantial synergies and trade-offs between different N-forms and environmental problems.
24. In taking account of these conclusions, the Executive Body of the CLRTAP in December 2007 (www.unece.org/env/eb/welcome.25.html) established a new Task Force on Reactive Nitrogen (TFRN). This Task Force provides a platform for addressing the links between the transboundary air pollution and other impacts of Nr.
25. In parallel, nitrogen is appearing more clearly on the agenda of other international activities. For example, UNEP has recently established the Global Partnership on Nutrient Management (GPNM), which has identified problems related to Nr as an emerging global environmental issue.
26. Further, there are initiatives to strengthen the long-term competitiveness of the European food chain in relation to EU sustainability objectives, including aims to develop resource efficiency and social responsibility, with clear potential for better management of the European nitrogen cycle.
27. All these developments are in line with recent EU thinking on the need for integrated approaches. The basic principles were identified under the IPPC Directive, have been expanded under the TSAP, WFD etc., and are consistent with underlying goals of the EU Sustainable Development Strategy.

The multiple benefits and threats related to reactive nitrogen make it essential that European research should contribute the understanding to underpin future policy development

Box 1: The multiple roles of reactive nitrogen in international agreements and European directives.

■ United Nations Millennium Development Goals.

Nitrogen issue: In particular Goal 1 “to eradicate extreme hunger and poverty” and Goal 7 “to ensure environmental sustainability”.

■ United Nations Framework Convention on Climate Change, and the Kyoto Protocol.

Nitrogen issue: N as a driver of changes in the global radiative balance (interactions with CO₂, N₂O, CH₄, aerosol, ozone).

■ UNECE Convention on Long-range Transboundary Air Pollution, and the Gothenburg Protocol.

Nitrogen issue: N as a contributor to transboundary acidification, eutrophication and photochemical oxidants, and air quality impacts of particulate matter.

■ United Nations Convention on Biological Diversity.

Nitrogen issue: Adverse effects on species composition and the functioning of terrestrial, aquatic and marine ecosystems.

■ UNECE Convention on the Protection and Use of Transboundary Watercourses and International Lakes ('Water Convention').

Nitrogen issue: Eutrophication of watercourses, lakes and groundwaters and its effects on ecological condition and human health.

■ EU Council Directive 2001/81/EC on National Emissions Ceilings (NEC Directive) and the Thematic Strategy on Air Pollution.

Nitrogen issues: N as a contributor to transboundary air pollution, acidification, eutrophication and air quality, including photochemical oxidants and particulate matter.

■ EU Council Directive 96/61/EC concerning integrated pollution prevention and control (IPPC Directive).

Nitrogen issue: All nitrogen emissions from industrial installations, including large pig and poultry farms, and their cumulative environmental impact, managed by a permitting regime.

■ EU Council Directive 92/43/EEC on the Conservation of natural habitats and of wild fauna and flora (Habitats Directive, and links with the Birds Directive 79/409/EEC).

Nitrogen issue: Atmospheric nitrogen deposition and aquatic nitrogen inputs leading to significant adverse effects on community protected species and sites, especially those established under the Natura 2000 network.

■ EU Council Directive 91/676/EEC on nitrates from agricultural sources (Nitrates Directive).

Nitrogen issue: Drinking water quality and adverse effects on the ecological condition of freshwaters.

■ EU Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy (WFD).

Nitrogen issue: Reduction in good ecological condition of watercourses, lakes and groundwater.

■ EU Council Directive 91/271/EEC concerning urban waste-water treatment (UWW Directive)

Nitrogen issue: Drinking water quality and adverse effects on the ecological condition of freshwaters.

■ EU Thematic Strategy for Soil Protection and proposed Soil Framework Directive COM(2006) 232.

Nitrogen issue: Loss of soil quality through acidification, nutrient imbalances, changes in soil biodiversity and carbon storage.

■ EU Council Directive 98/83/EC on the quality of water intended for human consumption.

Nitrogen issue: Nitrate concentrations in drinking water.

■ EU Directive 2008/56/EC of the European Parliament and of the Council establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive)

Nitrogen issue: Reduction in biodiversity and good ecological condition of marine waters.

■ Convention on the Protection of the Marine Environment of the Baltic Sea Area (HELCOM).

Nitrogen issue: Eutrophication of the Baltic Sea area and its catchment including inland waters, with adverse effects on marine ecology, fisheries and bathing water quality. The Baltic Sea Action Plan addresses eutrophication as one of the most serious and difficult environmental challenges.

■ Commission for the Protection of the Marine Environment of the North-East Atlantic (OSPAR), including the OSPAR Eutrophication Strategy.

Nitrogen issue: Loss of ecological quality through nutrient enrichment including nitrogen.

■ Convention for the Protection of the Mediterranean Sea against Pollution (Barcelona Convention) and Convention on the Protection of the Black Sea against Pollution (Black Sea Convention)

Nitrogen issue: Eutrophication of the Mediterranean Sea and Black Sea and their catchment including inland waters, with adverse effects on marine ecology, fisheries and bathing water quality.

28. The emerging ambitions of the international conventions and European legislative efforts require a new level of integration in European research related to nitrogen.
29. The foundations of this new emphasis are already being laid in current research programmes, such as through NitroEurope and the links developing with the other collaborative efforts. In addition, the NinE networking programme of the European Science Foundation has specifically set itself the task of building the links between the historically separate research themes related to nitrogen.
30. The NinE programme has identified nine key environmental issues related to nitrogen, with their logo (see Figure) providing the mnemonic "ACT AS GROUP", which emphasizes the need to develop integrated approaches across the nine issues:

- ▣ Aquatic eutrophication and water quality
- ▣ Coastal eutrophication
- ▣ Terrestrial eutrophication and biodiversity
- ▣ Acidification of soils and waters
- ▣ Stratospheric chemistry and ozone
- ▣ Greenhouse gases and global warming
- ▣ Ozone, vegetation and human health
- ▣ Urban air quality and health
- ▣ Particles, health, visibility and global dimming.

31. A key development arising from NinE is a major review of nitrogen related issues: the 'European Nitrogen Assessment' (ENA). The objective is 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. The ENA represents a European contribution to the International Nitrogen Initiative (INI), which will be considered by TFRN and the CLRTAP, and made available to other international conventions.

32. The objective to develop integrated approaches needs to be tackled by several efforts in parallel, building the links between the most closely-related issues. For example, COST Action 729 (Assessing and managing nitrogen fluxes in the atmosphere-biosphere system in Europe) focuses on the links between Nr and air pollution, greenhouse gases and biodiversity, thereby contributing to the stepwise development of an integrated perspective.



Algal bloom of *Nodularia spumigena* covering much of the southern Baltic Sea (SeaWiFS image courtesy of NASA and the NERC Satellite Receiving Station, University of Dundee)



Summary of the nine linked concerns addressed by the European Science Foundation (ESF) research networking programme: Nitrogen in Europe (NinE). For explanation see Paragraph 30

33. The current suite of European projects that are establishing the necessary Nr research capacity will have largely finished by the end of 2010 (e.g., NitroEurope, NinE, COST 729). Europe therefore now needs to build on these achievements to develop the future strategy for nitrogen research for the period 2010-2017. The aim for this period must be to develop a 'full nitrogen approach' that links the benefits, multiple environmental threats and policy issues.
34. In developing this future nitrogen strategy, several boundary conditions, scientific concerns and policy messages need to be recognized:
- The model of very large integrated projects, such as NitroEurope IP with an EC contribution of €16.6M over five years, is less favoured in FP7. The new model is for a larger number of Collaborative Projects of generally less than €8M.
 - NitroEurope is a good example of a major effort to develop integration between previously separated disciplines, while being focused on one targeted question. Yet, the future research challenge is to further integrate between an even wider set of themes. Under the FP7 model, this requires the development of a cluster of collaborative projects.
 - The impact of nitrogen on greenhouse gas balance represents a key environmental concern. In particular, there is a major challenge to assess the role of Nr interactions with global radiative balance in relation to future policies, especially the reform of Common Agricultural Policy and the development of European bioenergy policy. These developments raise key questions which should be a priority under the climate change research programme.
 - By contrast, many of the nitrogen research challenges cross the existing programme boundaries within and outside the area of global change and ecosystems. Collaborative research projects are required that address and link the nitrogen threat in each of the areas of greenhouse gases, atmospheric chemistry, biodiversity, soil quality and freshwater and marine water quality.
- There are strong European research communities in each of the policy areas mentioned. Yet these communities are currently rather separated. Specific action is therefore essential to draw these communities together in order to develop the 'full nitrogen approach' needed to support European policies.
 - Scientific expertise on nitrogen is not evenly spread across Europe. Future collaborative research projects should contribute to the needed capacity building in Member States where nitrogen research is currently less well developed.
 - Changes in the European nitrogen cycle and future European policies should be related to the global picture, so that actions to protect Europe's environment avoid exacerbating Nr threats elsewhere. The collaborative research has the potential to support global capacity building, fostering better N management worldwide.
35. To address these challenges *it is proposed to establish a cross-cutting research theme on the European nitrogen problem* under Framework 7 that links the domains of greenhouse balance, atmospheric chemistry, biodiversity, soils and waters with the development approaches for sustainable nitrogen management. This should include targeted calls for new Collaborative Projects addressing the major nitrogen threats and mitigation options. In parallel coordination measures are needed to maximize the synergies between the projects, nitrogen related issues and European policy areas.

Priorities for European nitrogen research

36. While the need for an integrated research effort on nitrogen is clear, the component priorities and clustering of project topics require further debate. Under the ongoing European Nitrogen Assessment, five key societal threats of excess Nr have been identified: global radiative balance, air quality, water quality, biodiversity/ecosystem integrity and soil quality. By contrast, it remains a major challenge to set the relative priorities between these threats for Europe as a whole and for the different regions.
37. The developing research strategy must also recognize the existence of a 'stairway to integration'. It would be unrealistic to investigate and attempt to resolve all nitrogen-related threats in a single large project. The experience of the current research and coordination activities shows that integration of scientific communities and policy concerns is a gradual process. Themes for future European research projects should drive the scientific community toward the next steps of integration.
38. Bearing in mind these issues, we here illustrate the scope of seven potential large collaborative projects that could be addressed under FP7. *Such a cluster of projects should be supported by coordination activities to foster the sharing of common protocols and datasets, encourage the development of integrated analyses and support the provision of results to the relevant international conventions. It should be an obligation for the individual projects to engage in this coordination and integration process, for which suitable resources should be reserved.*
39. The following topics highlight our view of the emerging priorities to be addressed in the next stage of European nitrogen research.

40. **Project Concept 1: Integrating the biospheric and atmospheric effects of nitrogen on global radiative balance.** (In support of FCCC and CLRTAP.) *Measurements and models should be implemented to quantify the role of European reactive nitrogen in altering overall radiative balance, combining the biospheric effects (such as through terrestrial fluxes of N₂O, CO₂ and CH₄) with the atmospheric chemistry effects (including aerosol and ozone production etc). The approach should integrate long-term observations of the relevant fluxes with mechanistic studies and model development, including attention to reduce key uncertainties, such as estimates of non-symbiotic biological N fixation and denitrification losses to N₂. Methods should be developed to upscale the nitrogen impacts for different time periods and spatial scales. Numerical GIS models should be developed, verified and applied to examine scenarios of how current and future policies would drive the overall effect of nitrogen on radiative balance at European and global scales.* (Large collaborative project: €8M, 2011-2014.)

41. **Project Concept 2: Developing new approaches to quantify and minimize the impacts of atmospheric nitrogen deposition on European habitats.** (In support of CBD, CLRTAP, Habitats Directive, WFD and EU policies on soils and eutrophication.) *The project should investigate the contribution of atmospheric nitrogen deposition as a threat to terrestrial biodiversity, especially in relation to the aspirations of the 6th Environmental Action Programme. Observational and experimental analyses should be applied in combination with appropriate numerical models to improve estimates of overall loss of stock and quantify the relative role of nitrogen oxides and ammonia in relation to other threats to ecosystem integrity. Improved indicators should be developed at field and European scales, combined with the investigation of novel mitigation options to help meet international air pollution and biodiversity commitments. Options proposed must consider potential synergies and trade-offs, especially with other forms and impacts of reactive nitrogen. Attention should be given to widening the European scope of existing knowledge, including southern and eastern countries.* (Medium-sized collaborative project €5M, 2011-2014.)



42. Project Concept 3: Quantifying the multiple roles of atmospheric chemistry on European impacts of reactive nitrogen. (In support of the CLRTAP, FCCC and CBD.)

The project should integrate the effects of atmospheric reactive nitrogen, including impacts on human health, ecosystems, visibility and radiative balance. The interactions between oxidized and reduced nitrogen, aerosol, tropospheric and stratospheric ozone and nitrous oxide should be addressed as a basis to investigate the overall response to changing N emissions. Ground-based flux measurements and remote sensing data should be combined with numerical modelling to investigate chemical non-linearities and uncertainties. Models should be developed and applied at different spatial scales, including Europe as a whole, to integrate future mitigation options, including the link between air pollution and other N threats, and the situation in less-well studied parts of Europe. Economic analyses should be developed as a basis to compare costs of nitrogen-related threats at the regional scale, including the estimation of damage costs associated with different nitrogen impacts and forms. (Large collaborative project: €6M, 2012-2015.)

43. Project Concept 4: Integrating the role of nitrogen in catchment, coastal and marine eutrophication. (In support of Nitrates Directive, WFD, Water and Marine Conventions.)

The research should quantify the contribution of nitrogen in relation to other nutrients (especially phosphorus and silica) as factors of eutrophication through multiple spatial and temporal scales. It should consider examples of lakes and small headwater catchments to regional watersheds and Europe as a whole, including the impacts on coastal zones and marine areas at risk. Measurements and models, including data from remote sensing, should be integrated to understand the spatial and seasonal dynamics of N limitation and excess, the roles of different N forms, the interaction between terrestrial and aquatic systems, and the consequences for ecological condition of freshwater, estuarine and coastal habitats. Spatial and temporal GIS models should be applied to quantify the contributions of different nutrient sources (including agriculture, sewage, industry and atmospheric deposition) and sinks/retention. Effects of improved management of N sources, including the interactions with other N pathways and policy areas should be explored via scenario analysis. (Large collaborative project: €8M, 2012-2015.)

44. **Project Concept 5: Integrating the consequences of EU and international policies on nitrogen-related impacts in European landscapes as a basis to develop locally optimized solutions.** (In support of FCCC, CLRTAP, CBD, WFD, CAP and EU policies on soils and eutrophication.) *Research should investigate the consequences of market globalization and interactions between agricultural, forestry, environmental and energy policies on N fluxes and their impacts on European landscapes, including the key interactions with greenhouse gases and other nutrients. Surveys, measurements and spatial modelling should be applied to study areas (indicatively 10-50 km²) to illustrate the key interactions. The consequences of spatial relationships on environmental impacts and their mitigation should be addressed, including the implications for regional and European upscaling. Spatial models tracing the nitrogen cascade, together with the application of N budgeting approaches, should be tested on the different scales to examine options of how future European policies could simultaneously mitigate the interacting effects of excess N on greenhouse gases, air quality, water, soils and biodiversity. Relative costs of different impacts should be investigated, with landscapes scenarios used to illustrate mitigation priorities, including consideration of societal preferences. Models should be used to quantify the effectiveness of packages of measures on different N species and to identify cost optimum solutions related to environmental targets.* (Large collaborative project ca. €9M, 2013-2016.)

45. **Project Concept 6: Understanding nitrogen flows and emissions in the food production and consumption chain of Europe.** (In support of FCCC, CLRTAP, CBD, WFD, CAP and EU policies on soils and eutrophication.) *Socio-economic and environmental research approaches should be combined to investigate the factors and actors that influence human diets across the EU, and how these diets affect the N flows and emissions in EU, and relationships associated with global versus local food origin. The primary aim of this research should be to increase insight into the knowledge, attitude and behaviour of consumers and stakeholders in the food chain with regards to the relationship between (animal) protein consumption – food production – N losses from food production to the environment – human health effects and the environmental consequences. The research should obtain increased insight into the social network and decision environment of consumers as regards dietary choices, and should contribute to further developing theories on diet choices. Consequences of future changes in diets on land use changes in EU and elsewhere should be explored via scenario analyses, and examined in relation to changes in N use in food production, environmental losses of N and the consequences for global food security.* (Large collaborative project ca. €5M, 2012-2015.)





46. **Project Concept 7: Managing the European nitrogen cycle to increase nitrogen use efficiency by 50%.** (In support of FCCC, CLRTAP, CBD, WFD, CAP and EU policies on soils and eutrophication.)
Research should identify and test options to increase the nitrogen use efficiency in food production by a target of ~50% relative to current mean values, with the focus on reducing reactive N and denitrification losses to the environment. Fundamental theoretical and experimental research should search for the minimum N input (and other inputs) that is needed to allow maximum utilization of all other production resources, including consideration of potential co-benefits for reducing energy dependence of food production systems, and potential interactions with animal welfare. Estimated minimum inputs should be tested experimentally across Europe, considering contrasting European production systems and the role of different feed sources including legumes. The results of these tests should be used to derive target values showing a reduced external N input per unit output. Options to recycle and feed back waste from the human consumption system into the food production system should be explored. The pros and cons of such recycling should be examined relative to the costs needed to increase eco-efficiency in the food production sector by 50%. The research should contribute to the development of international guidelines and capacity building. (Large collaborative project ca. €8M, 2013-2016.)

47. The overall outcome of such a cross-cutting programme should be an improved understanding of how different parts of the nitrogen cycle fit together, together with the consideration of key mitigation options, thereby underpinning the development of future European and international nitrogen management strategies.

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1. A large number of nitrogen-related research projects are currently running under FP6 and FP7. In some cases initial links have already been established through NitroEurope, NinE and COST 729, while in all cases there is a need for much more understanding and interaction. The following short survey identifies: a) the major collaborative projects with significant nitrogen relevance, and b) smaller EU-funded projects related to nitrogen. This list is necessarily only a sample of the overall European effort, which includes substantial national contributions.

Major European Collaborations Relevant for Nitrogen

2. **NitroEurope IP: The nitrogen cycle and its influence on the European greenhouse gas balance.** (www.nitroeuropa.eu) SUSTDEV-2004-3.I.1.1. (Coordinator: Mark Sutton) The NitroEurope Integrated Project addresses the major question: What is the effect of reactive nitrogen (Nr) supply on net greenhouse gas budgets for Europe? The central interactions addressed include N-deposition, CO₂, N₂O, CH₄, with linkages to NH₃, NO_x and N leaching. The IP establishes the first European network of nitrogen flux observations, experimental manipulations and landscape observatories, exploiting these through model development at plot to European scales, combined with verification activities allowing the results to be related to official estimates under FCCC and CLRTAP reporting. The critical mass provided by NitroEurope is also providing a foundation to develop a more integrated approach for future nitrogen research.
3. **ACCENT: Atmospheric composition change: A European network** (www.accent-network.org) SUSTDEV-2002-3.I.2.a. (Coordinator: Sandro Fuzzi) The overall goals of the ACCENT Network of Excellence are to promote a common European strategy for research on atmospheric composition change, to develop and maintain durable means of communication and collaboration within the European scientific community, to facilitate this research and to optimise two-way interactions with policy-makers and the general public. The ACCENT joint research programme focuses on aerosols, biosphere-atmosphere interaction and transport and transformation of pollutants, including Nr species.
4. **EUCAARI: European integrated project on Aerosol cloud Climate and Air quality interactions** (<http://www.atm.helsinki.fi/eucaari>) SUSTDEV-3 Global change and ecosystems. (Coordinator: Markku Kulmala) EUCAARI, investigates (I) the reduction of the current uncertainty of the impact of aerosol particles on climate by 50% and quantification of the relationship between anthropogenic aerosol particles and regional air quality, and (II) the quantification of the side effects of European air quality directives on global and regional climate. New ground-based, aircraft and satellite measurements will be integrated with existing data, while a hierarchy of models will be developed based on the results of the laboratory and theoretical investigations, providing tools and recommendations for different stakeholders.
5. **BEGIN: Biodiversity of European Grasslands the Impact of Atmospheric Nitrogen Deposition.** A small-medium sized project under the EuroDIVERSITY programme of the European Science Foundation. (www.esf.org/activities/eurocores/programmes/eurodiversity/projects/begin.html) (Coordinator: David Gowing) The BEGIN project recognizes nitrogen eutrophication as perhaps the most important threat to European plant biodiversity. It aims to determine the extent to which N-deposition is impacting species richness on a wider scale across European grasslands and to elucidate the mechanisms. It includes a combination of field observations at European sites, assessment of the predictive ability of the relationships developed, determination of the timefactor of nitrogen driven biodiversity loss and development of recommendations to mitigate damage.
6. **ALTER-Net: A Long-Term Biodiversity, Ecosystem and Awareness Research Network** (www.alter-net.info/) SUSTDEV-2002-3.III.1.1 (Coordinator: Terry Parr) ALTER-Net is a Network of Excellence that aims to help deliver on the 2010 target by promoting a better integrated and stronger European biodiversity research capacity. It aims to establish a lasting infrastructure for integrated ecosystem research, combining ecological and socio-economic approaches, and with greater emphasis on communication with relevant audiences. Nitrogen is one of the key drivers of biodiversity change across Europe, as recognized by establishment of the Nitrogen Working Group under the SEBI2010 process (Streamlining European Biodiversity Indicators for 2010), with input from ALTER-Net scientists.

7. **SEAMLESS: System for Environmental and Agricultural Modelling: Linking European Science and Society.** (www.seamless-ip.org) SUSTDEV-2004-3.V.2.1.a Farming system management and multifunctional use of agriculture to implement the Sustainable Development Strategy. (Coordinator: Martin van Ittersum) The SEAMLESS Integrated Project aims at developing a computerized, integrated and working framework (SEAMLESS-IF) to assess and compare, ex-ante, alternative agricultural and environmental policy options, allowing: 1) Analysis at the full range of scales (farm to EU and global), while focusing on the most important issues emerging at each scale; 2) Analysis of the environmental, economic and social contributions of multifunctional agriculture towards sustainable rural development; 3) Analysis of a broad range of issues and agents of change, such as climate change, environmental policies, rural development options, including effects of an enlarging EU, international competition and effects on developing countries.
8. **INTARESE: Integrated Assessment of Health Risks from Environmental Stressors in Europe** (www.intarese.org) SUSTDEV-2004-3.VII.1.1.1 (Coordinator: David Briggs, Imperial College, London, UK) This Integrated Project supports implementation of the European Environment and Health Action Plan by providing the methods and tools that are essential to enable integrated assessment of environmental health risks. It will develop a methodological framework and set of tools and indicators for integrated assessment that can be applied across different environmental stressors (including pollutants and physical hazards), exposure pathways (air, water, soil, food) and policy areas. The framework, tools and data will be tested and demonstrated through integrated assessments of exposures and health risks in a number of specific policy areas, including transport, housing, agriculture, water, wastes, household chemicals and climate. Results from these will be used both to refine the assessment methods and to provide specific information on health implications of current and potential future policies.
9. **REDNEX: Innovative and practical management approaches to reduce nitrogen excretion by ruminants** (www.asg.wur.nl) FP7-KBBE (Coordinator: Ad van Vuuren, Contact: Boudewijn Kroes, ASG Veehouderij BV, Lelystad, The Netherlands). The objective of REDNEX is to develop management approaches for dairy cows that reduce nitrogen excretion into the environment through the optimization of rumen function, by improving understanding and prediction of dietary nitrogen utilization for milk production and excretion in urine and faeces. The project uses a detailed mathematical model of N utilization by the cow to integrate results and aims to improve the absorption efficiency of amino acids, allowing a reduction in N intake. Practical tools will be developed to predict N losses on-farm and the impact on profitability, including the use of biomarkers to indicate N status.
10. **CC-TAME: Climate Change – Terrestrial Adaptation & Mitigation in Europe** (www.cctame.eu/) (FP7-ENVIRONMENT) (Coordinator: Michael Obersteiner, International Institute for Applied Systems Analysis, IIASA, Laxenburg, Austria). The CC-TAME project concentrates on assessing the impacts of agricultural, climate, energy, forestry and other associated land-use policies considering the resulting feed-backs on the climate system in the European Union, including the interactions with methane and nitrous oxide emissions.
11. **NSINK: Training in sources, sinks and impacts of atmospheric nitrogen deposition in the Arctic.** (www.nsink.group.shef.ac.uk/) (FP7-PEOPLE) (Coordinator: Andy Hodson, University of Sheffield, UK). The NSINK Initial Stage Training Network targets the enrichment of Arctic terrestrial and aquatic ecosystems by reactive atmospheric nitrogen from low latitude emission sources. The problem is recognized to need holistic studies that trace nitrogen sources to sinks and consider the dynamics of nitrogen processing. The network therefore brings together training activities from atmospheric sciences, snow physics, hydrology, biogeochemistry and aquatic ecology, including ice core and lake sediment studies.

Smaller EU-funded projects related to nitrogen

12. There is a large number of smaller relevant projects, particularly under the Training and Mobility Programme and under SME cooperative research. Substantial potential exists for better linkage of these types of activity into the integrated nitrogen effort needed in FP7. The examples listed below illustrate the range of issues.
13. The following projects relate to nitrogen sources and terrestrial interactions:
 - a. **RHIBAC** Rhizobacteria for reduced fertiliser inputs in wheat (FOOD-2004-T5.4.6.5) Nicolaus von Wirén, Universitaet Hohenheim, Germany.
 - b. **GRASSLAND** Effects of climate warming and altered biodiversity on the carbon, water and *nitrogen* balance of grasslands under drought conditions (MOBILITY-4.2), Reinhart Ceulemans, University of Antwerp, Belgium.
 - c. **SPANAMICO** Spatial distribution of N processes and microbial communities in arable soils at micro- and nano- scales (MOBILITY-2.2), Anthony O'Donnell, University Of Newcastle Upon Tyne, UK.
 - d. **Soil Carbon Storage** Soil C cycling and ecosystem processes: effects of plant diversity, plant community composition, *N deposition* and herbivory on soil C storage dynamics (MOBILITY-2.2), Richard Bardgett, Lancaster University, UK.
 - e. **NIREC** Efficient removal and recycling of nitrogen from organic waste as fertiliser. (SME-1 Co-operative Research). Werner Fuchs, Universitaet Fuer Bodenkultur, Vienna, Austria.
 - f. **PIGMAN** A sustainable solution for pig manure treatment: Environmental compliance (SME-1 Co-operative Research). Kyriakos Christodoulou, Wasteman & Envirotech Ltd, Cyprus.
 - g. **CORN** Characterization of organic reduced nitrogen species [in the atmosphere] (FP7-People). Albrecht Neftel, Forschungsanstalt Agroscope Reckenholz-Taenikon Art, Zurich, Switzerland.
 - h. **NITFOR** The impact of nitrogen on the fate of recently assimilated carbon in forest soils (FP7-People) David Hudson, University of York, UK.



14. The following projects relate to nitrogen processing in aquatic systems
- i. **DOUBLECHECK** Double-check of dissimilatory nitrate reduction to either ammonium or dinitrogen in aquatic habitats (MOBILITY-4.1), Dirk de Beer, Max-Planck-Institut fuer Marine Mikrobiologie, Germany.
 - j. **QUALIWATER** Diagnosis and Control of Salinity and Nitrate Pollution in Mediterranean Irrigated Agriculture (INCO -2003-B1.1) Ramón Aragüés, Mediterranean Agronomic Institute Of Zaragoza, Spain.
 - k. **GNOM** Groundwater-derived Nutrient and Organic Matter: alteration during transit through coastal sediment (MOBILITY-2.2) Bernhard Wehrli, Limnology Research Center, Department of Surface Waters, Switzerland.
 - l. **DEFUNIREG** Diversity and ecological function of benthic nitrate reducing populations along an estuarine nitrate gradient, (MOBILITY-2.1) David Nedwell, University of Essex, UK.
 - m. **NITROQUEST** The roles of anaerobic and aerobic microbial processes on nitrogen loss from intertidal and estuarine sediments (MOBILITY-2.1). Marcel Kuypers, Max-Planck-Institut fuer Marine Mikrobiologie, Germany.
 - n. **ERAMMON** The ecological roles of planktonic archaeal and bacterial ammonia oxidizers in the oceanic *nitrogen* cycle (MOBILITY-2.1). Clive Edwards, University of Liverpool, UK.
 - o. **MARCYAN2** Ecological control of *nitrogen* fixation in marine Cyanobacteria (MOBILITY-2.1). Theo Davidse, Netherlands Institute of Ecology, The Netherlands.
 - p. **NITROFORAM** The new players in the marine nitrogen cycle: benthic foraminifera (FP7-People). Bo Riemann, Aarhus Universitet, Denmark.
 - q. **ELNOX** Elemental nitrogen oxidation: A new bacterial process in the nitrogen cycle (FP-Ideas) Heike Wojack, Max Planck Gesellschaft zur Foerderung der Wissenschaften, Munich, Germany.
 - r. **ANAMMOX** Anaerobic ammonium oxidizing bacteria: unique prokaryotes with exceptional properties (FP7-Ideas). Peter Spooormakers, Radboud Universiteit Nijmegen - Stichting Katholieke Universiteit, The Netherlands.
 - s. **N-TOOLBOX** Toolbox of cost-effective strategies for on-farm reductions in N losses to water (FP7-KBBE). Deborah Grieves, University of Newcastle, UK.
15. The following projects relate to upscaling and integration:
- t. **GAINS-ASIA** Greenhouse Gas and Air Pollution Interactions and Synergies (POLICIES-3.4 Forecasting and developing innovative policies for sustainability in the medium and long term) Markus Amann, International Institute for Applied System Analysis – IIASA.
 - u. **Trade-offs between climate and air pollution policies** (2.2.1 Climate change: the Kyoto protocol and beyond). Frank Dentener, JRC Institute for Environment and Sustainability.
 - v. **THRESHOLDS** of Environmental Sustainability (FP6-SustDev). Includes studies on coastal eutrophication in relationship to nutrient fluxes from watersheds. Carlos Duarte, Instituto Mediterraneo de Estudios Avanzados, Islas Baleares, Spain
16. This summary of current European research activities related to nitrogen highlights the major challenge for better integration. Informal contacts have been established between several of the major IPs and Networks of Excellence, but the degree of interaction is currently extremely limited. The situation is even more extreme for the smaller EU projects, where there appears to be mostly very little integration with the wider European activity. New efforts are therefore needed to better link European nitrogen research, which is especially important to improve the information flow for the development of European policies.

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For further information please contact the office of the TFRN at:

tfrn@ceh.ac.uk
www.clrtap-tfrn.org/european-research-strategy