NitroEurope IP

The nitrogen cycle and its influence on the European greenhouse gas balance

SIXTH FRAMEWORK PROGRAMME

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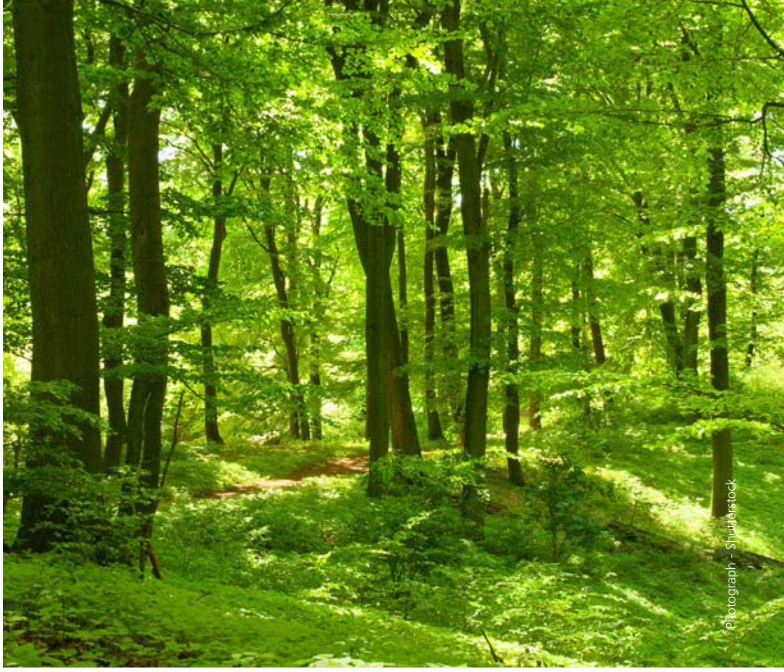
1 Key messages for policy makers



- Humans have more than tripled the circulation of reactive nitrogen (N_r) in Europe, mainly through the production and release of fertilizers, in addition to fossil fuel combustion and biological nitrogen fixation.

- NitroEurope has combined experiments and modelling to quantify nitrogen fluxes and their influence on the European greenhouse gas budget. Additional synthesis activities have shown how these effects compare with the climate effects of N_r via aerosol and ozone.

- The new methods developed and comprehensive datasets obtained show how N_r interacts with other drivers of change at site, landscape, regional and European scales, pointing to opportunities for better N_r management and the development of mitigation options.

- A comprehensive nitrogen budget has been established, showing that Europe produces 15.6 Tg N_r annually, with 11.2 Tg from fertilizers, 3.4 Tg from combustion sources and 1 Tg from biological nitrogen fixation. In addition to the combustion emissions, agricultural N_r use is very leaky, wasting about 13 Tg to air and water annually.

- Atmospheric deposition of N_r increases the carbon storage of European forests, but this is constrained by an increase in N_r losses, while the ammonia (NH_3) fraction of N_r deposition also represents a loss of productivity from agricultural systems.

- Comparing the warming effects of N_r emissions (N_2O formation, ozone warming and phytotoxic effects) with the cooling effects (faster forest growth, altered methane lifetime and aerosol formation) leads to a rough balance over Europe (-16 (-47 to +15) mW m^{-2}).

- Cost-benefit analysis indicates that the threats of N_r particles to human health and of N_r deposition to biodiversity loss greatly outweigh their potential climate benefits.

- There are many opportunities to reduce the climate warming effects of N_r losses.

  - Efforts to reduce the N_r-related warming effects of tropospheric ozone must decrease both NO_x and volatile organic compounds (VOCs), requiring ongoing improvement in combustion technologies and further efforts to reduce transport mileage and energy use.

  - Efforts to reduce N_2O emissions must focus on improving overall nitrogen use efficiency in agriculture, for which the implementation of technical measures to reduce ammonia emissions, denitrification to N_2 and nitrate leaching is essential.

  - The overall European nitrogen cycle is driven by the human quest for luxury consumption of animal products. Of the N_r in crops produced or imported to Europe (12 Tg) only 15% is used to feed people directly, with 85% going to feed animals.

  - Avoiding dietary excess of meat and diary products would provide a major contribution to decreasing the climate warming effects of N_2O, while reducing the threat of N_r emissions to human health and biodiversity at the same time.

2 Technical summary

1 The NitroEurope IP has established an unprecedented level of collaboration across Europe to investigate the ways in which reactive nitrogen (N_r) affects the greenhouse gas balance. The 5-year programme has joined 62 institutes, combining measurements and models over multiple spatial scales.

Flux measurement

2 Intensive measurements at a series of 13 flux 'super sites', have quantified N budgets and net greenhouse gas exchange (NGE), improving our understanding of the component fluxes. These have been supported by low-cost flux methods applied at 9 'regional sites', with air chemistry and indicator measurements at 56 'inferential sites'.

3 The comparison of total atmospheric and agricultural N_r inputs with long-term CO_2 flux datasets demonstrates higher carbon sequestration with increased N_r supply, with the relationship modified by land-use and climatic interactions.

4 The intensive flux datasets quantify how gaseous and water N losses increase with N_r inputs, constraining the benefit of N_r in increasing net carbon storage. Combined with changes in nitrous oxide (N_2O) and methane (CH_4) fluxes, most sites experience net greenhouse gas uptake. Nitrogen has a net benefit for NGE at the field scale, but not as big as previously been proposed because of the N_r loss processes.

5 Special topic studies have investigated the dynamics of N fluxes, showing how particle growth and evaporation processes are important in determining net N_r inputs to semi-natural ecosystems, and providing understanding in how fire affects NGE of Mediterranean shrublands, in addition to enabling the moisture and temperature sensitivity of soil gas fluxes to be quantified.

Global change effects

6 A network of manipulation experiments has investigated the ways in which global change affects N fluxes and their impact on greenhouse gas balance. Experiments over different land use types have addressed the effects of land management, temperature, water availability, CO_2 and N_r deposition.

7 The experiments in forests have quantified how soil warming and N status both increase N_2O emissions, while in organic soils soil pH and groundwater dynamics were most important. These factors also controlled CH_4 emission rates from wet soils, with CH_4 soil uptake rates in dry soils being reduced by both warming and N_r availability.

8 Agricultural soils are the main source of N_2O emission in Europe, highlighting the importance of developing appropriate management practices. It is estimated that better nutrient use efficiency, improved soil management and improved agronomy reduce emissions by 10 to 30%.

9 Over shrublands, NGE was dominated by CO_2 exchange, with smaller fluxes of N_2O and CH_4, while wetlands provided peak CH_4 fluxes. N_r input as NH_3 gave a larger increase in N_2O and CH_4 from wetland compared with wet deposition, coupled with larger phytotoxic effects. Climate and N_r supply had interacting effects on CO_2 fluxes, highlighting the complexity of simulating future conditions.

Plot scale modelling

10 Efforts have focused on further development of biogeochemical models for improved simulation of terrestrial C and N cycling, especially in relation to trace gas exchange, using a wide range of models. Testing the models in relation to experimental datasets has provided the basis for application in up-scaling to landscape and European scales.

11 An innovative aspect has been the use of Bayesian Calibration of the models to assess uncertainty and improve parametrization in the biogeochemical models. This has allowed model uncertainties to be compared with field measurements, as well as provided a basis to

identify model weaknesses and over/under parametrization, reducing overall uncertainties.

12 Examples of the processes investigated include the evaluation of competing hypotheses on processes driving spring-thaw N_2O and the explanation of how grazing can actually decrease rather than increase N_2O emissions in continental steppeland.

13 Application of the developed models to the NitroEurope measurement sites gives a better understanding of N and C cycling and its link to net GHG fluxes, and a sound basis for application in upscaling and testing mitigation options. One example shows how balanced fertilization can reduce N_2O emissions from cropland by 20%.

Landscape analysis

1 Up-scaling from plot to regional scale needs to account for the complex interaction between individual landscape elements and their relation to land management. These interactions have received little study previously, with NitroEurope filling this gap by investigating the N and GHG interactions within explicit spatial contexts.

2 Detailed inventories were established for 6 European landscapes, providing harmonized data for application of a newly development modelling framework 'NitroScape' and a reference for verification measurements and scenario testing. A shared measurement strategy for characterizing landscape level nitrogen flows was adopted.

3 The NitroScape modelling framework was established by coupling existing component models (atmospheric, farm, ecosystem and hydrological models) to simulate spatially distributed N fluxes in a dynamic way using the Palm® model coupling system.

4 First testing of the NitroScape model has shown the importance of landscape scale interactions. It highlights the importance of spatial relationships between source and sink elements, for example with more than 10% of N_2O emissions in the landscape caused by either short range NH_3 dispersion or nitrate transfer through groundwater. Testing of example scenarios has shown the value of NitroScape as a new tool for assessing the effect of landscape structure and management/environmental management on nitrogen fluxes and impacts.

European up-scaling and integration

5 European Integration within NitroEurope has developed and applied GIS-based tools to assess changes in N_r and NGE fluxes for terrestrial ecosystems for the EU27. This included the development of a multicomponent model (INTEGRATOR), establishing a consistent database, application of upscaled ecosystem models and scenario studies.

6 Comparisons of models provided the basis to assess uncertainty on a European scale, including NH_3, N_2O and nitrate leaching. These show comparable estimates for NH_3 emissions, while differences in N_2O emissions are larger, reflecting the larger variation in model approaches.

7 Scenarios of changed N inputs induced by altered livestock numbers and land management, including the IPCC-SRES A1 and B2 scenarios, were evaluated using various terrestrial ecosystem models.

8 Results show that the impact of the IPCC scenarios on NH_3 and N_2O emissions is limited. Under the A1 scenario both European NH_3 and N_2O emissions are projected to increase by less than 4-8% between 2010 and 2030. By comparison, the B2 scenario indicates a slight decrease of similar magnitude over the same period.

9 Given these small estimated changes, achieving major reductions in emissions for N_2O and NH_3 is expected to depend on better farm management methods, requiring an improvement in nitrogen use efficiency (NUE) by reducing the N losses (NH_3, denitrification to N_2, nitrate leaching), as a basis to reduce total N_2O emissions.

Independent verification, uncertainties and policy analysis

10 Independent verification activities at the European scale focused on estimates of nitrogen wet deposition, inverse modelling of N_2O and CH_4 emissions, uncertainty analysis and assesment the needs of policy stakeholders.

11 Precipitation chemistry data from several sources including the EMEP, ICP-Forest, ICP-IM and other national programmes were evaluated with quality assurance procedures and combined to establish a new estimate of wet nitrogen deposition at the European scale.

12 Atmospheric measurements combined with inverse atmospheric models were used to provide independent top-down estimates of N_2O and CH_4 fluxes using five modelling systems, as a basis to for a model ensemble approach to assess overall uncertainties, including a novel bias correction scheme to handle the low signal-to-noise ratio. The top-down estimates of N_2O emissions are consistent with bottom-up inventories reported to the UNFCCC showing how the top-down approach can reduce the overall uncertainty in N_2O emissions.

13 Five protocols for model uncertainty assessment were established, considering the suitability of different model types, parameter uncertainty and uncertainty in independent evaluation data, with these applied to ecosystem models, INTEGRATOR and the inverse models. The models were aggregated to a common resolution, including gap filling allowing the common uncertainties to be assessed.

14 Structured interviews were conducted with policy stakeholders identifying their needs and the importance of rapid transfer of new science outcomes. For this reason a strategy paper on 'Interactions of reactive nitrogen with climate change' was developed for the Executive Body of the UNECE Convention on Long-range Transboundary Air Pollution, and made available in support of the IPCC AR5 process and the UNFCCC.

Long term curation and data management

15 Data management has included the establishment of databases, grouped according to plot data (fluxes, manipulation, modelling), landscape data, and European wide datasets. Beyond the end of NitroEurope these databases will be integrated into a wider database portal, *Environment and Climate interactions—Observations and Responses in Ecosystems* (ENCORE), which is currently being developed. ENCORE will coordinate access to high-quality climate-change related data throughout Europe, in which NitroEurope and other projects will be curated.

Synthesis and integration

16 The results of NitroEurope have been synthesized playing a key role to underpin development of the European Nitrogen Assessment. Key elements include the advancement of process understanding, establishment of European maps and a new European Nitrogen Budget, and estimation of the net effect of N_r emissions on the European radiative balance.

17 The policy relevant findings of NitroEurope are also being transferred to the UN process, both through the Task Force on Reactive Nitrogen (TFRN) of the UNECE Air Convention and through the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). The TFRN has been established with the direct support of NitroEurope partners engaging with policy stakeholders. It has delivered a special report on nitrogen and climate to the Executive Body of the Air Convention, and is currently contributing to the revision of the Gothenburg Protocol.

18 One of the key messages to emerge is that reducing N_2O emissions will require common efforts between the Air and Climate conventions. In particular, reducing N_2O emissions will require efforts to improve nitrogen use efficiency (NUE) in agriculture, which are fundamentally dependent on reaching agreement to reduce both NH_3 emissions and nitrate leaching. The current negotiations to revise the Gothenburg Protocol leading to reductions in NO_x and NH_3 emissions are therefore essential to meet multiple targets for air quality (particulate matter, ozone), climate (N_2O and ozone), water and soil quality (NO_3 leaching) and biodiversity (N deposition).

3 Project overview, aims and scope

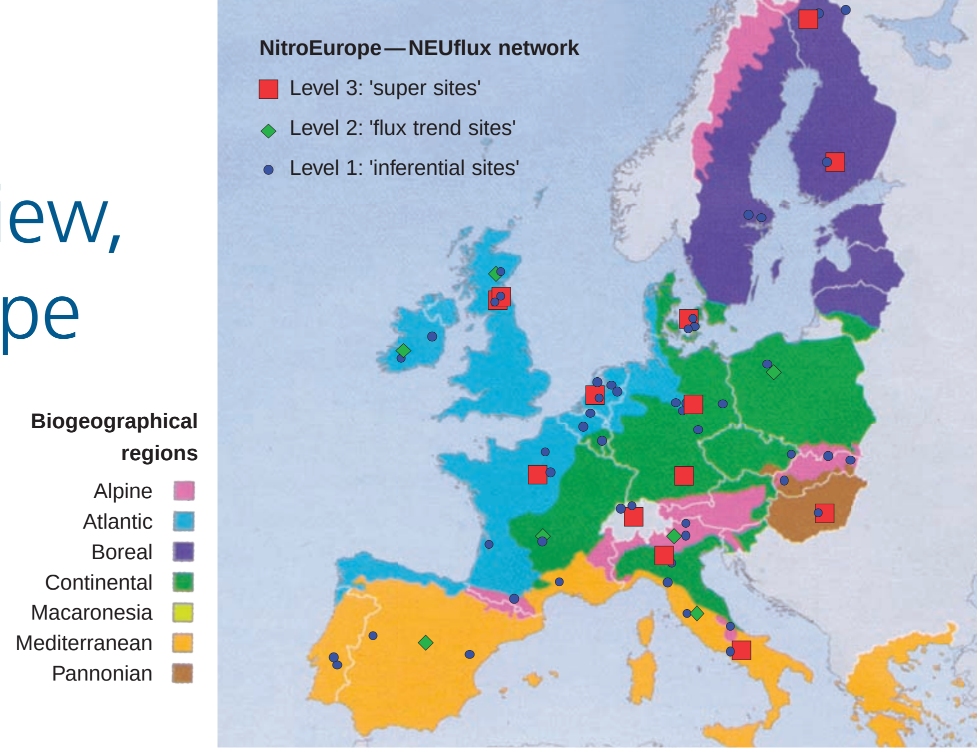


Figure 1 A map of the NitroEurope measurement network—Level 1, 2 and 3 sites.

The NitroEurope IP—or NEU for short—addresses the major question: What is the effect of reactive nitrogen (N_r) supply on net greenhouse gas budgets for Europe? Its objectives have been to:

1 establish robust datasets of N fluxes and net greenhouse-gas exchange (NGE) in relation to C-N cycling of representative European ecosystems, as a basis to investigate interactions and assess long-term change,

2 quantify the effects of past and present global changes (climate, atmospheric composition, land-use/land-management) on C-N cycling and NGE,

3 simulate the observed fluxes of N and NGE, their interactions and responses to global change/land-management decisions, through refinement of plot-scale models,

4 quantify multiple N and C fluxes for contrasting European landscapes, including interactions between farm-scale management, atmospheric and water dispersion, and consideration of the implications for net fluxes and strategies,

5 scale up N_r and NGE fluxes for terrestrial ecosystems to regional and European levels, considering spatial variability and allowing assessment of past, present and future changes,

6 assess uncertainties in the European model results and use these together with independent measurement/inverse modelling approaches for verification of European N_2O and CH_4 inventories and refinement of IPCC approaches.

These objectives are met by a programme that integrates: 1) an observing system for N fluxes and pools, 2) a network of manipulation experiments, 3) plot-scale C-N modelling, 4) landscape analysis, 5) European up-scaling and 6) uncertainty and verification of European estimates. Cross-cutting activities address management, databases, training & dissemination.

Within NitroEurope, 62 partner institutions and more than 300 scientists have collaborated over the course of five years to deliver a first, comprehensive analysis of the European nitrogen cycle. These findings are of substantial importance to assess the influence on greenhouse gas (GHG) emissions on a European scale, and the relationships between the full range of environmental effects of reactive nitrogen (N_r).

NitroEurope has interacted with a variety of international activities with a focus on nitrogen research, such as the European Science Foundation programme Nitrogen in Europe (ESF-NinE), COST Action 729, the United Nations Economic Commission for Europe (UNECE) Task Force on Reactive Nitrogen (TFRN), and the International Nitrogen Initiative (INI) and other programs of IGBP and SCOPE. The synthesis activity of NitroEurope has taken place in close cooperation with these activities, implemented through the European Nitrogen Assessment (ENA), substantially extending the range and impact of the project beyond the original plan. In this way, the findings of NitroEurope have been fed directly to support policy analysis by the Member States of the European Union and Parties to the UN Framework Convention on Climate Change (FCCC), the Intergovernmental Panel on Climate Change (IPCC), the Convention on Biological Diversity (CBD), and especially the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP).

4 Main findings

4.1 Observations quantifying nitrogen fluxes and pools

Nitrogen and greenhouse gas budgets were calculated for 56 sites across Europe (see Figure 1). The sites cover the main European climate zones and key ecosystems types: 30 forests, 8 wetlands/shrublands, 9 grasslands and 9 arable. Given the infeasibility of deploying a large network for all reactive nitrogen (N_r) measurements, a measurement strategy was developed that matches different data objectives to three levels of measurements. This tiered strategy included:

Level 1: 56 'Inferential Sites', combining basic reactive nitrogen concentration monitoring and indicators with micrometeorological datasets to infer nitrogen fluxes.

Level 2: 9 'Regional Sites', focusing on long-term time-integrated flux measurements, increasing regional coverage.

Level 3: 13 'Super Sites' with intensive measurements quantifying nitrogen budgets and advancing process understanding.

The Level-1 sites were established in 2006 to infer N_r deposition fluxes including dry deposition using inferential modelling, with wet deposition measurements at selected sites (Tang *et al.*, 2009). Air chemistry was measured using the DELTA denuder/filter method, which separates gaseous (NH_3, HNO_3, SO_2, HCl) and aerosol (NH_4^+, NO_3^-, SO_4^{2-}, Cl^- and Na^+, Ca^{2+}, Mg^{2+}) species using monthly time-integrated sampling. (DELTA; Figure 2). This was combined with a modelling framework to infer deposition fluxes (Flechard *et al.*, 2011). Results from four years of measurements demonstrated the atmospheric input of a wide range of N_r species across the European network, with the largest component contribution to estimated dry deposition resulting from gaseous ammonia (NH_3, Figure 3), which mainly originates from agricultural activities. The contribution from wet deposition ranges from <20%, e.g. in Spain, to >50% in parts of Northern Europe and the Alps. These results permit analysis of net greenhouse gas exchange in relation to atmospheric and agricultural nitrogen inputs across the NitroEurope IP network combined with carbon flux data from the CarboEurope network (Figure 3). A clear positive relationship can be seen between nitrogen inputs and gross primary productivity, which is moderated both by management and climate differences for each of the main ecosystem types considered.

For the 7 **Level-2 sites** low-cost flux methods were developed to provide cumulative sampling methods. A COnditional Time Averaged Gradient (COTAG; Famulari *et al.*, 2010) system was developed and tested to provide monthly average ammonia and nitric acid fluxes and was established at 15 of the Level-2 and Level-3 field sites across Europe. For measurements of soil nitrous oxide and methane fluxes a low-cost technique for sampling cumulative gases over long time periods (several weeks) was developed (Ambus et al, 2010). In this new approach, referred to as the SIGMA method (System for Inert Gas Monitoring by Accumulation), autochambers were applied for a period of 18 months at the Level-2 sites (Figure 5). A low cost approach was developed to estimate biological N fixation in intensively managed grasslands (Klump *et al.*, 2010).

Figure 2 The DELTA low-cost measurement system, at the Level-1 oak forest, Puechabon, France.

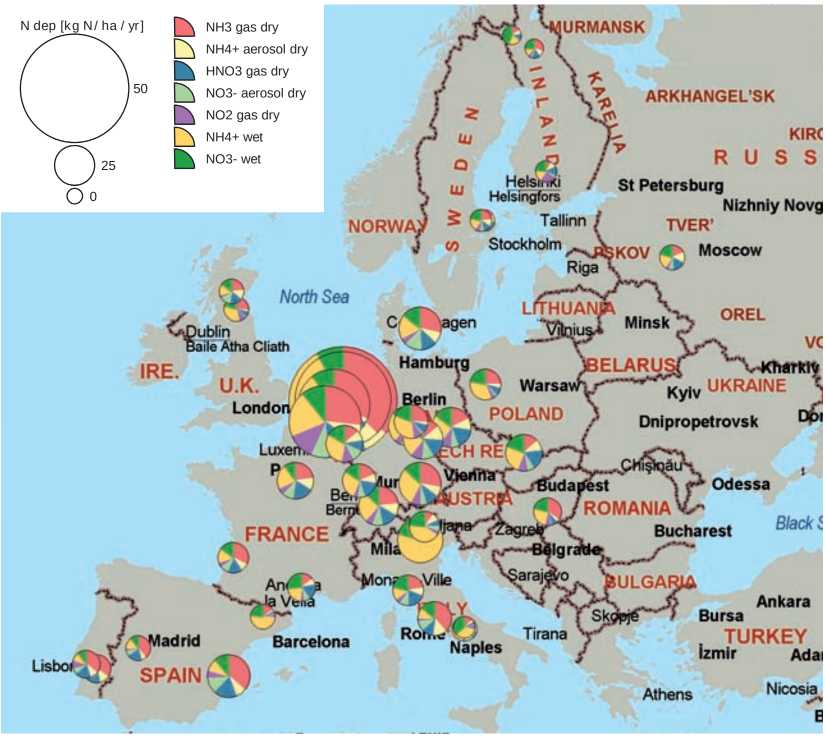


Figure 3 The composition of dry deposited nitrogen species to semi-natural vegetation across Europe, as measured and modelled by the Nitroeurope IP. Contributions from wet deposition include site based measurement and EMEP model estimates.

At each of the **Level-3** sites (4 forests, 3 grasslands, 2 wetlands and 4 arable fields; e.g. Figure 6) the major components of the nitrogen budget were measured at a high spatial and temporal frequency for 4.5 years. Measurement techniques included a combination of classical micrometeorological and chamber methods (Skiba *et al.*, 2009). Examples of nitrogen budgets for some of the Level-3 sites (Figure 7) demonstrate that in 'natural' ecosystems (forests, moorlands, shrublands, natural grasslands) the rate of atmospheric nitrogen deposition determines the rate of nitrogen losses. Atmospheric nitrogen deposition increases emissions of the greenhouse gas nitrous oxide, the atmospheric pollutant nitric oxide and the pollutant of waters, nitrate. In agricultural ecosystems nitrogen fertilisers and harvest products (i.e. grass, cereal, animals) dominate the

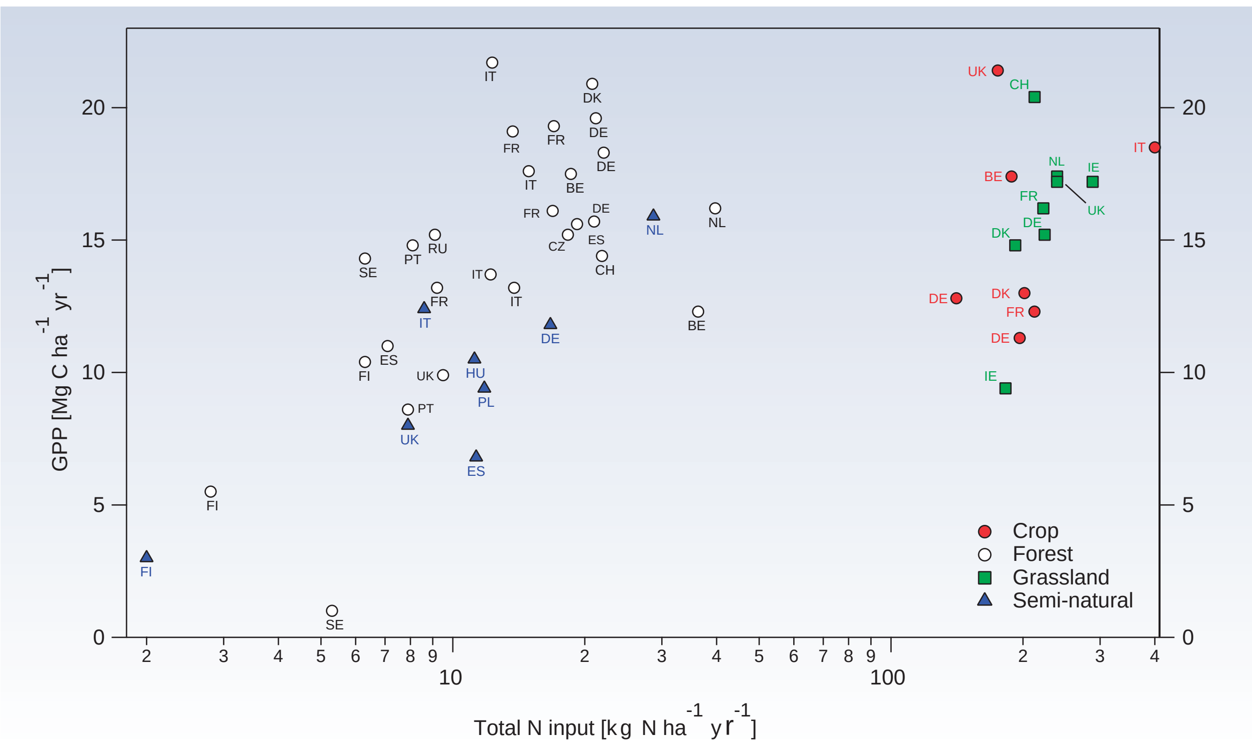


Figure 4 Nitrogen input effects on gross primary productivity (GPP). In semi-natural ecosystems GPP appears to be related to atmospheric nitrogen deposition, whereas in agricultural ecosystems nitrogen supply is dominated by nitrogen fertiliser additions.

Figure 5 The low-cost COTAG gradient mast + denuders and the SIGMA chamber. Both systems were developed in the NitroEurope IP and are shown here at the Level-2 alpine grassland 'Monte Bondone', Italy.

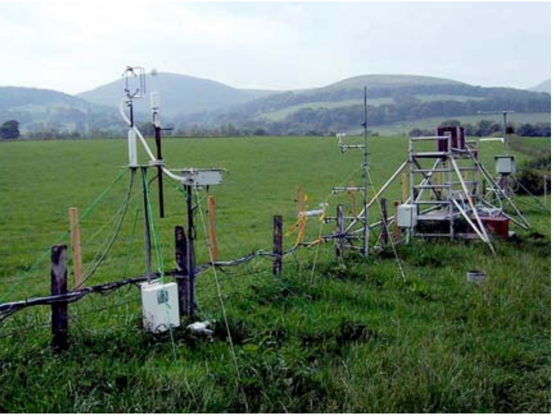


Figure 6 The intensive measurement station at the Level-3 grazed grassland 'Easter Bush', UK.

nitrogen budgets (Ammann *et al.*, 2010), while the conversion of fertiliser N to hay (e.g., CH-*Oen*) is much larger than the conversion to sheep (meat and wool) (e.g., UK-*EBu*).

Each of the **Level-3** sites were sinks for carbon dioxide (CO_2). At the arable and grassland sites the sink strength for CO_2 was offset by emissions of the much stronger greenhouse-gas nitrous oxide (N_2O). The application of nitrogen fertiliser (including grazing excreta at Easter Bush) was the main source of the N_2O. The rice paddy soil in Italy (IT-Cas) and the natural wetland in North Finland (FI-Lom) were large sources of the greenhouse gas methane (CH_4). At the grazed grassland in the UK (UK-EBu) the sheep (~7 adult sheep per hectare) were also a significant source of CH_4.

Overall, comparing this range of European ecosystems, nitrogen supply is expected to have the largest effect by altering the CO_2 sink strength and by increasing N_2O emissions. Wetland or grazing management (rather than N_r per se) were the main reasons for CH_4 emission, while the effect of N_r on methane uptake made only a small contribution to the net greenhouse gas exchange when expressed in CO_2 equivalents.

For the forest and peatland sites the results shown in Figure 6 highlight the large magnitude of N losses in response to increasing N inputs. The scale of these N losses clearly demonstrates

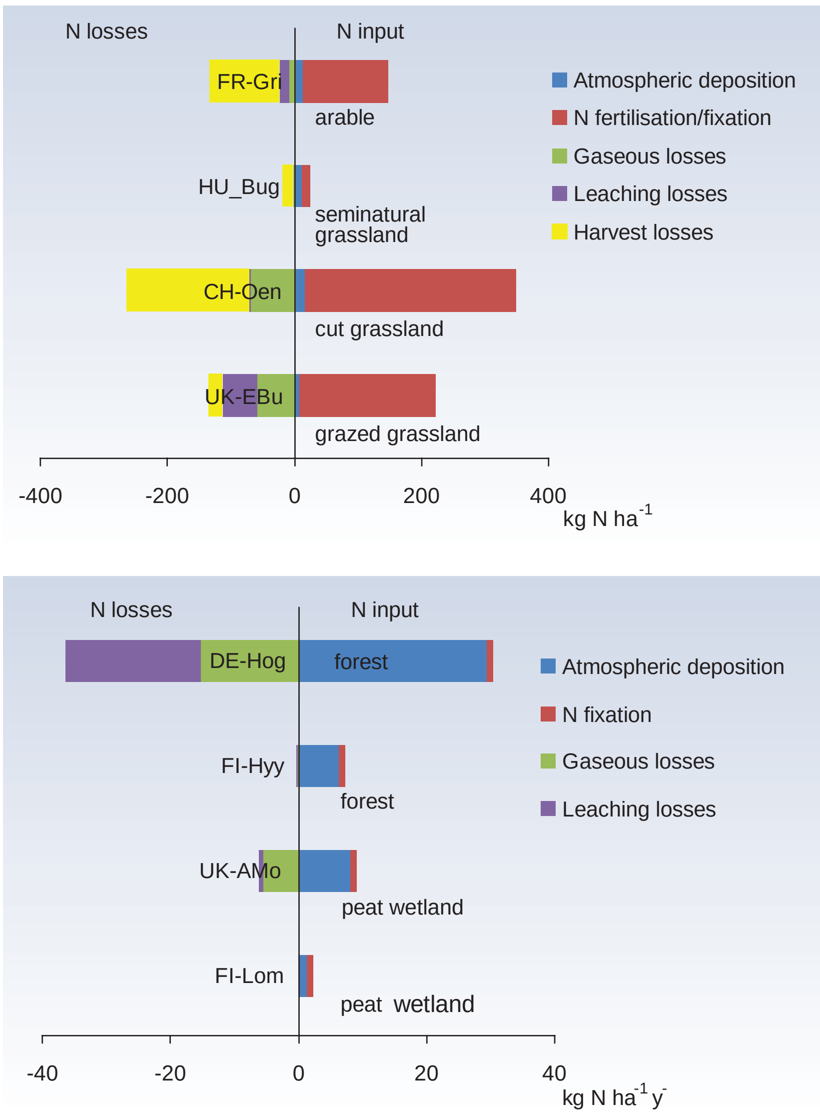


Figure 7 Nitrogen budgets at Level-3 sites. Nitrogen inputs are wet and dry atmospheric deposition, biological nitrogen fixation. Losses of nitrogen are harvest (the nitrogen content in crop or in animals leaving the field), gaseous losses of nitrous oxide, nitric oxide, ammonia and nitrogen gas and leaching of nitrate and organic nitrogen compounds.

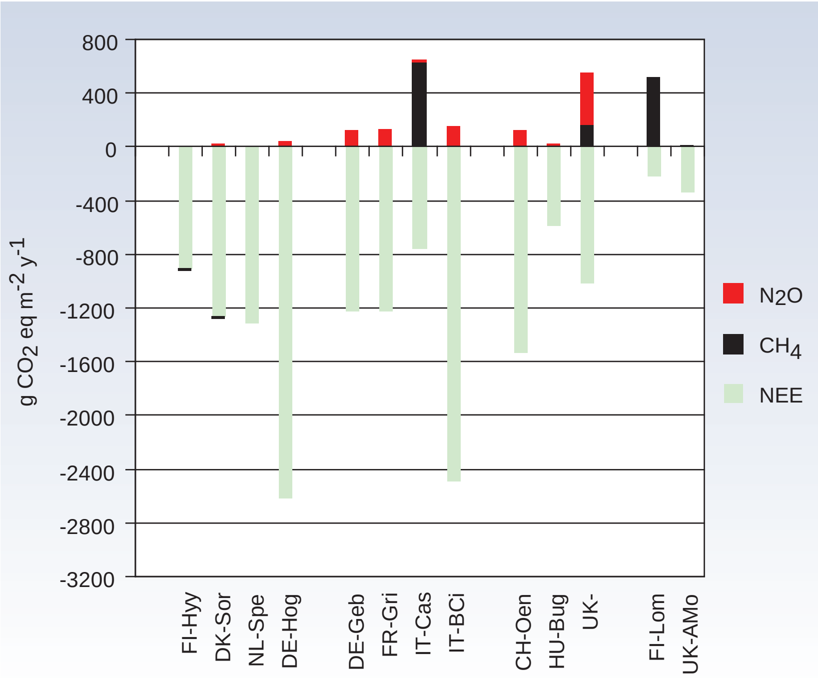


Figure 8 Field-level greenhouse gas budgets in CO_2 equivalents (i.e. taking into account the higher warming potentials of N_2O (298) and CH_4 (25)) for the Level-3 forests FI-Hyy, DK-Sor, NL-Spe, DE-Hog, the arable fields DE-Geb, FR-Gri, IT-Cas (rice paddy), IT-BCi, the grasslands CH-Oen, HU-Bug, UK-EBu, and the peat wetlands FI-Lom, UK-AMo. Negative fluxes = greenhouse gas sink, positive fluxes = greenhouse gas source.

why there are limitations to the increase in CO_2 updake in response to N deposition, as debated during the course of NitroEurope (Magnani et al., 2007; de Vries *et al.,* 2008; Sutton *et al.,* 2008). While some of the added N allows an increased carbon storage, at increasing rates of N input over half of the added N may be lost by increased emissions to the air (N_2, NO_x, N_2O) and water (NO_3, organic N_r).

Specialist flux measurements: In addition to the comprehensive

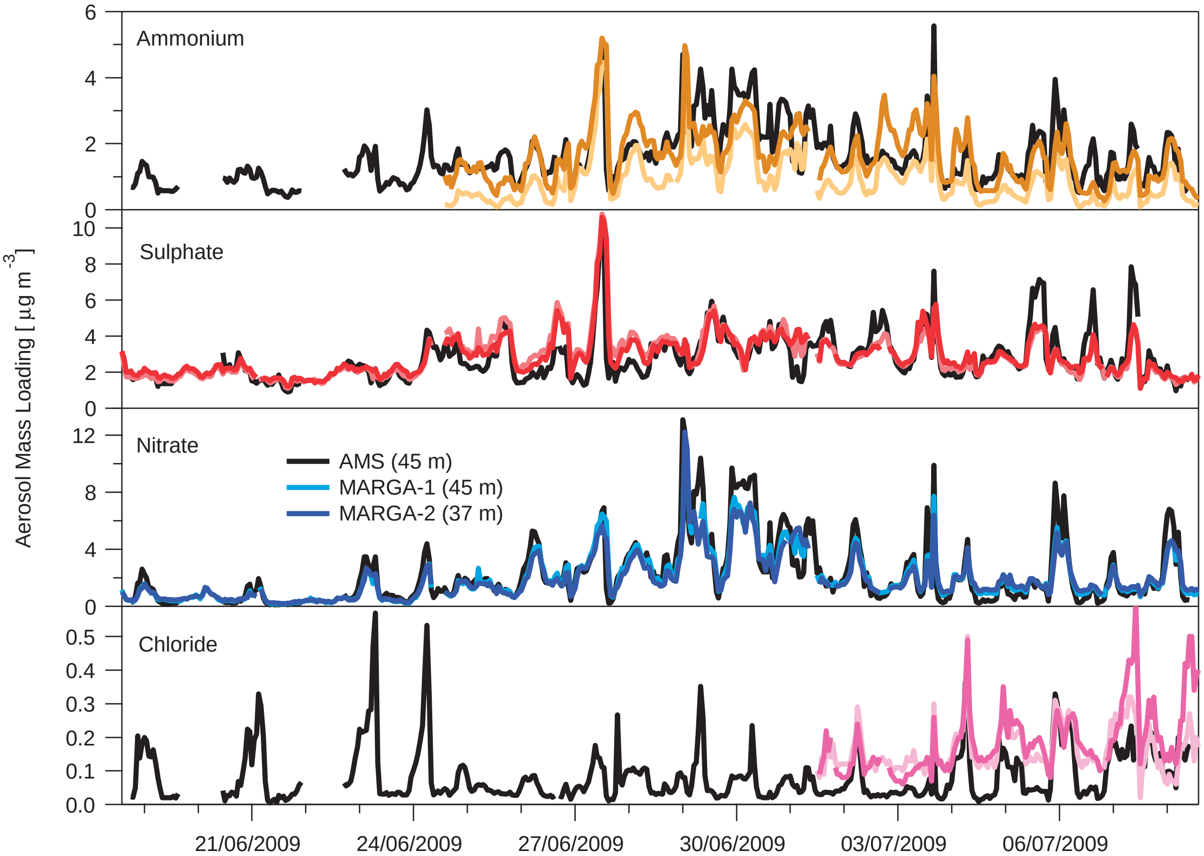


Figure 9 Time-series of the submicron aerosol chemical components, measured by the AMS (thin solid lines) and the MARGA at two measurements heights of 37 (dark coloured line) and 45 m (light coloured line) in the Dutch forest *Speulderbos* (Level 3 site).

Figure 10 Soils collected from the NitroEurope network to measure greenhouse gas fluxes under controlled conditions (Schaufler *et al.*, 2010).

programme of nitrogen and greenhouse gas budget measurements common to all Level-3 sites, the NitroEurope measurements included (a) the development of new advanced measurement and analysis approaches for the fluxes of individual nitrogen compounds and (b) their application at the Level-3 sites as 'Special Topic' investigations. Collaborative measurement campaigns included a validation study of flux chambers for nitrous oxide and methane (Christiansen et al. 2011), a field intercomparison of ammonia analysers (von Bobrutzki *et al.*, 2010) and an integrated field campaign at the *Speulder Bos* site (NL-Spe).

The aim of the Speulder Bos campaign was to study in detail the deposition of the nitrogen components contained in aerosol and the interaction between gas-phase ammonium (NH_3), nitric acid (HNO_3) and aerosol ammonium nitrate (NH_4NO_3), through measurements above and within the tree canopy. Figure 9 compares the aerosol composition

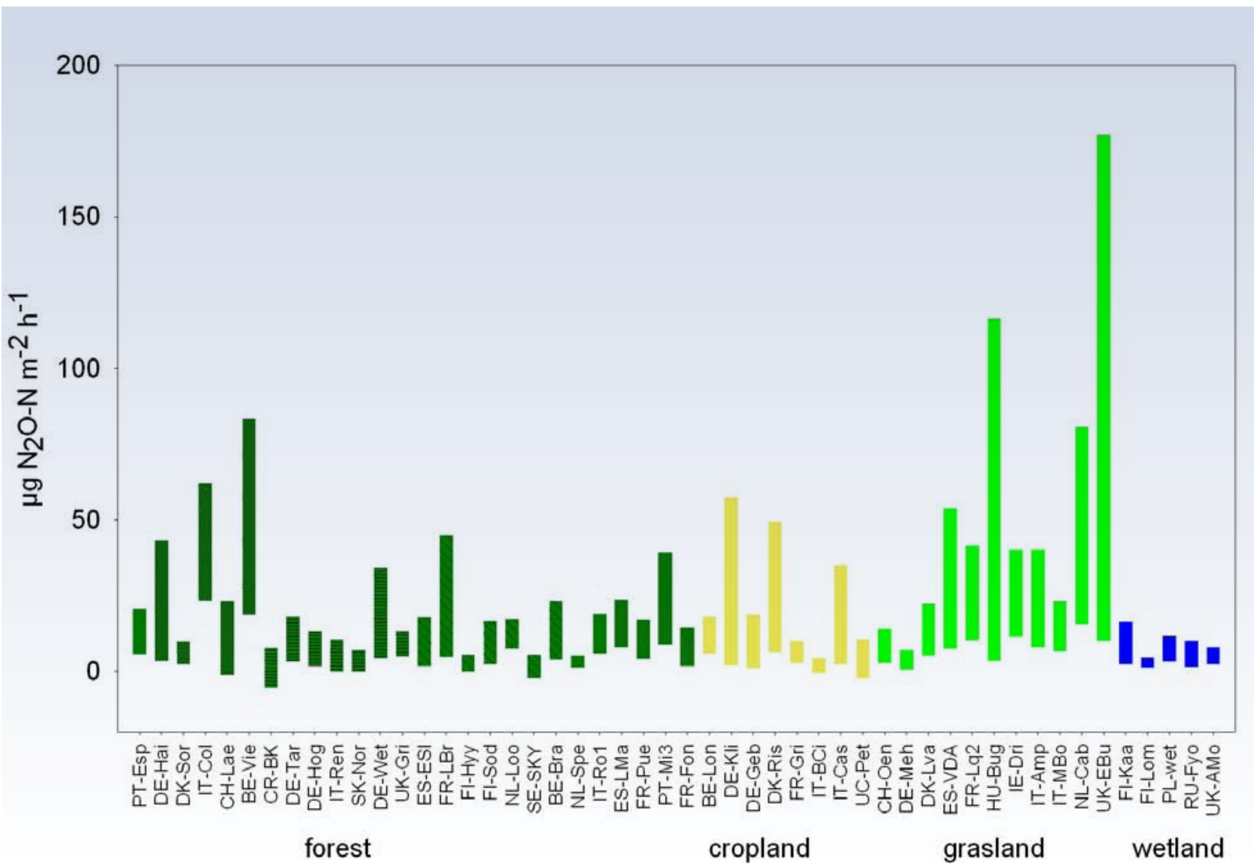


Figure 11 Variations in potential nitrous oxide fluxes across European forests (olive), croplands (yellow), grasslands (green) and wetland/shrublands (blue).

measured with a High Resolution Aerosol Mass Spectrometer (AMS) (De Carlo *et al.*, 2006) which detects PM_1 non-refractory aerosol mass that evaporates at 600 °C, with a wet-chemistry analyser (MARGA), based on a steam jet aerosol collector (SJAC), coupled to online chemical analysis by ion chromatography (Thomas *et al.*, 2008). This instrument detects the water soluble components in PM_1. This measurement dataset provides evidence of how gas and aerosol processes interact within the canopy air space during the course of emission/deposition, as also investigated over fertilized grassland (Nemitz *et al.,* 2009; Sutton *et al.,* 2009).

Soil, vegetation and microbial measurements In order to fully understand the nitrogen cycling in terrestrial ecosystems, it is important to take into account the plant and soil pools, processes and interactions between nitrogen and carbon. For this purpose soil and plant samples were sent from all measurement sites to NitroEurope partners in Italy, France, Denmark, Estonia, Austria and the Netherlands specialising in such analyses (Figure 10).

The measured data established empirical relationships which served as a basis for modelling to investigate the drivers and limiting factors of nitrogen cycling and greenhouse gas fluxes (e.g., Figure 11). In addition, a concerted effort was undertaken to assess the effect of fire in Mediterranean ecosystems (Figure 12). This enterprise triggered a large collaboration involving several new groups and served as an incentive for future European research in the area. Initial results showed that burning increased nitric oxide emissions, but reduced methane uptake and soil respiration rates.

Figure 12 The effect of burning on soil carbon and nitrogen pools and fluxes was studied in *Quintos de Mora*, Spain.

4.2 Manipulation experiments

Global, climate and land use changes will affect how N_r impacts on greenhouse gas emissions from terrestrial ecosystems. In order to understand the magnitude of such changes and the underlying mechanisms, experiments with major drivers of change were conducted at 31 sites across Europe in forest, arable, shrubland and grassland ecosystems (Figure 13), and intensive measurement campaigns of N_2O, CH_4 and CO_2 were conducted.

Forest Greenhouse gas exchange of mainly N_2O and CH_4 were measured for a wide range of European forests ranging from Sweden to Portugal and included coniferous and broadleaved forests. The manipulations included changes in N deposition, climate, soil hydrological condition, harvest intensity, wood ash addition, tree species and afforestation of arable land.

Soil hydrology dynamics was found to control the temporal and spatial variability of N_2O fluxes (Figure 14). Increasing soil temperatures also lead to elevated N_2O emissions by up to 73% compared to non-warmed plots (Figure 15). The emissions of N_2O were positively related to mineral soil N status (Figure 16), but responses of N_2O fluxes to N_r addition were negligible at a C:N ratio >25 in the mineral soil. For organic forest soils, soil pH and groundwater dynamics were found to be most important for N_2O and CH_4 dynamics.

The main factor controlling CH_4 emission was soil moisture with hydrological manipulations affecting emissions the most (Figure 14). In drier conditions where uptake of CH_4 dominates, the uptake rate showed a negative relationship with soil water content and inhibition of CH_4 oxidation by increased N_r levels in the soil was indicated. Increased soil temperatures decreased CH_4 uptake rates by 10–20% compared to non-warmed plots (Figure 15).

Figure 13 The climate change experiment CLIMAITE at *Brandbjerg*, Denmark, with manipulation of temperature, precipitation and atmospheric CO_2 in a shrubland ecosystem.

The changes of N_2O and CH_4 fluxes from external drivers on undisturbed forests are expected to occur on a decadal scale. However, management practices such as clear cuts can have immediate effects on GHG fluxes through changes in soil hydrology, soil temperature and N status. In aggrading forests fluxes of N_2O

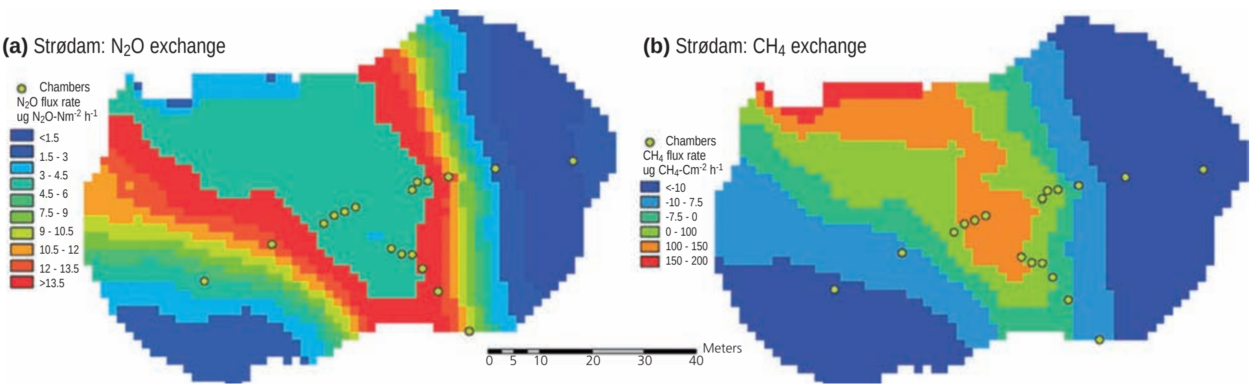


Figure 14 Spatial distribution of a) N_2O and b) CH_4 as controlled by hydrological conditions in a small beech forest catchment at Strødam, Denmark (Christiansen *et al.*, 2010).

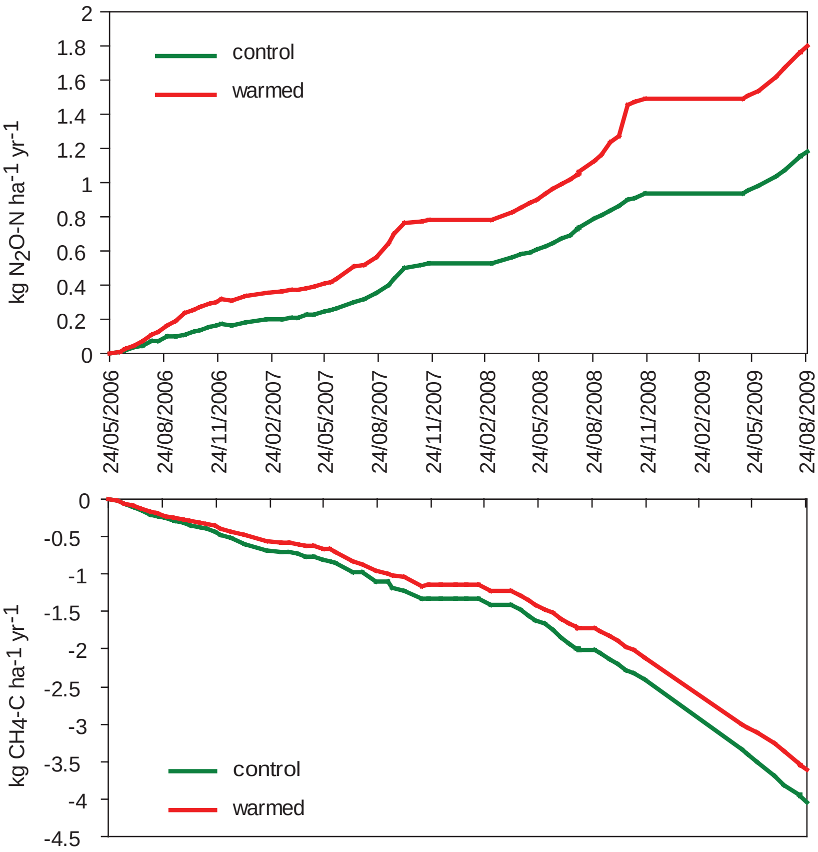


Figure 15 Effects of soil warming by 4°C at *Achenkirchen*, Austria. The graph shows how accumulated fluxes of N_2O (kg N_2O-N ha^{-1} y^{-1}) increase and CH_4 (kg CH_4-C ha^{-1} y^{-1}) decrease in the period 2006–2009.

and CH_4 are of little importance for the GHG balance since much CO_2 is sequestered in biomass, but as the forest matures and soil drivers (N status, pH etc.) favour GHG exchange, the importance of N_2O and CH_4 for the forest GHG balance increase.

Agriculture and grasslands

Agricultural soils are a major source of nitrous oxide in Europe, and management strategies to reduce greenhouse gas emissions are important. However, the effect of such management can be difficult to assess against a background of fluxes that are highly variable in time and space. A network of seven arable experimental sites in Europe and one in Zimbabwe has therefore focussed on nitrous oxide emissions and management related environmental drivers including alternative tillage treatments, organic and conventional system management, changes in nutrient management, land use change and drainage treatments.

Nitrous oxide fluxes varied widely between sites and as a result of manipulation treatments. Average site emissions (throughout the study period) varied between 0.04 and 16.85 kg N_2O-N ha^{-1} y^{-1} with largest variability associated with the grassland sites (Figure 17). Within the arable sites the fluxes varied between 1.0 and 4.9 kg N_2O-N ha^{-1} y^{-1}, with the highest fluxes observed from the Belgian tillage experiment at *Maulde*. Single variables were often poor predictors of emissions.

There was a large variability in fluxes related to mitigation treatments and generally greater than that among years and sites. In Zimbabwe the clearance of woodland and additions of N fertiliser were shown to be important in stimulating emissions, although annual emissions from most treatments were generally low (see Figure 18).

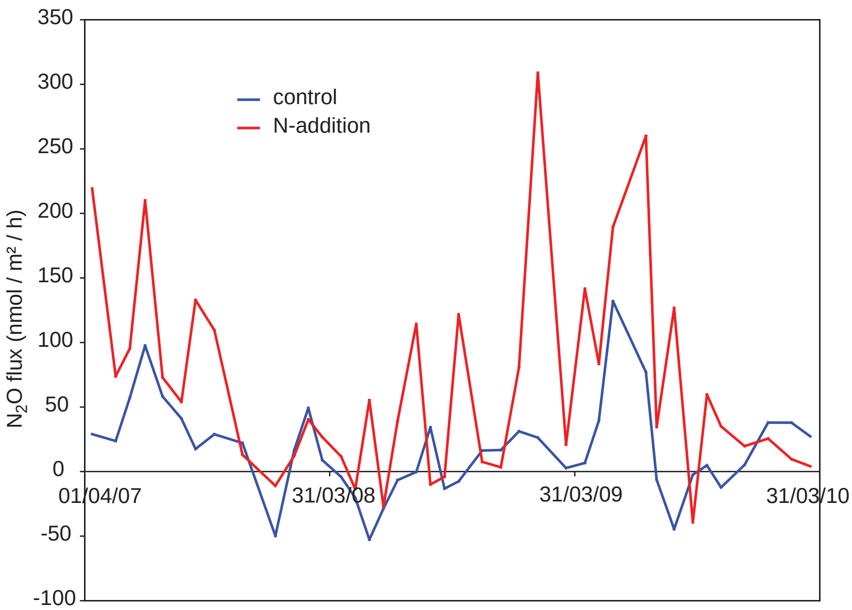


Figure 16 Effects of long-term nitrogen addition on N_2O fluxes from the soil at *Alptal*, Switzerland.

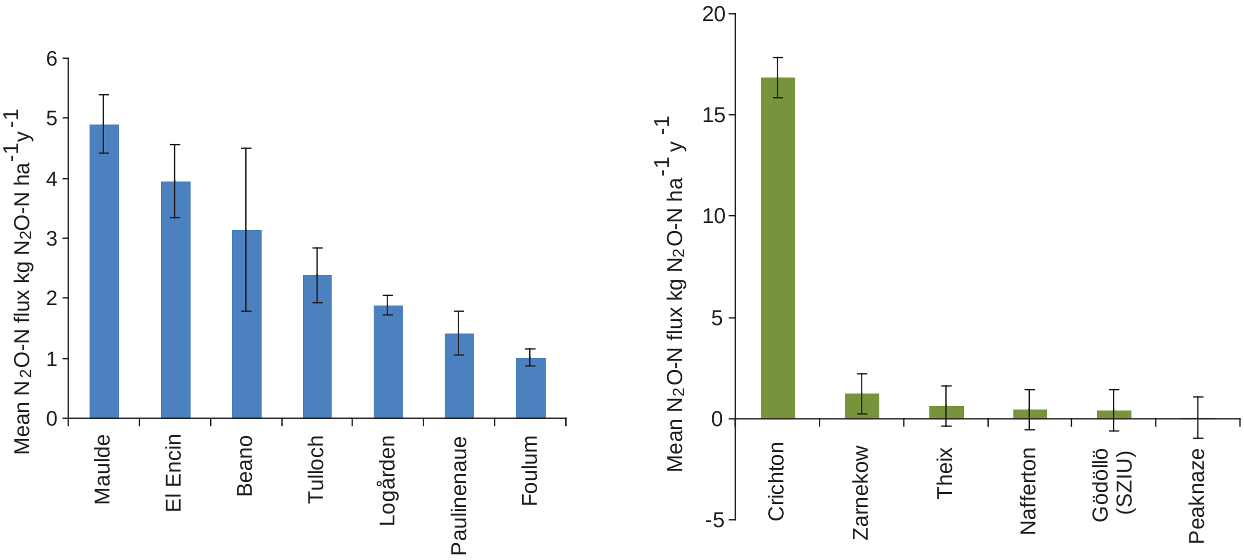


Figure 17 Nitrous oxide fluxes averaged across treatments and across years from the seven arable and six grassland sites included in the NitroEurope manipulation study. Bars represent standard errors.

Characterising the magnitude of potential mitigation is an essential prerequisite for the implementation of policies designed at reducing greenhouse gas emissions from the agricultural sector. It has been suggested that interventions that include better nutrient use efficiency, improved soil management and improved agronomy could achieve a reduction in emissions of 10 to 30%.

Shrublands Measurements of GHG exchange were conducted in nine European shrubland manipulation experiments with manipulation of climate related factors and nutrient and water availability. Among the shrublands, GHG exchange exhibited large spatial heterogeneity and fluxes were generally small, typically dominated by CO_2, although the wetlands do provide peak fluxes of CH_4 at times.

Changes in N_2O fluxes were mostly dominated by hydrological changes such as drought/rewetting or changes in water table depth, but were also strongly dependent on nitrogen availability, with weaker interactions with temperature and nutrient availability (Table 1). Nitrogen form (dry deposited ammonia gas or wet deposited ammonium or nitrate) was also important for N_2O emissions in peatlands (NH_3 and NO_3^- > NH_4^+, see Figure 19) and linked to the concentration of nitrate in the surface soil water in peatland, likely as a consequence of nitrification. Drought reduced the flux of N_2O and CH_4, but generally not CO_2 (Figure 20., from Sowerby *et al.* 2010). N_2O emission showed significant interactions among climate related factors (Figure 21, from Carter *et al.*, 2011)

Fluxes of CH_4 were generally characterised by oxidation rather than emission, except

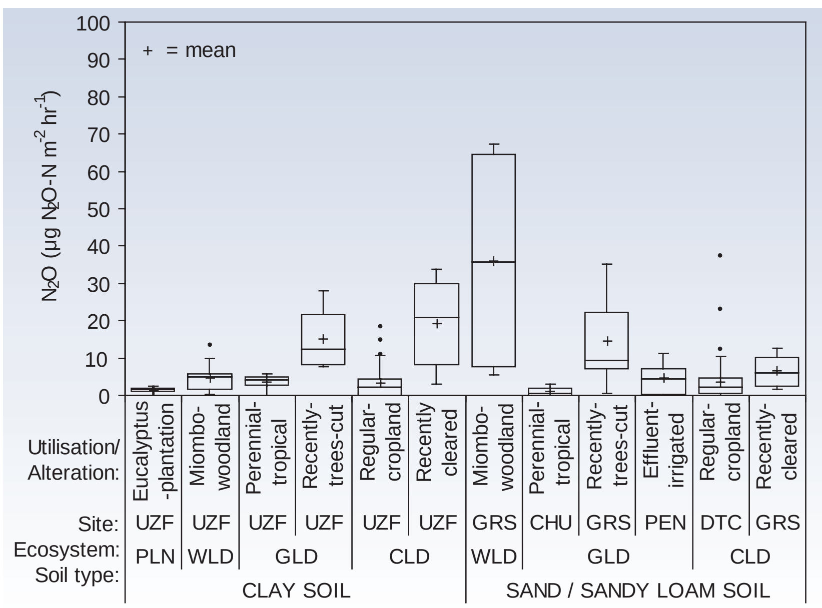


Figure 18 Nitrous oxide emissions from a range of land use systems in Zimbabwe.

Table 1 Summary of drivers for GHG fluxes in shrublands as found in NitroEurope.

	N_2O	CH_4	CO_2	Indirect effects and interactions
Water	Dominant driver (if N status allows N_2O emissions). Precipitation variability, water table changes, drying/rewetting. (Carter *et al.*, 2011; Sowerby *et al.*, 2010)	Dominant driver. Water table, rewetting pulses. (Carter *et al.*, 2011; Sowerby *et al.*, 2010)		Repeated drought have long term effects on soil structure, soil carbon and microbial community (Sowerby *et al.*, 2008; 2010)
Nitrogen	High N status is main pre-requisite for N_2O emissions (Carter *et al.*, 2011)	N form important in wet bogs		N form or high levels of N may affect species composition affecting GHG emissions. Nitrogen input affects on pH—relevant for studies on various N forms
Temperature	Potential minor effect through stimulated N availability and interactions with labile C in elevated CO_2 (Carter *et al.*, 2011).	Minor effect on effluxes from wetlands. Warming increase CH_4 uptake at well-drained heathland site (Carter *et al.*, 2011)	Reduced at drought (Sowerby *et al.*, 2010)	Remove water and potentially nitrogen through growth stimulation—potential effect on N_2O emission
Other Nutrients		No effect	Short term stimulation of emission by nutrient addition if microbes limited (Lund *et al.*, 2009). Stimulate plant uptake (Lund *et al.*, 2009)	
Management				Management/disturbance is not an issue for most of the shrubland sites except from catastrophic events such as wild fires.

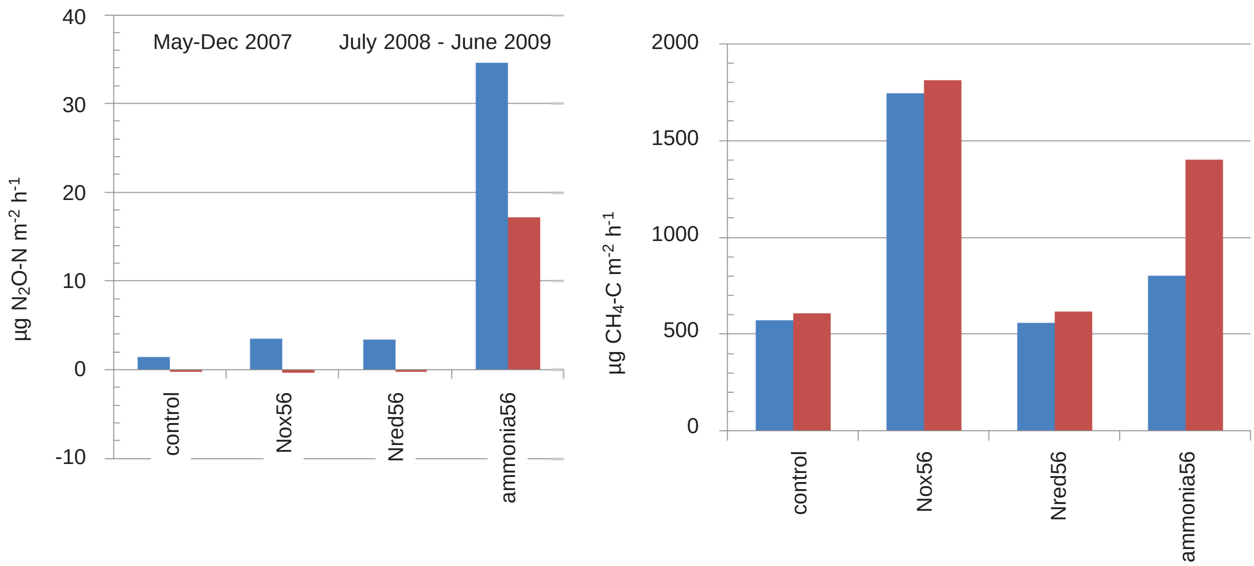


Figure 19 Mean N_2O-N and CH_4-C fluxes between May and December 2007 (blue) and July 2008 and June 2009 (red) measured using static chambers on a peat bog *Whim* in the Scottish Borders treated with additional precipitation, control (0 kg N ha^{-1} y^{-1}), sodium nitrate (Nox56), ammonium chloride (Nred56) or exposed to ammonia, through free air release, at 56 kg N ha^{-1} y^{-1} since 2002. (n=10, the error bars are large due to spatial heterogeneity and only the effects of ammonia on N_2O fluxes are significant).

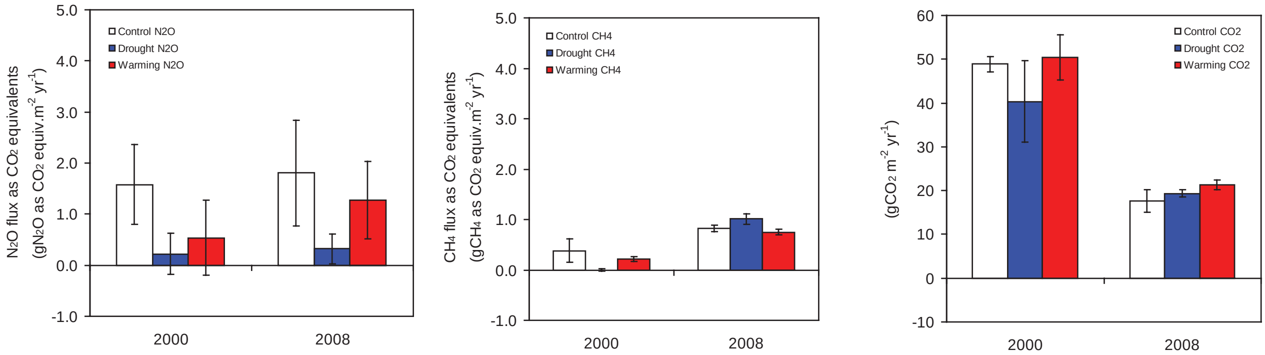


Figure 20 GHG flux from the *Clocaenog* site; measured in 2000 (following 1 drought period) and 2008 (following 10 repeated summer drought periods). All data converted to GHG equivalents, based on conversion values in IPCC 3rd Assessment Report (2001). Note: the change in scale between N_2O/CH_4 and Soil respiration. Error bars show the standard error of the mean, n=3.

from wetlands and were largely controlled by water table depth and rewetting cycles. The CH_4 uptake increased with increasing soil temperature and decreasing soil moisture, while nutrient availability had no effect (Lund *et al.*, 2009). Nitrogen form also affected the CH_4 emissions in wet bogs with high CH_4 emissions associated with nitrate addition related to increased soil pH. The risk from N deposition increasing CH_4 and N_2O production is relatively small unless peatlands are close to an ammonia source <1 km, or until the level of N deposition starts to impact the vegetation *i.e.* reduce moss or higher plant cover.

Generally, GHG fluxes at the sites were dominated by soil respiration (e.g. Sowerby *et al.* 2010). Therefore factors affecting the carbon uptake in plants (e.g. nitrogen, nutrients and water availability) or release from the soil (e.g. water and temperature) are important for the overall GHG exchange. Repeated drought treatment has had the most significant impact, with impacts being seen throughout the year, not just during periods of drought or re-wetting following the drought (Sowerby *et al.*, 2008; 2010).

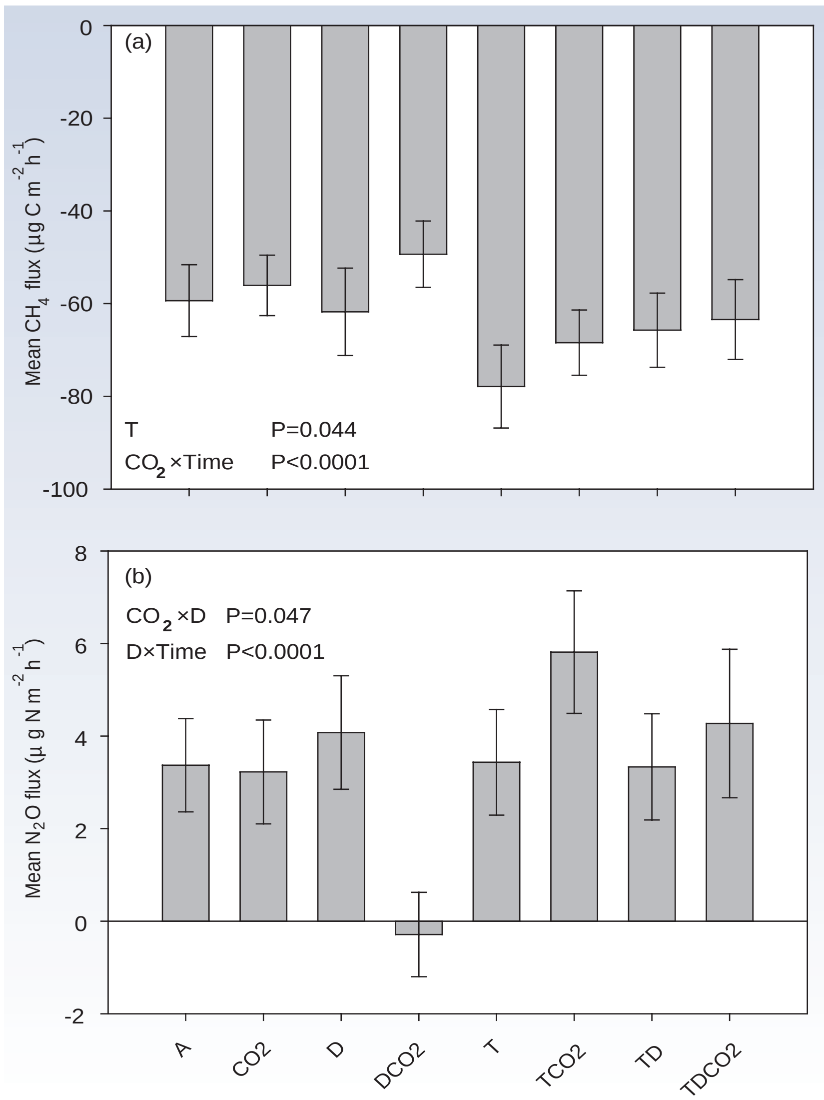


Figure 21 Mean CH_4 fluxes (a) and mean N_2O fluxes (b) across measuring campaigns in the full-factorial study at *Brandbjerg* (DK) for the ambient treatment (A) in addition to elevated CO_2 (CO_2), drought (D) and elevated temperature (T) as single treatments and in all combinations (CH_4, n=54; N_2O, n=66; means ± SE). Figure from Carter *et al.*, 2011).

4.3 Plot-scale modelling of C-N interactions

The main focus of the plot scale modeling work has been on the further development and provision of biogeochemical models for an improved simulation of C and N cycling in terrestrial ecosystems and associated C and N trace gas exchange. A focus of model development at the site scale has fed into upscaling to landscapes and the European scale. Several models have been involved, specifically the multi-ecosystem models COUP, DailyDAYCENT and MOBILE-DNDC, the agro-ecosystem models CERES-EGC, ECOSSE and FASSET as well as ecosystem specific forest (BASFOR) and grassland models (PASIM and PROGRASS).

Even though the most advanced biogeochemical models have been included in NitroEurope, the models still have weaknesses with regard to the representation of specific soil-plant processes and/or uncertainties about environmental drivers and parameter values (Van Oijen *et al.,* 2011). To narrow these shortcomings, protocols for various aspects of *Uncertainty Quantification* and *Uncertainty Analysis* (UQ/UA) were developed and applied. An innovative aspect here was the use of *Bayesian Calibration* for assessing parametric uncertainty and improving parameterization of parameter-rich biogeochemical models. This approach allowed e.g. to quantify uncertainties of model outputs in comparison to field measurements (Figure 22), to identify model weaknesses and over-parameterization of processes requiring further improvements or simplifications. It could also been shown that *Bayesian Calibration* is a promising tool to quantify and reduce uncertainties in initial carbon distribution in the most widely applied soil biogeochemical models. This is of outstanding importance, since the initial distribution of soil organic matter into two or more kinetically defined conceptual pools influences the simulations of biosphere-atmosphere-hydrosphere exchange of CO_2, N_2O, NO_3 and other C and N compounds (Yeluripati *et al.*, 2009). Giving a specific focus to N_2O emissions at various arable field sites in France, the work of e.g. Lehuger *et al.* (2009) shows that *Bayesian Calibration* of the nitrous oxide emission module of the agro-ecosystem model CERES-EGC model allowed significant reduction in uncertainties in in simulated soil N_2O emissions. Based on this type of work carried out within NitroEurope it will be possible to obtain more realistic estimates of N_2O emissions from arable soils at regional or continental scales.

On the basis of the evaluation of model uncertainties, NEU stimulated the further improvement of model structures and process descriptions. An example of this is the evaluation of competing hypotheses on processes driving spring-thaw N_2O emissions, with spring-thaw N_2O emissions being periods which may dominate annual N_2O emissions in cool temperate climates. Figure 23 shows, that implementation of three competing hypotheses

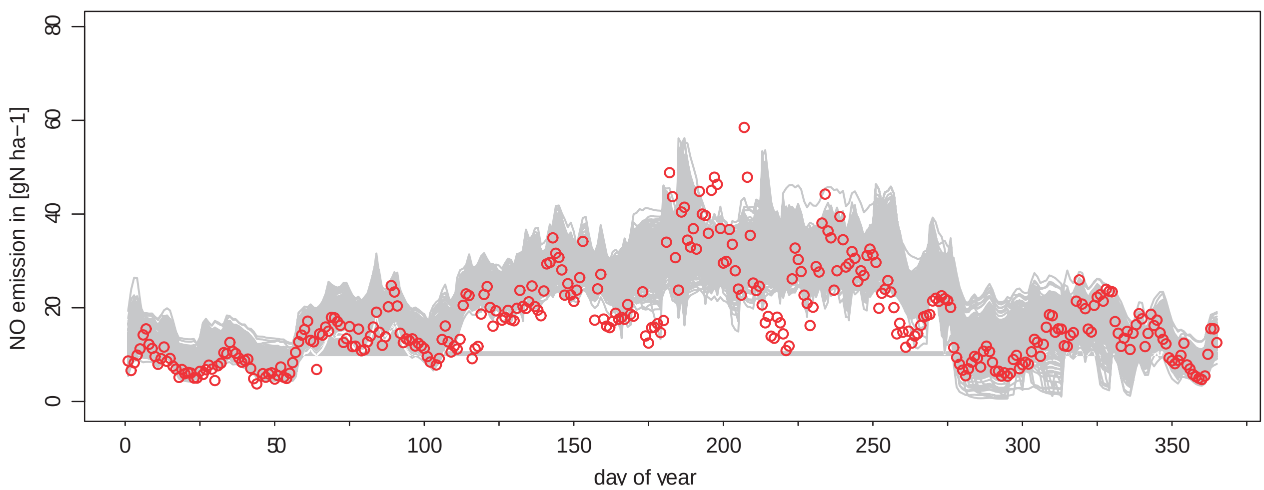


Figure 22 Annual time course of measured and simulated soil NO emissions at the NEU Level-3 site *Höglwald*, Germany. The shaded area represents the model uncertainty due to uncertain values of model parameters needed for simulating soil NO emissions.

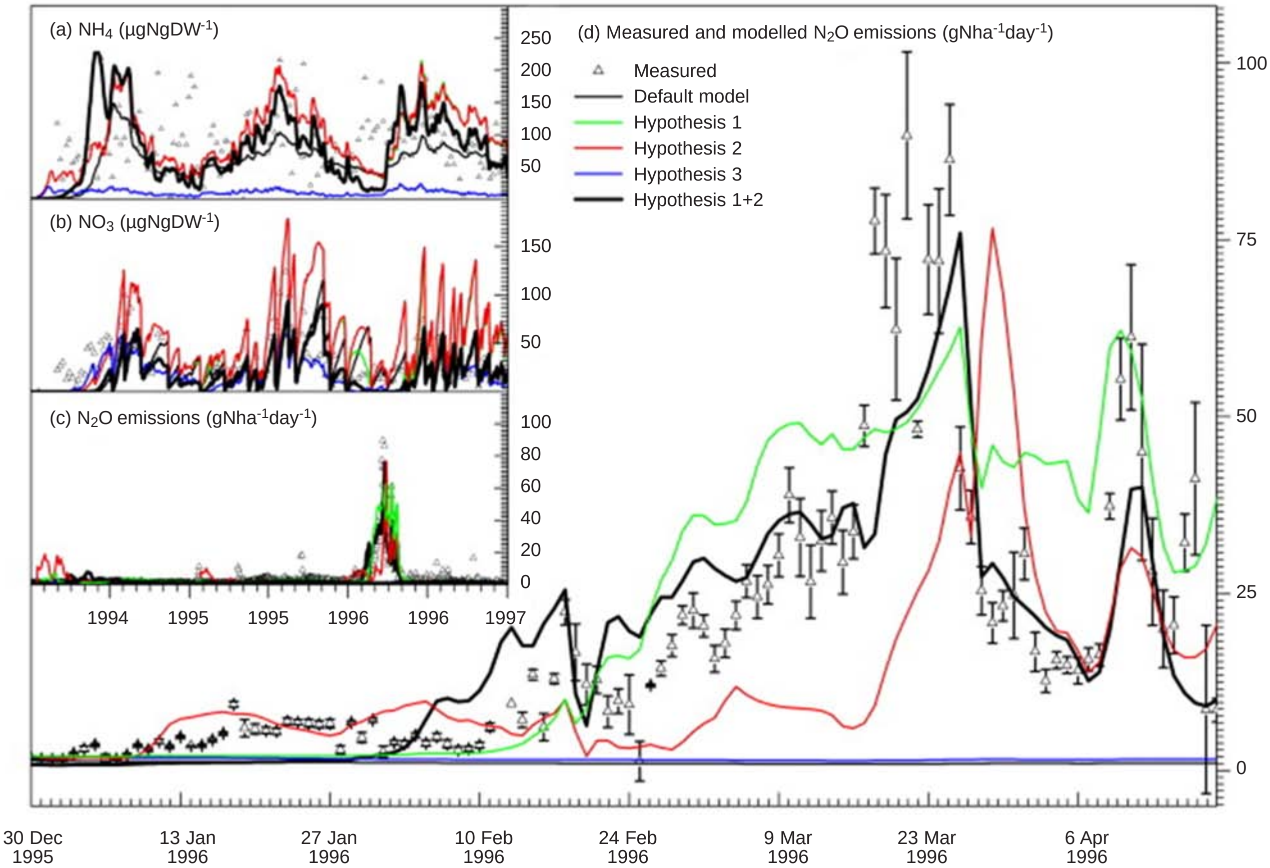


Figure 23 Simulated and measured ammonium concentration in the upper soil 1994–1997, (b) nitrate concentration in the upper soil 1994–1997, (c) N_2O emissions from the soil 1994–1997, (d) close up of the freeze–thaw event in spring 1996. Hypothesis 1: Lower oxygen diffusion stimulates anaerobiosis and denitrification, Hypothesis 2: Microbes, dying of frost, deliver dissolved organic carbon to the soil which drives growth when temperatures increase again, Hypothesis 3: N_2O reductase is more sensitive to lower temperatures than other N-reductases. Please note that Hypothesis 1 and the default simulation cannot be identified in the figure because they are both very near to the axis (De Bruijn *et al.*, 2009).

in one of the NEU core models allowed on the one hand to identify relevant processes and mechanism and on the other hand to dismiss other explanations. It further demonstrates that a close cooperation of measuring and modelling communities is needed to further advance the state of knowledge, while providing the theoretical basis to understand unexpected observations. For example, research published in *Nature*, of how grazing can actually decrease N_2O emissions in continental steppeland (Wolf *et al.*, 2010).

One of the major tasks of the plot scale modelling component was the application of models to various field sites of the NitroEurope network in order to gain a better understanding of N and C cycling and N_2O emissions at ecosystem scale for various systems across Europe. Figure 24 shows results of the application of two NEU core models (FASSET, MOBILE-DNDC) to the experimental site at *Foulum*, Denmark (Chirinda *et al.*, 2011). By this thorough testing of models at various field sites confidence was gained that models are ready for regional application for European upscaling. To facilitate regional application some models were re-structured to speed up computational performance and further processing of results, e.g. for the calculation of national and European wide inventories.

Another aspect of this work has been the simulation of impacts of alternative farming management practices on ecosystem N dynamics and N_2O emissions. The aim of this activity is to identify at various field sites of the NitroEurope network potential mitigation options for GHG emissions. This work also helps in quantifying the sensitivity of different input parameters on model results, especially N_2O emissions and crop productivity. Figure 25 shows simulated N_2O

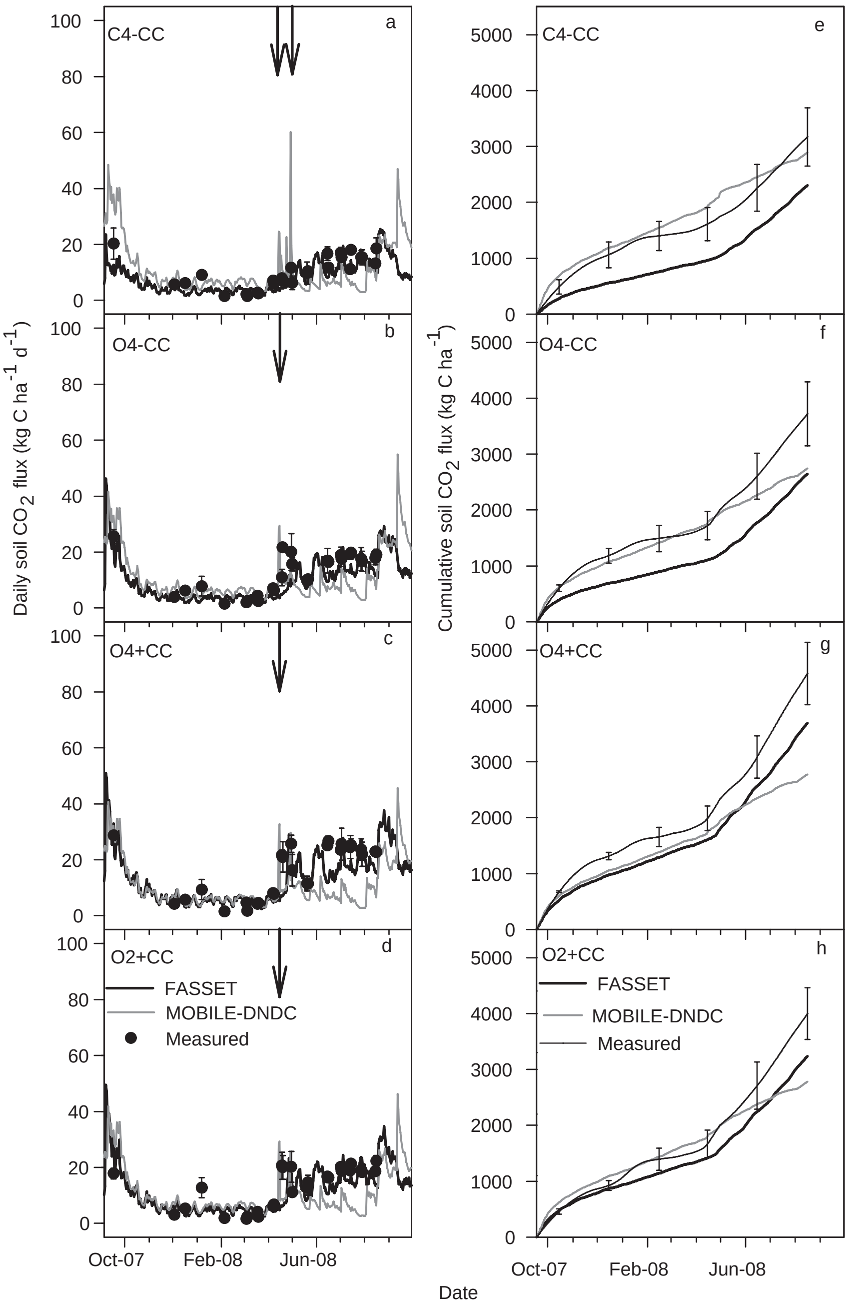


Figure 24 Daily and cumulative soil heterotrophic CO_2 respiration as predicted using the FASSET (thick black lines) and MoBiLE-DNDC (grey lines) models and compared with field measurements (closed symbols and thin black line with error bars) in plots from one mineral fertilizer based (C4–CC) and two organic rotations with (O4+CC) and without (O4–CC) a catch crop and also an organic crop rotation that included a grass-clover ley and catch crop (O2+CC). Field measurements are means of two replicates. The arrows indicate times of fertilization. Bars indicate standard error (n=2).

emissions following balanced N fertiliser application as compared to normal fertiliser application at the *Grignon* arable site using the ECOSSE model. If fertiliser is applied to meet the crop demands (*Balance N fertiliser*)—with yields remaining unaffected—total cumulative N_2O emissions in the period between 16/07/2003–22/04/2008 can be reduced from 8.8 kg N_2O-N/ha to 6.9 kg N_2O-N/ha, a reduction of about 22%.

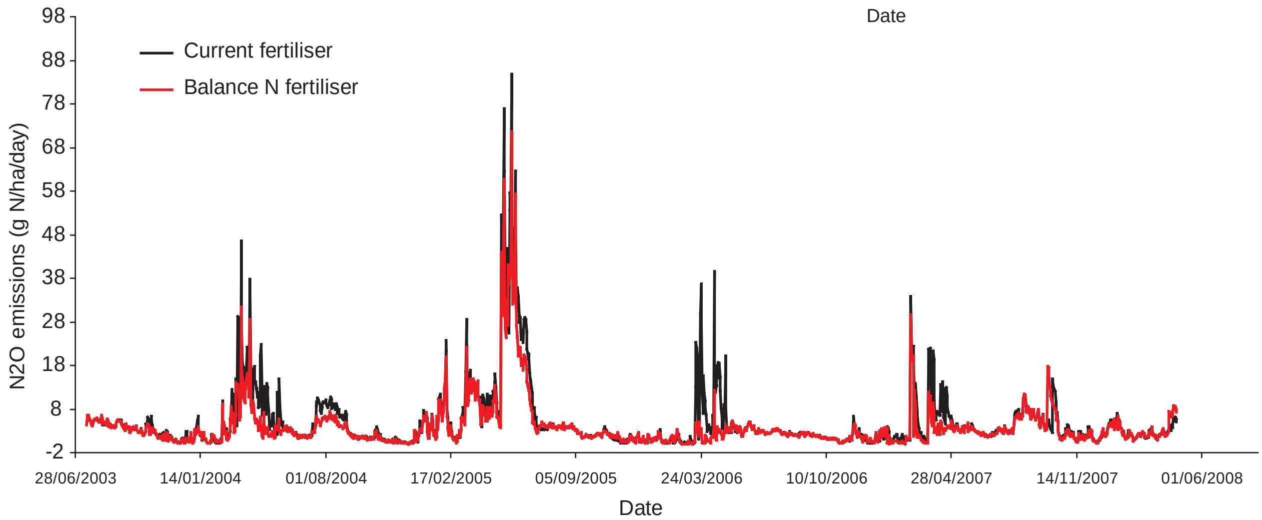


Figure 25 Simulated reductions in soil N_2O emissions by balance N fertiliser application as compared to normal fertiliser application from 16/07/2003–22/04/200 at the Grignon arable site.

4.4 Landscape analysis

In rural landscapes, upscaling from the plot to the regional scale involves accounting for the complex interactions between individual landscape elements (patchwork of crops, grassland, forest and other ecosystems, hedgerows, rivers, farmsteads, *etc.*) as well as their relations with farm management. Up to now, neither regional nor plot models include those effects of local spatial interactions and the constraints/possibilities implied by decisions on N management at the farm and landscape levels on GHG and N_r fluxes. The landscape analysis within NitroEurope aimed at filling this gap by investigating such interactions for European landscapes in an explicit spatial context (land use, topography, hydrology, *etc*) and with a special focus on N_r interactions with GHG fluxes. This work has been organised around (i) the development of a landscape model, the so-called *NitroScape* model, (ii) its verification on a network of European landscapes and (iii) scenario studies using this model for investigating environmental and policy issues.

The landscape analysis was naturally linked with other NitroEurope components. At smaller scale, it makes it possible to link between sources and sinks, integrate farm management and perform assessment of indirect effects due to spatial relationship. At larger scale, it allows assessing the importance of local heterogeneity and local interactions when upscaling, and analysing sub-grid processes.

Establishing a network and a database for European landscapes

One key output is the establishment of a network of European landscapes aiming at studying the N flows and processes and their consequences in agricultural areas. Six landscapes (in Denmark, France, Italy, The Netherlands, Poland and Scotland) were selected to be representative of the variability in climate and farming systems in Europe. They all include livestock farming and local sensitive ecosystems. This should make it possible to analyse not only biogeochemical cycles and GHG/ N_r fluxes and budgets, but also other issues such as impact on biodiversity, air and water quality. The establishment of this network required developing a dedicated database, as well as defining rules for data collection in farm survey, maps and data needed to verify the landscape scale model.

A landscape database was conceived using an *Open Source Relational Database Management System* (PostgreSQL) established at the landscape Data Centre of NitroEurope-IP (http://www-egc.grignon.inra.fr/datum/). It integrates data of very different types: meteorological data, biophysical variables, farm survey data and spatial data. The database structure was designed to ensure consistency between data collected by different partners and consistency between

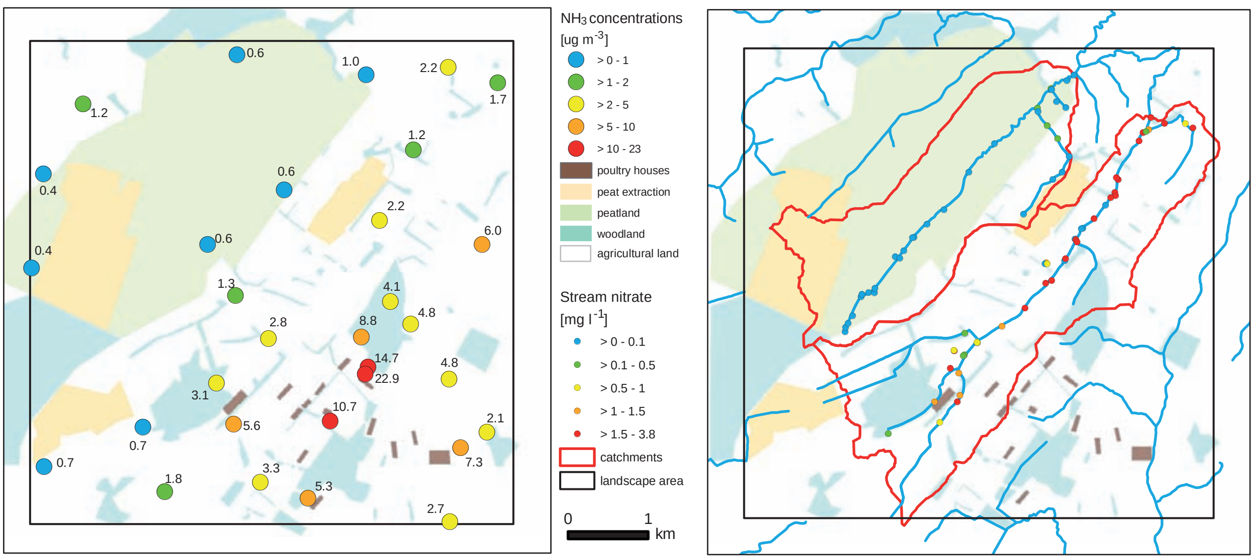


Figure 26 Example of verification data measured in the Scottish landscape: average ammonia concentration from April 2007 to March 2008, measured with Alpha samplers.

NitroScape inputs/outputs and field/farm/landscape data regarding units and temporal/ spatial resolutions (Drouet *et al.*, 2011).

Data collection for studying landscapes includes consideration of the nitrogen issues to be studied, and balance the size of the study area against the effort of collecting and processing detailed data. To achieve this, a methodology had to be developed that uses generic, re-useable method/ tools to be applied over a range of landscapes, collect the appropriate level of detail for the needs of the modellers, provides technical support for data collection from farmers, data cleaning and entry into a common system, checking consistency and respect confidentiality of data where required. The reflections and application to the six NitroEurope landscapes allowed deriving rules for setting-up surveys at landscape scale that might be applicable for other landscapes and other issues (Dragosits *et al.*, 2011).

Another strategic issue at the landscape scale is to verify a model, *e.g. NitroScape*. Faced with the large heterogeneity in flows of reactive nitrogen (N_r) in a landscape, landscape scale analysis requires a more integral approach than at plot scale that combines measurement techniques to characterize the flows of reactive nitrogen. The word 'characterise' is used in recognition that it is not possible to measure all N_r flows at all locations in a landscape, and therefore the measurements provide indicators of characteristic flows rather than a complex set of actual values that could be compared to model outputs. A common strategy was established and applied to all landscapes (Theobald *et al.*, 2011).

More detailed measurements aiming at studying specific landscape processes (*e.g.* atmospheric plumes, transects in the streams) were performed during a common experiment in the Danish landscape where the skills of the different groups involved in the NitroEurope landscape analysis were gathered.

Landscape modelling

Modelling provides a tool to explore and quantify the complexity of interactions in landscapes. This requires modelling a range of natural and anthropogenic processes over a range of space and time scales,

making sure that all relevant processes and their possible interactions are accounted for. Models exist for the major landscape elements (agricultural land, forestry, wetlands, surface waters, farms) but linking these models into a coherent entity represents a challenge.

The *NitroScape* model couples four existing types of models (atmospheric, farm, agroecosystem and hydrological models) to simulate N_r fluxes within a landscape in a spatially distributed and dynamic way (Duretz *et al.*, 2011). A key-issue was to ensure consistency between models in terms of time and space scales, as well as representation of processes and exchange of variables.

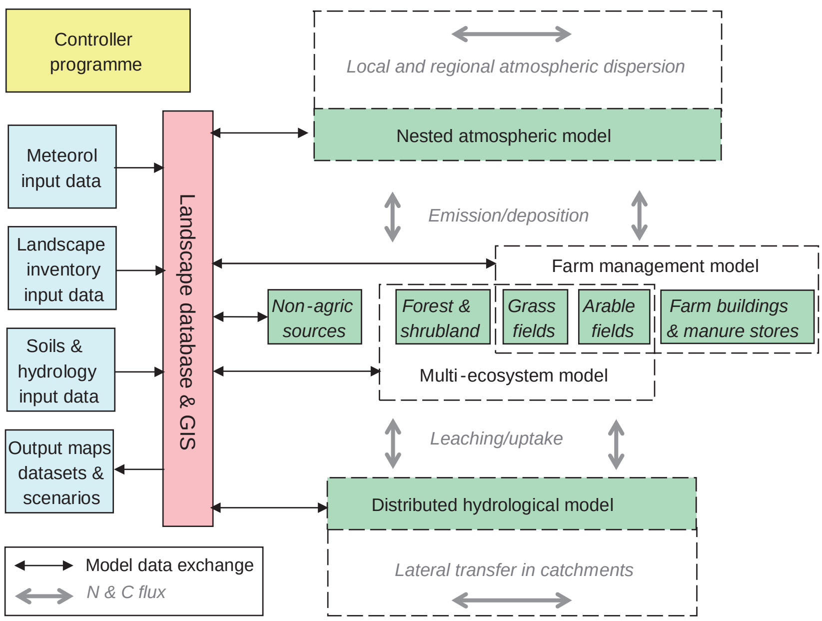


Figure 27 NitroScape modelling framework.

Consequently, the selection of the models was critical. The second stage was to choose the best way to have the selected models work together. The Palm® coupler, developed at *Cerfacs* mostly for atmospheric research and data assimilation, was selected.

In order to highlight the main issues at landscape scale, simulations were carried out on a theoretical landscape with pig farms (large N_r source), crops and fallows (mostly sink for N_r). Simulations showed the effect of spatial interactions between landscape elements and short-range transfers on N_r fluxes and losses to the environment. As expected, the position of ecosystems relative to the farmstead was critical, but *NitroScape* made it possible to quantify the magnitude of deposition and emission fluxes, as well as to analyse their variability in space and time and their dependence on local factors. More than 10% of N_2O emissions were due to indirect emissions caused by either short-range ammonia deposition or nitrate transfer through groundwater. The nitrogen budgets and transformations of the low-nitrogen ecosystems varied considerably, depending on their location within the landscape. *NitroScape* thus represents a new tool for assessing the effect of landscape structure and possible changes in farm management or environmental measures on N_r fluxes.

NitroScape was also used to investigate the importance of natural and anthropogenic processes at landscape scale. First, the spatial interactions and their effects on the additional N_2O emissions were estimated using four configurations of *NitroScape* which considered, or not, different types of transfer within the landscape. Indirect N_2O emissions were shared approximately equally between atmospheric and hydrological transfers. *NitroScape* made it possible to identify the origin and the driving factors (*e.g.* land use, landscape heterogeneity) of these emissions. Second, *NitroScape* was used to compare the N flows of two scenarios: an overall reduction in N inputs of 20% across the entire cereal area, or the establishment of unmanaged buffers along the streams and the semi-natural areas corresponding to taking 20% of the cereal area out of production, but maintaining N total inputs to the cereals at the landscape scale. It showed that some fluxes were significantly affected (*e.g.* ammonia volatilization and deposition, nitrate leaching) while others were not (N_2O emission, N output though the stream). Of course, these results are scenario dependent, but this illustrates the potential of a landscape model to analyse complex situations at landscape scale and derive rules that can be useful for decision-making and environmental protection.

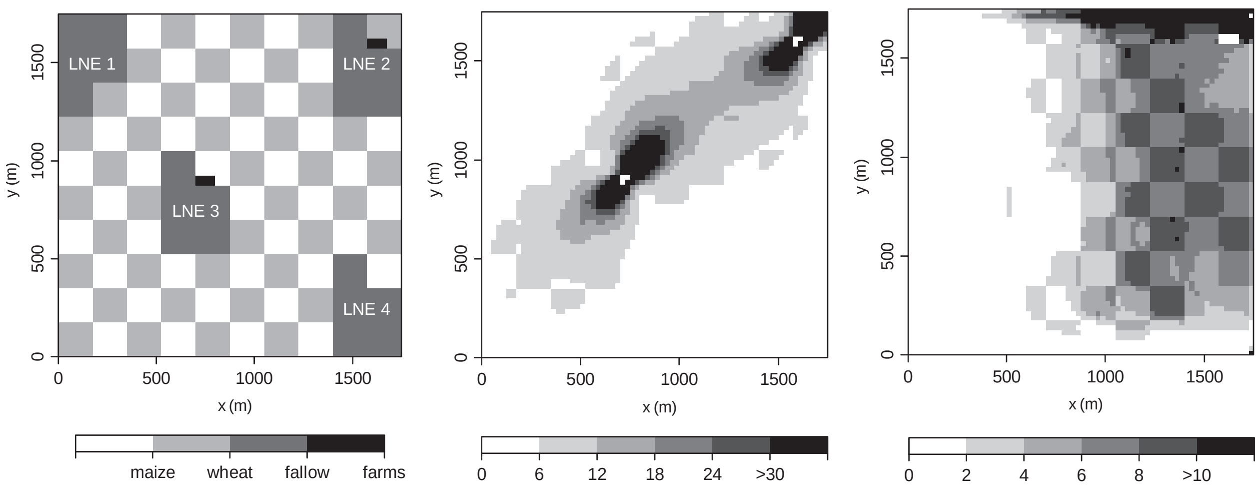


Figure 28 Results from *NitroScape* (Duretz *et al.*, accepted): land use (left), ammonia deposition (kg/ha/y) (centre) and N_2O emissions (kg/ha/y) (right).

4.5 European integration and up-scaling

The main aim of the European Integration component within the NitroEurope-IP was to develop and apply GIS-based integrated assessment tools to assess changes in reactive nitrogen fluxes (N_r) and net greenhouse-gas exchange (NGE) for terrestrial ecosystems at European level. Nr fluxes and NGE were derived as a function of changes in land use, livestock intensity, climate and land management practices. Main tasks were: (i) the development of a multi-component European-scale model (INTEGRATOR), (ii) the setup of a consistent European database with basic data and scenario results for use in (detailed) models, (iii) application of various available ecosystem models (e.g. INTEGRATOR, IDEAg/CAPRI-DNDC and Mobile DNDC) to assess the present day situation and (iv) scenario studies, and related uncertainties, including impacts of emission abatement measures, focusing on the period 1970–2030.

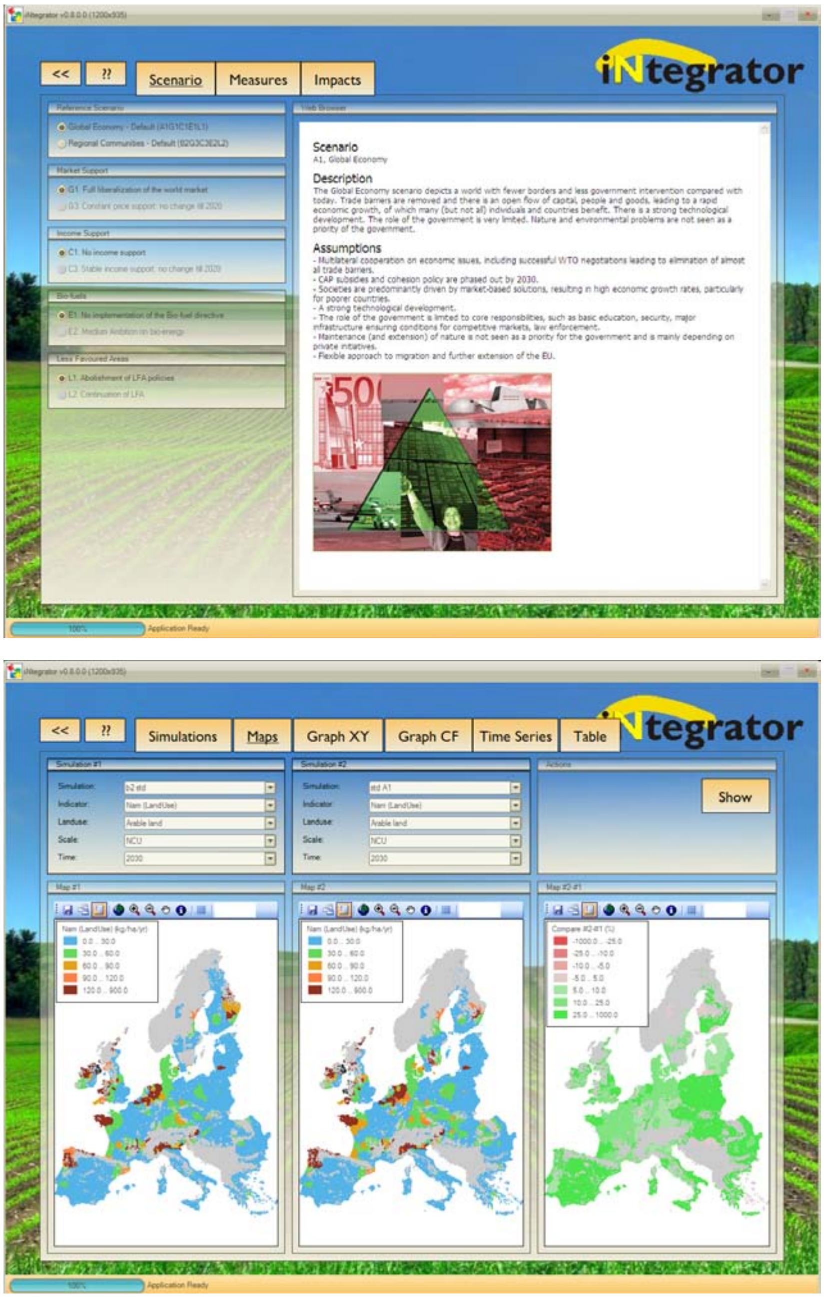


Figure 29 Screenshot of the INTEGRATOR model showing information on the scenario used (top) and results of a run for the year 2030 for two scenarios (below).

The INTEGRATOR model

The INTEGRATOR model integrates modules to compute manure input from animal numbers and excretion, a distribution model to distribute the manure over the various land uses within a region, and various models to estimate N fluxes, including N uptake, NH_3, N_2O, NO_x and N_2 emissions and N leaching and runoff to both ground water and surface water and the emissions of the greenhouse gases CO_2 and CH_4. The model incorporates modified versions of existing modules for estimating N fluxes from agriculture (MITERRA), CO_2 sequestration in forests (EFISCEN and YASSO), meta-models based on results from detailed models (such as DNDC) and regression models based on empirical data (e.g. for CO_2 emission from peat lands and for N_2O emissions from ecosystems). To facilitate the use of INTEGRATOR, a user friendly interface was developed to perform simulations, for different scenarios, evaluate mitigation measures and compare results in terms of graphs, tables and maps (Figure 29).

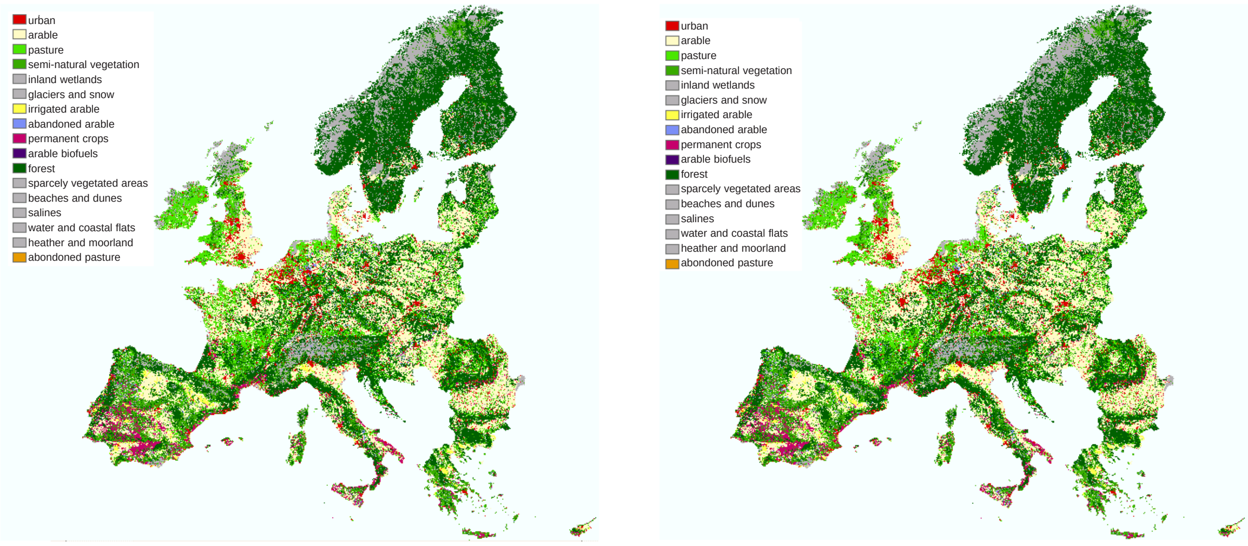


Figure 30 Predictions of land cover by CLUE for 2030 for the A1 (Global Markets) scenario (left) and the B2 (Regional communities) scenario (right).

Establishing a database for European upscaling

Computations by both INTEGRATOR and detailed ecosystem models were made for about 41,000 spatial units in Europe (NCUs), comprising of unique combinations of soil, administrative region, slope and altitude for the period 1970-2030. To do so, a data base (AFOLU) has been set up including all data needed for modelling (http://afoludata.jrc.ec.europa.eu/index.php/public_area/home). Data in AFOLU include soil data, climate data, fertiliser and manure application data for various crop rotations including timelines for farm management practices. A geostatistical model was developed and applied to predict five basic soil properties (pH, organic carbon, organic

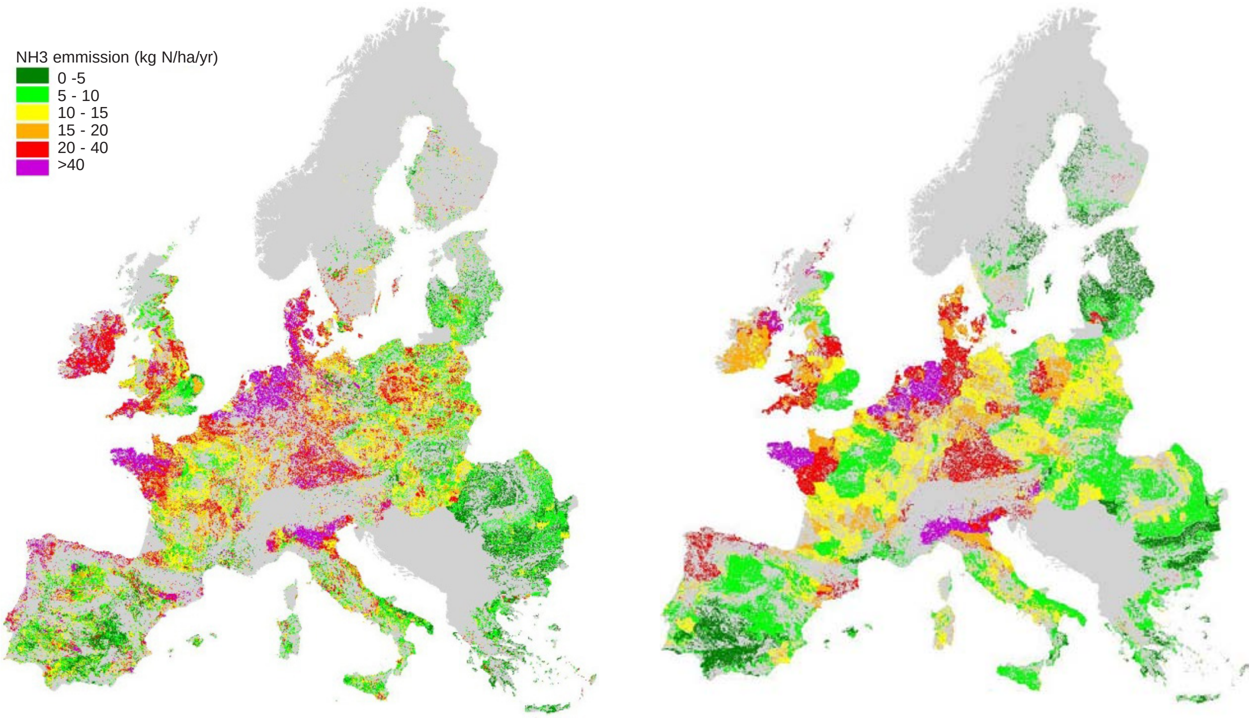


Figure 31 Total NH_3 emissions from agriculture in the year 2000 in EU 27 calculated with IDEAg (left) and INTEGRATOR (right). Gray shading in the EU 27 denote non agricultural areas. Countries outside EU 27 are also included by gray shade.

nitrogen, clay content and bulk density) for three soil horizons at the European scale and quantify the associated prediction uncertainties. A climatic database with daily weather data for the period 1900–2000 was derived by combining the monthly ATEAM/CRU datasets (interpolated monthly climate data at 10’x10’ spatial resolution) since 1900 and the daily MARS weather data since 1975. Manure application rates for the period 1970–2030 were based on downscaled agricultural livestock data for the period 1970–2030, making use of data in FAO (Food and Agriculture Organization of the United Nations) statistics (up to 2000) and IMAGE model predictions for Intergovernmental Panel for Climate Change *Special Report on Emissions Scenarios* (IPCC SRES) A1 and B2 scenarios (Neumann *et al.*, 2009). Crop rotations and timelines of farm management practices were derived by a model that simulates the crop rotations and timelines as a function of historical or future daily weather.

Predictions of land use change for various scenarios

High resolution (1 km × 1 km) land-use reconstructions in Europe (EU 27 + Norway, Switzerland and Croatia) between 1970 and 2000 were made by the CLUE model, using a digitized land use map in 1970 as the starting point. Results were validated on the BIOPRESS dataset, which comprises 69 sets of land cover

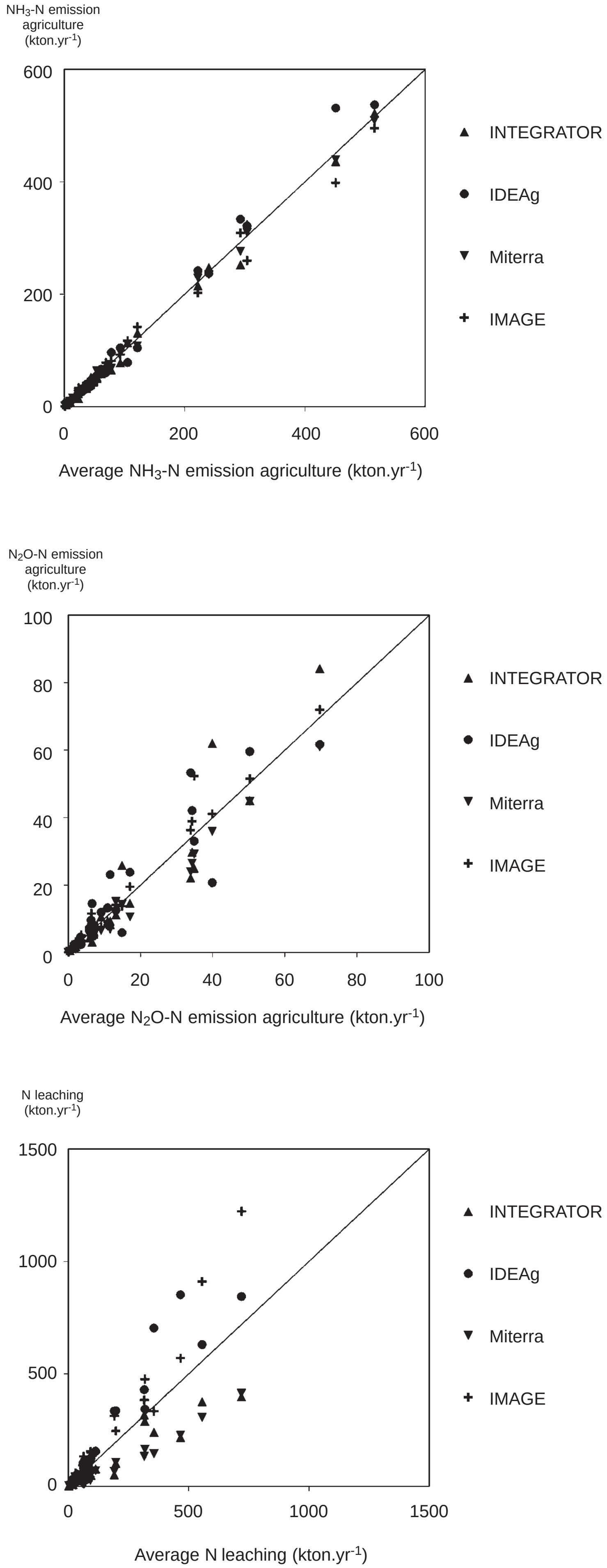


Figure 32 A comparison of total emissions for NH3-N, N_2O-N and sum of N leaching and runoff for the year 2000 at country level within EU27 derived with INTEGRATOR, IDEAg, MITERRA and IMAGE.

inventories over time in areas of approximately 30×30 km. The validated model was used to make land use predictions for two contrasting future scenarios ('Global Markets' and 'Regional Cooperation'), each subdivided into three different policy settings concerning Common *Agricultural Policy* (CAP) reform, bio-energy production and *Less Favoured Areas*, for the period 2000–2030. The 2030 maps of these two main contrasting scenarios (A1 and B2) are shown in Figure 30.

Assessing current (year 2000) Nr and GHG emissions

A comparison of nitrogen (N) budgets for the year 2000 of agro-ecosystems was made for the EU 27 countries by four models with different complexity and data requirements, i.e. IDEAg, INTEGRATOR, MITERRA and IMAGE. As an example, results are given of the calculated geographic variation in NH_3 emissions by the models IDEAg and INTEGRATOR (Figure 31). In general NH_3 emissions calculated by IDEAg are higher than by INTEGRATOR in Western and Central Europe, but the reverse is true for the Nordic countries. The variation in NH_3 emissions is in general comparable with the geographic variation in N surpluses, which in turn are strongly related to the variation in manure N inputs.

A comparison of country emissions of NH_3, N_2O and of N leaching (including runoff; kton $N.yr^{-1}$) for the EU 27 countries for the year 2000 as derived with INTEGRATOR, IDEAg, MITERRA and IMAGE is given in Figure 32. Results show comparable estimates for NH_3 emissions, due to the use of comparable databases and little differences in model approach. Differences in N_2O emissions are larger, reflecting the larger variation in model approaches, while the sum of N leaching plus runoff is systematically higher for IDEAg and IMAGE than for INTEGRATOR and MITERRA (De Vries *et al.*, 2011).

Scenario analysis

The impact of changes in N inputs, induced by changes in livestock and land management, and climate on nitrogen fluxes from agricultural soils to air and water in the EU 27 during the period 1970–2030 was evaluated using various terrestrial ecosystem models. The models involved include Mobile DNDC, DayCent, CAPRI-DNDC and INTEGRATOR. We evaluated two IPCC-SRES scenarios, i.e. the A1 and B2 scenario. The changes in land use, livestock and national fertilizer N use in response to these scenarios were calculated by the GTAP-IMAGE model. Furthermore, a crop rotation optimizer was developed which translated regional crop share information from CAPRI (http://www.capri-model.org) into a mixture of cropping sequences for all NCUs. Results by INTEGRATOR for NH_3 and N_2O emissions are shown in Figure 33. Results show that the impact of the IPCC scenarios on the change in NH_3 and N_2O emissions at EU 27 scale is limited.

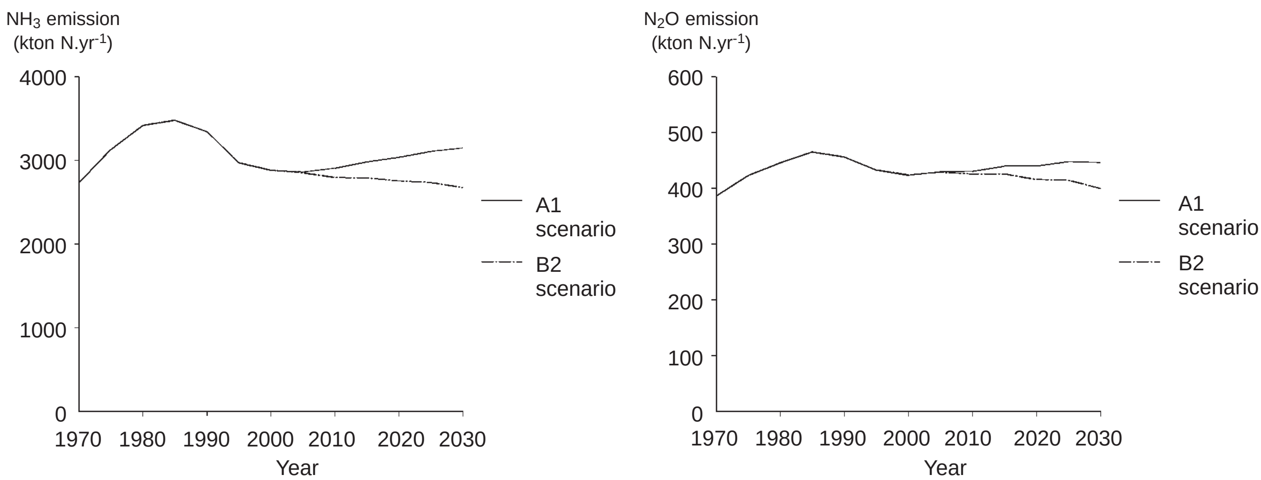


Figure 33 Trends in predicted ammonia emission (left) and nitrous oxide emission (right) by INTEGRATOR for the period 1970–2030 in response to the A1 and B2 scenario.

4.6 Independent verification, uncertainties and policy analysis

Within the framework of NitroEurope it was recognized that independent estimates of nitrogen budgets and greenhouse gas (GHG) emissions were needed for verification of the extensive measurement and modelling efforts, ranging from ecosystem to European scale. A source of independent data is the wet deposition, monitored by national and international organizations across Europe, in support for national or European policy. The data gathered is harmonized and analysed to produce deposition maps of inorganic nitrogen as independent estimate in support of and in addition to NitroEurope results.

Precipitation chemistry data is obtained from EMEP, International Cooperative Programmes on Forests and Integrated Monitoring (ICP-Forest, ICP-IM) programmes under the Convention of Long-Range Transboundary Air Pollution (CLRTAP) of the United Nations Economic Commission for Europe (UNECE). The locations of the monitoring sites are not evenly spread across Europe, causing some serious data gaps in certain regions of this continent. The precipitation chemistry record obtained covers the period 2002–2008 and as such the actual number of locations available depends on the year of observation. The precipitation analysed is collected by a multitude of different sampler designs (wet-only and bulk samplers).

Annual mean concentrations were derived from the data obtained and quality checks as ionic balance and investigating highly correlated elements (van Leeuwen *et al.*, 1996) were carried out. Corrections were applied to the bulk samplers for the contribution of dry deposition onto the collection surface.

The wet deposition fluxes are obtained by multiplication of the derived interpolated annual concentration field with the precipitation field (e.g. Holland *et al.*, 2005 and van Leeuwen *et al.*, 1996) for the respective year on the European scale. The E-OBS dataset provided in the ECA&D project (Haylock *et al.*, 2008) is used as the precipitation field. These products are in itself products of geostatistical analysis for over 2300 precipitation stations across Europe.

The result of this data collection and geostatistical processing, is shown in Figure 34 below. It gives the wet deposition of total nitrogen (NO_3 + NH_4) in kg N per hectare per year, based on data for 2007.

Inverse modelling of European N_2O and CH_4 emissions

Atmospheric measurements combined with inverse atmospheric models can provide independent top-down estimates of greenhouse gas (GHG) emissions. This is important in particular for N_2O and CH_4, for which considerable uncertainties of the bottom-up inventories exist. In NitroEurope, European N_2O and CH_4 emissions have been estimated for the years 2006 and 2007 using five independent inverse modelling systems based on different global and regional *Eulerian* and *Lagrangian* atmospheric

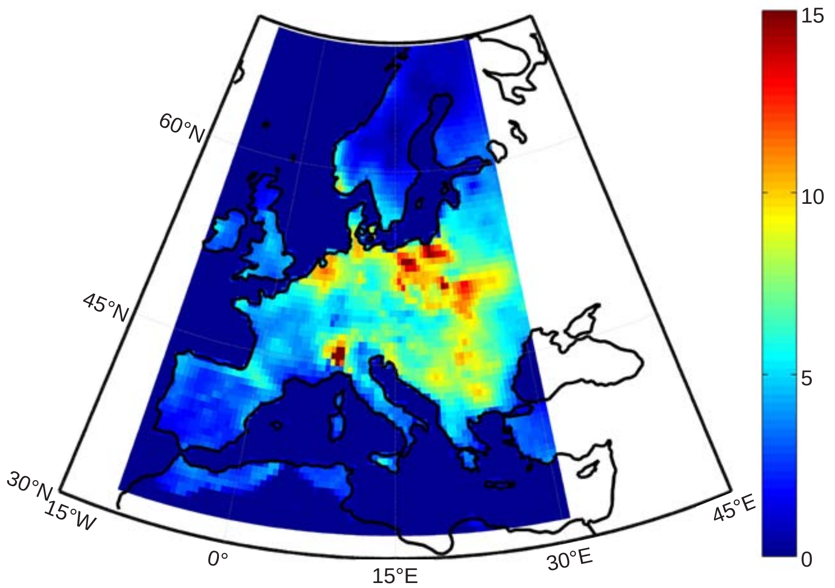


Figure 34 Wet deposition maps of inorganic nitrogen compounds (NH_4^+ and NO_3^-) across Europe derived from site measurements of precipitation chemistry using geostatistical methods.

transport models. The major objective of this model ensemble approach is to provide more realistic estimates of the overall uncertainties in the derived emissions.

We use continuous N_2O observations from 8 European stations (including several tall towers), complemented by further European and global flask sampling sites. A particular challenge is the low signal to noise ratio of the atmospheric N_2O measurements and significant N_2O calibration offsets, which are apparent in measurements from different laboratories. To correct for these calibration offsets, a novel bias correction scheme has been developed and applied (Corazza *et al.*, 2010) and is imperative for the utilization of measurements from heterogeneous networks.

The available observations constrain N_2O (and CH_4) emissions mainly from north-western and eastern Europe (see Figure 35).

The preliminary top-down estimates of European N_2O emissions are consistent with the bottom-up inventories reported to the *United Nations Framework Convention on Climate Change* (UNFCCC). This good agreement is rather surprising, since very large uncertainties are reported for the UNFCCC N_2O inventories (e.g. uncertainties for total N_2O emissions from north-western Europe >160%, mostly due to large uncertainties in emissions from agricultural soils). This illustrates that atmospheric measurements combined with inverse modelling can significantly reduce the overall uncertainty in N_2O emissions.

Uncertainty assessment in model results

Overall, five protocols for uncertainty estimates of model data and model results were written and were disseminated. These protocols were used to determine the uncertainty for different models. This is not straightforward as different approaches have to be used depending on the details of the model, the uncertainty in different parameters and the uncertainty in the data used for evaluation (if any available).

We used three types of models for quantifying Europe-wide N-emissions: ecosystem models, INTEGRATOR and inverse models. These models differed in resolution and in the emission sources they accounted for. The ecosystem models and INTEGRATOR were applied to all ~40 000 NCU's, whereas the inverse models operated at much coarser resolution. The inverse models calculated total emissions from all sources, INTEGRATOR focused on sources and sinks associated with ecosystems and their management, and the ecosystem models quantified the fluxes to and from ecosystem vegetation and soil. To test whether the different modelling results were compatible, results therefore had to be rescaled to a common resolution and set of sources. This was done by aggregating the results from the high-resolution models to form country-totals, and by applying corrections for the contribution from missing sources, derived from the EDGAR database of greenhouse gas fluxes. In the model comparison, the uncertainties associated with the structure and inputs of the models were considered where possible.

Impact on the policy process

Beyond verification of results attained within the project, NitroEurope also touched upon data use in the policy process.

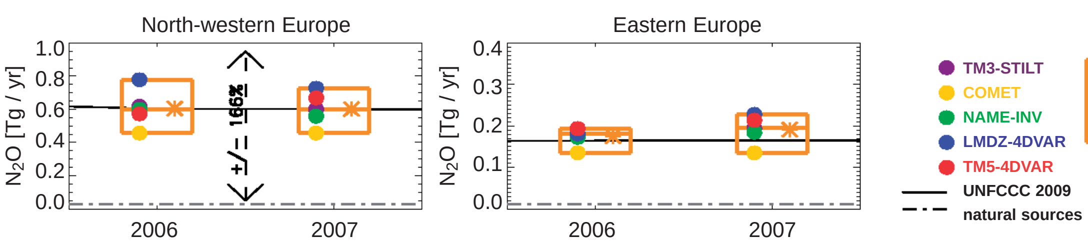


Figure 35 Annual total N_2O emissions for north-western Europe (UK, Ireland, Germany, and BENELUX) and eastern Europe (Poland, Hungary, Czech Republic, and Slovakia). While top-down emission estimates refer to the total emissions, emissions reported to UNFCCC cover only the anthropogenic emissions. For the European countries, however, the contribution of natural N_2O emissions is estimated to be rather small (<10% of total emissions, as estimated from bottom-up inventories).

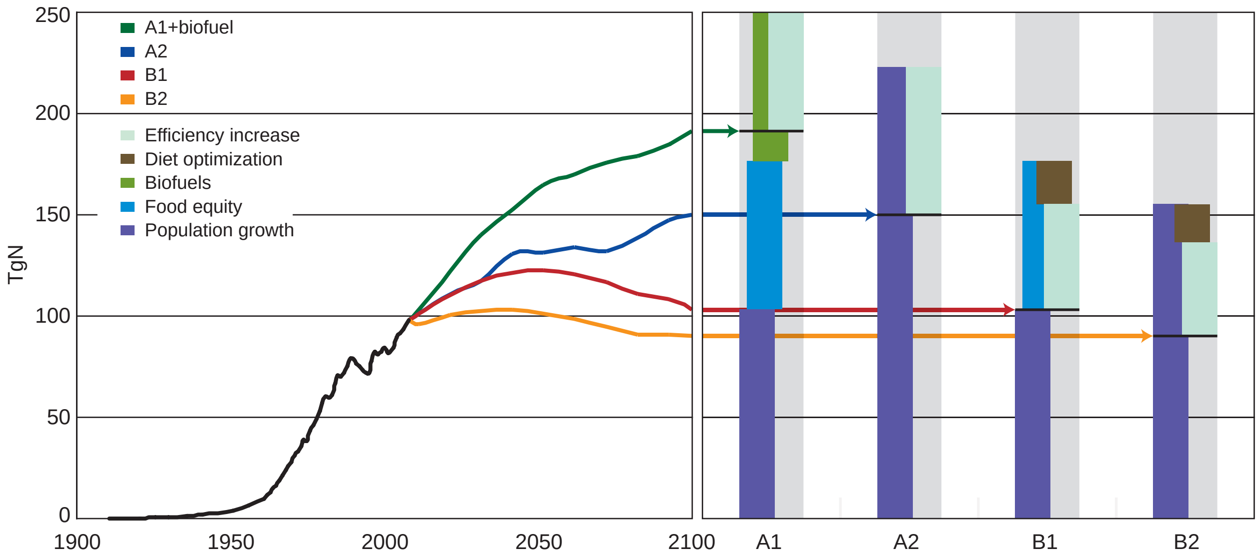


Figure 36 Global nitrogen fertilizer consumption scenarios (left) and the impact of individual drivers on 2100 consumption (right). The A1, B1, A2 and B2 scenarios draw from the assumptions of the IPCC emission scenarios.

For this purpose, a series of structured interviews was held with scientists-turned-policy-makers, in order to understand how to contribute to the quality of the policy process. Specific identified needs referred to the integration of different nitrogen policies and the need to make latest research results on such possible interaction available to the policy process. For that reason NitroEurope developed a strategy paper on 'Interactions of reactive nitrogen with climate change' (Erisman *et al.*, 2011) for the *Task Force on Reactive Nitrogen* (TFRN) under UNECE, which aims to be made available also to UNFCCC. Furthermore, as especially climate issues are strongly forward looking, research focused on the future development of nitrogen related issues and the environment. A publication by Erisman *et al.* (2008) indicates that globally, under very different scenarios, levels of nitrogen pollution may be expected to converge at a level somewhat higher than today, indicating that nitrogen related problems are here to stay independent of assumptions taken (see Figure 36). An assessment focussing specifically on Europe and covering latest projections for Europe (Winiwarter *et al.*, 2011) distinguishes driver-, and effect oriented scenarios, with only the latter ('with policy measures') indicating clear reductions. While technical fixes may be available to abate combustion emissions, reducing agricultural emissions will require integrated approaches that may include behavioural changes (low-meat 'healthy' diets).

4.7 Long-term curation and integration management of data

To address the challenge of managing the wide diversity of data generated by NitroEurope activities, including data access and managing Intellectual Property Rights (IPR) issues, the Data Management Committee (DMC) developed and implemented a Data Management Policy and Plan for the project duration and beyond. The DMC organised the operation of three NitroEurope data centres, each maintaining a database specific to different aspects of NitroEurope. The 'C1-C3 database' provides user-friendly storage and data retrieval facilities for field and manipulated plot measurements and plot-scale model output, the 'C4 database' caters for field measurements, farm data and spatial data for landscape modelling and verification, and the 'C5-C6 database' for European scale modelling and validation data. The databases are currently available to all NitroEurope scientists via log-in through the NitroEurope web portal (http://www.nitroeurope.eu). Additional registration for each of the databases provides additional security and detailed user rights management.

The databases will be maintained beyond the end of NitroEurope, with provision for optional access to non-NitroEurope scientists on a case-by-case basis. Such access rights are fully controlled by data owners. The NitroEurope databases will be integrated into a new project *Environment and Climate interactions—Observations and Responses in Ecosystems* (ENCORE), which is currently being developed. ENCORE will coordinate access to high-quality climate-change related data throughout Europe.

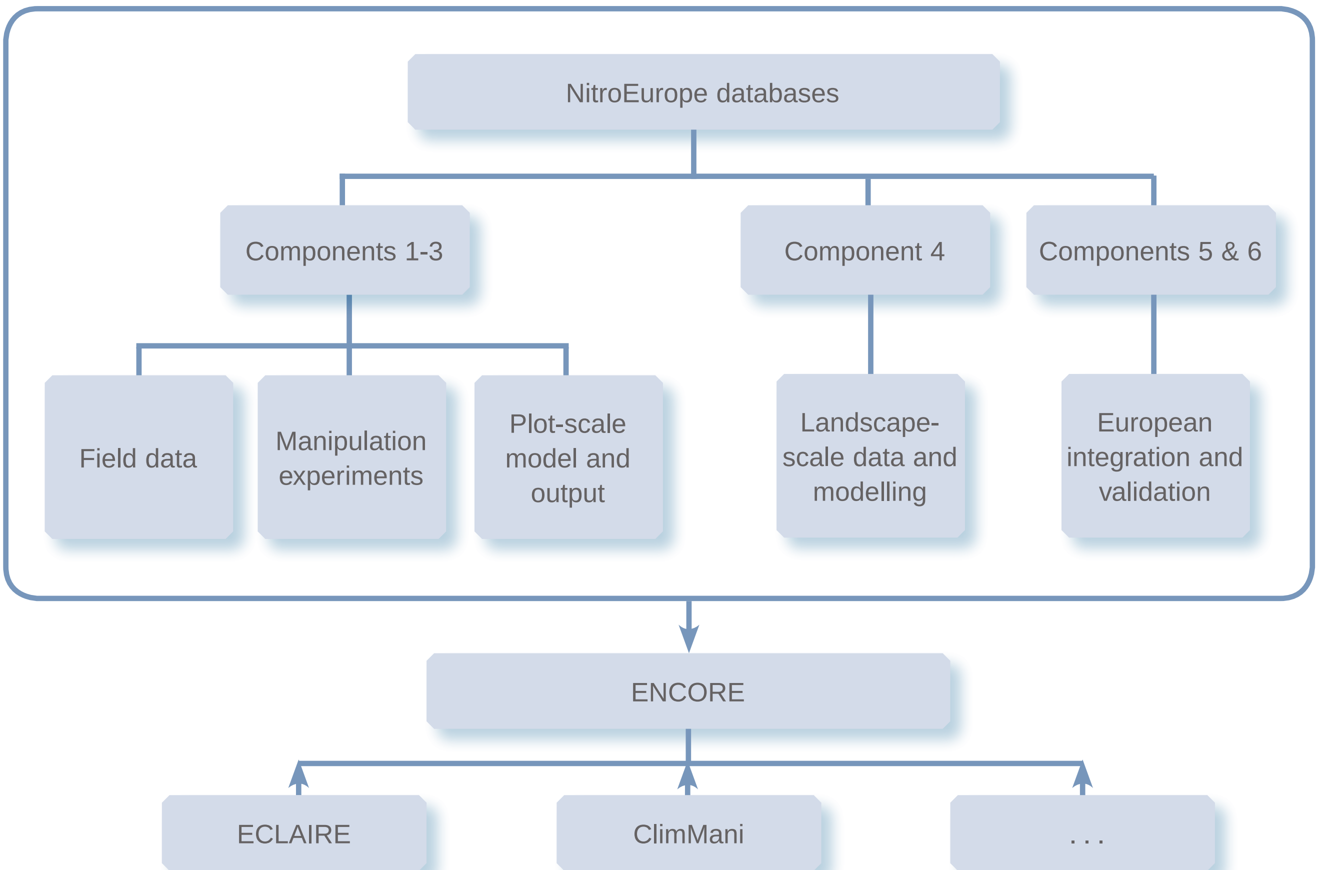


Figure 37 Overview of data management and storage in NitroEurope.

5 Synthesis and integration

Synthesis and integration activities within NitroEurope have worked to establish the links between the component activities and with issues beyond the scope of NitroEurope. This has focused especially on contributing to the European Nitrogen Assessment (Sutton *et al.,* 2011a), as well as to the establishment and development of the UNECE Task Force on Reactive Nitrogen (www.clrtap-tfrn.org). These activities have been conducted in partnership with other European programmes, which have significantly extended the scope of NitroEurope, including the Nitrogen in Europe (NinE) programme of the European Science Foundation, the COST Action 729 and the Network of Excellence ACCENT. At the same time, NitroEurope has contributed actively to the European Centre of the International Nitrogen Initiative (INI), with the NitroEurope coordinator acting as the European INI Centre Director, setting the work of NitroEurope clearly in a global context (e.g. Galloway et al., 2008).

European Nitrogen Assessment

The European Nitrogen Assessment—or ENA—has been established through the coordinated efforts of the NitroEurope team, working in partnership with the NinE and COST 729 partners. The ENA represents the first major continental assessment of all the linked threats and benefits of reactive nitrogen in the environment. As such it sets the work of NitroEurope on nitrogen and climate in context in relation to other threats, including air quality, water quality, soil quality and biodiversity. NitroEurope authors have contributed to all 26 chapters of the ENA, showing the importance of this linking approach.

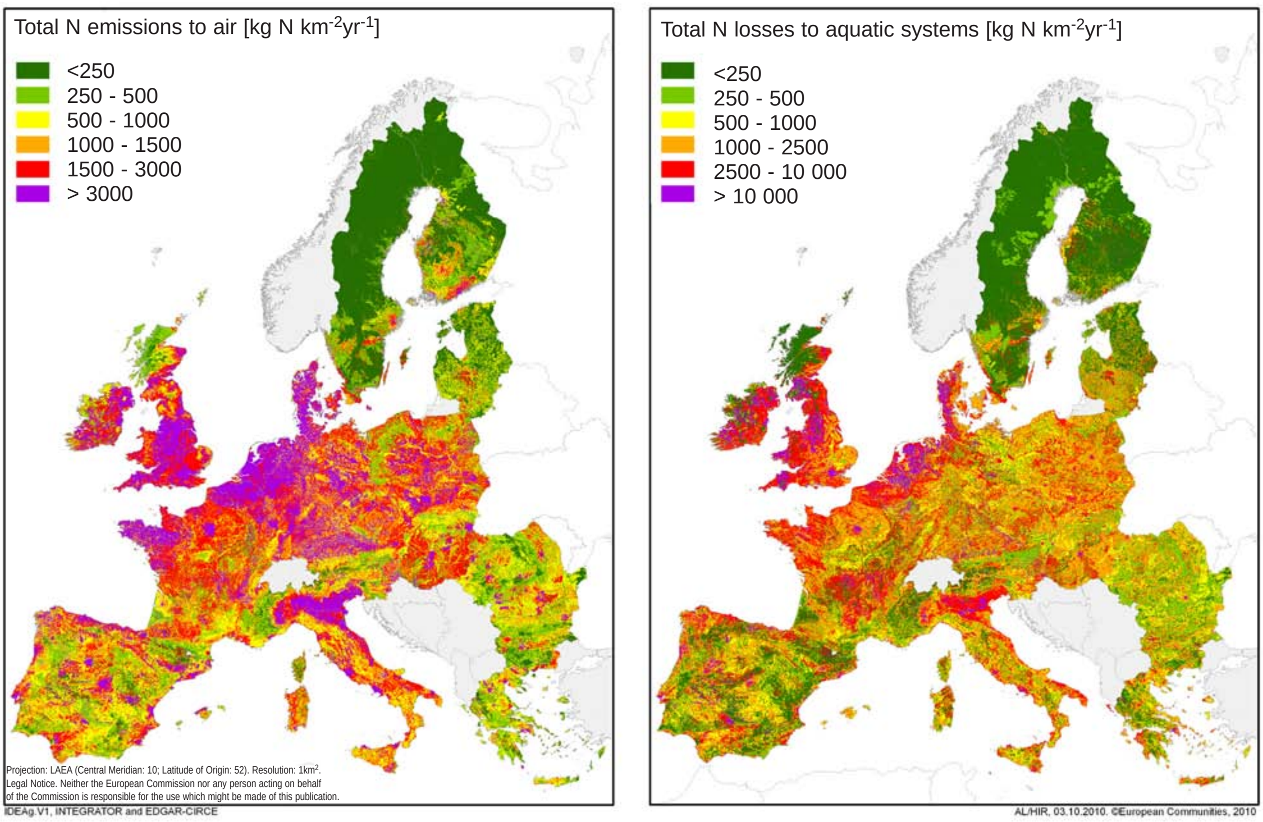


Figure 38 Distribution of reactive nitrogen emissions across Europe (kg N per km^2 for 2000) including emissions to air as NO_x , NH_3 and N_2O, and total losses to aquatic systems, including nitrate and other Nr leaching and wastewaters (taken from the European Nitrogen Assessment—Sutton *et al.,* 2011a).

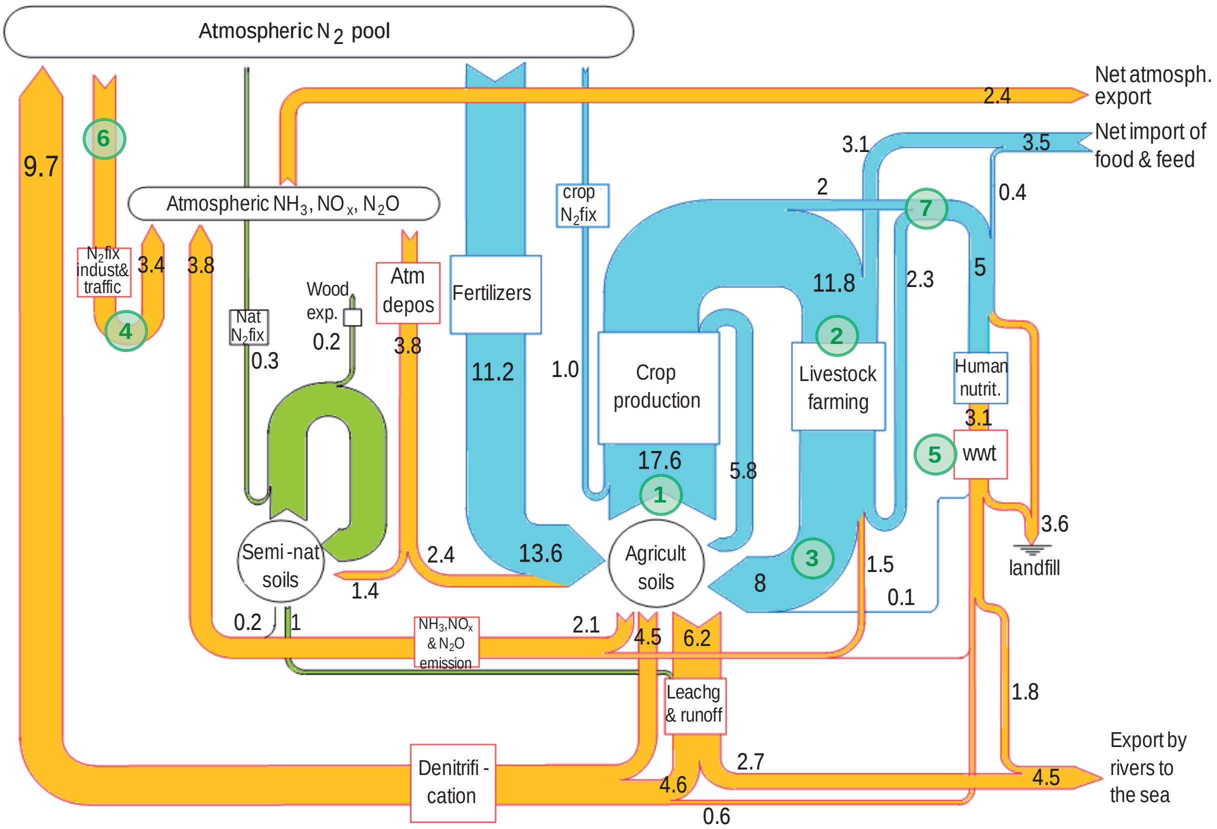


Figure 39 The nitrogen cycle at the scale of EU-27. Fluxes in green refer to 'natural' fluxes (to some extent altered by atmospheric N_r deposition), those in blue are intentional anthropogenic fluxes, those in orange are unintentional anthropogenic fluxes. The numbered green circles indicate a package of seven key actions for overall integrated management of the European nitrogen cycle (taken from the European Nitrogen Assessment—Sutton *et al.*, 2011a).

A key element of the ENA has been the establishment of Europe wide maps of nitrogen emissions, combining the NitroEurope outcomes (e.g. from INTEGRATOR) to provide the state of the art in locating European N emissions (see Figure 38 and Leip *et al.*, 2011). These maps and the underpinning models have allowed the establishment of a new nitrogen budget for Europe, showing all of the major flows (Leip *et al.*, 2011; Sutton *et al.*, 2011a, Figure 39). The European Nitrogen Budget shows several interesting features of high policy relevance. For example, as emphasized by Sutton *et al.* (2011b), 85% of European reactive nitrogen harvested in crops or imported into the EU (including grass) goes to feed livestock with only 15% feeding people directly. Given that the average European citizen eats 70% more animal products than is necessary for a healthy diet, this shows how nitrogen use in Europe is not primarily an issue of food security, but one of luxury consumption of animal products (mainly meat and milk products, see as well Reay *et al.*, 2011).

The most important chapter of the ENA related to NitroEurope is that on the threat of nitrogen on European greenhouse gas balance (Butterbach-Bahl *et al.*, 2011). This synthesis activity extended the scope of NitroEurope to consider not just greenhouse balance, but also the effects of particulate matter on European climate balance. The outcome of this synthesis is summarized in Figure 40, which shows that the component warming effects of N_r emimssions (N_2O emission, and tropospheric ozone effects) are at least balanced by the component cooling effects (including effect of N_r deposition on forest growth, altered methane atmospheric lifetime and increased aerosol loading). Overall, the Assessment estimates a net cooling of 15.7 mWm^{-2} with ranges from -46.7 to +15.4 mW m^{-2}.

However these coolling effects cannot be taken for granted. An economic analysis conducted as part of the Assessment, shows that the social damage costs of

particulate matter emissions on human health and of nitrogen deposition on ecosystems are about an order of magnitude larger than their potential climate benefits (expressed in billion Euro per year). Overall the total damage cost of N in the environment is estimated at 70 to 320 billion Euro per year across the EU. The message is that efforts must minimize particulate loading and nitrogen deposition, while putting effort on reducing N_2O emissions. To achieve the N_2O emission reductions needed will require a significant improvement in *Nitrogen Use Efficiency* in agriculture, which will also depend centrally on implementing measures to reduce NH_3 emissions, N_2 emissions and nitrate leaching (Brink *et al.*, 2011; Sutton *et al.* 2011a,b).

Task Force on Reactive Nitrogen (TFRN)

This Task Force was established during the life of NitroEurope, in large part due to the efforts of the project partners engaging with policy stakeholders of the UNECE Air Convention (Convention on Long-range Transboundary Air Pollution, CLRTAP). The TFRN is now chaired by two NitroEurope scientists, Mark Sutton and Oene Oenema, and is making use of the results of NitroEurope to develop the wider vision of future nitrogen management, linking climate with other threats (Sutton *et al.*, 2011b). Specific tasks where NitroEurope partners and results are feeding in to the work of the Task Force include:

- Developing a special report on nitrogen and climate (Erisman et al., 2011)
- Establishment of the European Nitrogen Budget and methods for further development of budgets *(Expert Panel on Nitrogen Budgets chaired by Wilfried Winiwarter, IIASA, and Albert Bleeker, ECN)*.
- Updating of the UNECE guidance document for control of ammonia emissions.
- Development of options for Annex IX of the Gothenburg Protocol on ammonia emissions, in support of revision of the protocol.
- Estimation of ammonia damage costs, and revison of the abatement costs.
- Assessment of the relationships between nitrogen and food, including the development of future scenarios, in support of different UN conventions.

Through the work of the TFRN and involvement of NitroEurope partners directly, the results will in parallel be incorporated within the forthcoming 5^{th} Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

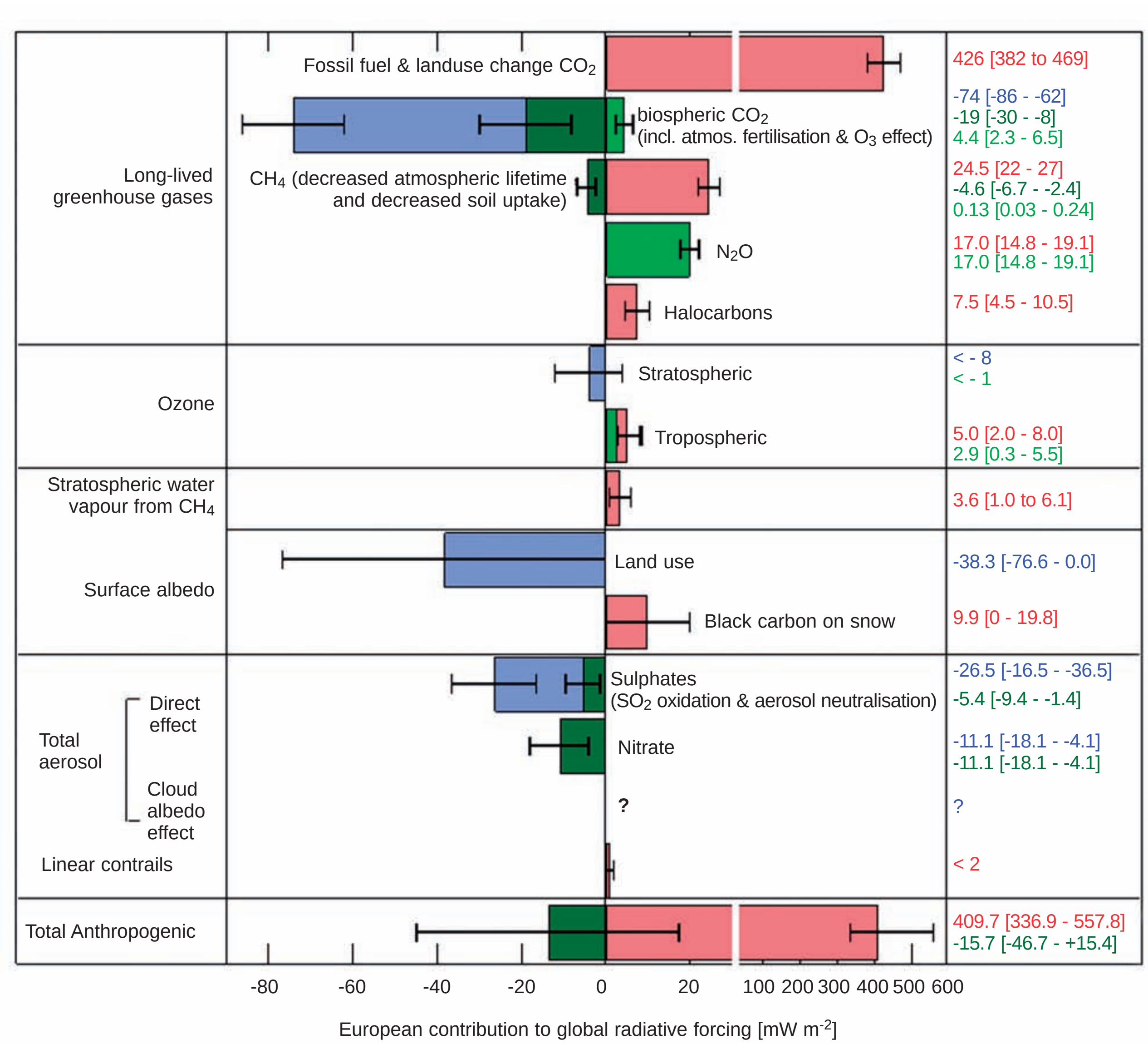


Figure 40 Estimate of the change in global radiative forcing (RF) due to European anthropogenic reactive nitrogen (N_r) emissions to the atmosphere. Red bars: positive radiative forcing (warming effects); light green bars: positive radiative forcing due to direct/indirect effects of N_r; blue bars: negative radiative forcing (cooling effects); dark green bars: negative radiative forcing due to direct/indirect effects of N_r. For biospheric CO_2, the dark green bar represents the additional CO_2 sequestered by forests and grasslands due to N_r deposition, while the light green bar represents the decrease in productivity due to effects of enhanced O_3 caused by NO_x emissions. For CH_4 the positive (not visible) and negative contributions represent the effects of N_r in reducing CH_4 uptakes by soil and the decreased atmospheric lifetime, respectively. Other contributions include the positive effect of tropospheric ozone from NO_x and the direct and indirect cooling effects of ammonium nitrate and sulphate containing aerosols. (taken from the European Nitrogen Assessment—Sutton *et al.*, 2011a).

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7 List of project partners

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NitroEurope has been working in close cooperation with several programmes and frameworks within Europe and beyond:

European Science Foundation
'Nitrogen in Europe' programme

COST Action 729

International Nitrogen Initiative

UNECE Convention on Long-Range Transboundary Air Pollution - Task Force on Reactive Nitrogen

Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

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