Modelling multidimensional problems – The case of integrated nitrogen management

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EXTENDED ABSTRACT

This paper aims to set the scene for the session by elaborating on the challenges of modelling issues of integrated nitrogen management. Reactive nitrogen (N_r) plays a vital role in different areas, such as air pollution, climate change, eutrophication and acidification of soils, ecosystems and surface waters and such like. It inherently presents a multi-pollutant, multi-effect and multi-media problem.

Historically, many of these individual problems have been addressed by models developed for a specific purpose, limited to single pollutants, effects or environmental compartments and media. In addition to that, relevant datasets and model approaches have been developed within different scientific and science-policy communities and hence their integration is facing not only technical and methodological problems, but as well needs communication and collaboration across disciplines, in many areas outside the comfort zones of modellers and decision makers alike.

While climate change and carbon have been receiving a significant amount of attention in science, policy and the general public in the course of the last decade, the changes of the global nitrogen cycle and its implications have emerged to – potentially – become an even greater challenge for science An ever ongoing increase in vehicular traffic, energy use, industry, and animal husbandry are the principal causes of the increased emissions of oxidized and reduced forms of nitrogen. The negative impacts of these emissions include: (i) air pollution, such as increased concentrations of nitrogen oxides (NO_x), ozone and fine particles, leading to effects on humans and vegetation and influencing the earth's radiation balance, (ii) elevated emissions of nitrous oxide (N_2O), being one of the most important greenhouse gases, thus affecting climate change and to climate change, (iii) eutrophication and acidification of terrestrial and aquatic ecosystems, with related impacts on plant species and faunal species diversity, (iv) surface water pollution with nitrate (NO_3) and ammonium (NH_4), including damage to fisheries in coastal ecosystems and (v) drinking water (ground water) pollution by nitrate pollution (e.g. Vitousek et al., 1997, Galloway and Cowling, 2002; Galloway et al., 2003; Matson et al., 2002;) The undesirable "cascading effects" of nitrogen, as Galloway et al. (2003) call them, thus affect different environmental media, across different time spans and different nitrogen species contribute to most contemporary environmental pressures. It is thus a formidable example for taking stock of the methods and approaches which form the state-of-the-art in environmental modelling and how they may be integrated and combined to tackle the nitrogen problem.

The relevance of nitrogen and the need for an integrated approach to address the complex issues of managing the nitrogen cycle have recently been highlighted at the 3rd of a series of workshops organised by the Swedish *ASTA* programme (http://asta.ivl.se/Saltsjobaden3.htm). It is anticipated, that under the UNECE *Convention on Long Range Transboundary Air Pollution* (CLRTAP) the development of strategies to address the nitrogen challenge will have a prominent role in the coming years.

The paper will discuss some approaches currently taken in research projects in Europe, e.g. the NitroEurope IP (http://www.nitroeurope.eu, in particular the work on the INTEGRATOR model), the IIASA RAINS/GAINS model (http://www.iiasa.ac.at/rains/gains/) and link to discussions and developments on concepts for model integration and coupling such as OpenMI (http://www.openmi.org/). It will present an overview and aims to inspire the discussion within the session and beyond.

1. INTRODUCTION

1.1. Why nitrogen?

The nitrogen cycle is of fundamental importance for human health issues, ecosystem functioning and global change: it provides a key control of the global carbon cycle through effects on primary production and decomposition; it is a major determinant of terrestrial and aquatic biodiversity; it affects particle and other chemical production in the atmosphere; and it has major impacts on greenhouse gas fluxes and stratospheric ozone depletion. It is therefore a matter of great concern that global cycling of reactive nitrogen (NH_3, N_2O, NO_3^-, NO_x, NO, N_{org}), is estimated to have more than doubled (Vitousek et al., 1997; Galloway et al., 2004), whereas, by comparison, the C cycle is less than 10% perturbed by human activities (IPCC, 2001). Despite this concern, much less effort has been given recently to quantifying the nitrogen cycle than to the carbon cycle. This may be partly due to the apparent simplicity of the "carbon story" and the dominant role of CO_2 as a greenhouse gas. By contrast, the complexity of multiple interactions and impacts makes the nitrogen problem less accessible to a wider audience. This has not been helped by previous research efforts on N_r being widely dispersed between the different N_r forms and their impacts: e.g., research on N_2O, NO and NH_3 fluxes have been considered separately, as have studies on N_r in atmospheric chemistry and N_r impacts on ecosystem functioning. It is therefore a major scientific challenge to bring together these issues and provide a clear picture of the role of nitrogen in global change.

In this context, an integrated research project has been established to address the core aspects of reactive nitrogen in the atmosphere. This project, NitroEurope IP, or NEU in short, is funded by the European Commission under the 6th Framework Programme and brings together more than 60 institutions across Europe and beyond.

1.2. Aims and structure of the paper

This paper does not attempt to present a sophisticated solution, or a single, integrated model to solve the problems associated with the nitrogen cycle. In contrast, it aims to review approaches currently developed and to assess, how recent developments in modelling paradigms may contribute to the solution of this complex problem.

Following a short general overview on the issues and problems associated with modelling the nitrogen cycle, the second part of the paper will discuss selected approaches towards an integrated assessment of nitrogen. Model and concept development are equally relevant to the establishment of a collaborative infrastructure and paradigms for dealing with problems of a complexity which has, for instance when developing models to deal with acidification or tropospheric ozone, not been tackled before.

2. THE NITROGEN CYCLE AND ITS CHALLENGES (TO MODELLING)

2.1. Multi-source, multi-effect, multi-spatial

There is a clear need to translate process understanding into quantitative models that can address interactions with other global change drivers, be applied in relation to practical land management decisions and that can be up-scaled to the whole of Europe to support the development of European sector policies. Modelling (aspects of) the nitrogen cycle is a complex task, affected by the spatial scale of the problem, the temporal variations between different stages of the N cascade, biogeochemical interactions and atmospheric processes and transport and finally, a variety of sources of nitrogen effects and impacts, as discussed in some detail below.

2.2. A variety of issues to be addressed

***Multi-sources/sectors*:** Sources of elevated N concentrations in air, soil and water are due to increased emissions of oxidized and reduced forms of nitrogen from various sources including transport, energy use, industry, and animal husbandry. Assessing budgets of nitrogen for the atmosphere and for terrestrial and aquatic ecosystems thus implies that a large variety of sources and interactions between air, soil and water has to be taken into account.

Multi-effects/interactions: The nitrogen cycle has many effects in view of the occurrence of various N compounds (NH_3, NH_4, N_2O, NO_x, NO_3^-) and its impact on other compounds (CO_2, ozone, particulate matter) in air, soil and/or water, as mentioned before. Even when limiting it to the links between N fluxes and the GHG budget the situation is complex. Apart from the obvious links between N and C cycles, there is a requirement to assess overall ecosystem nitrogen budgets, since other N_r losses, e.g. NH_3 emissions and leaching of nitrate (NO_3^-), are considered as indirect sources of N_2O emissions under the IPCC methodology (IPCC, 1996). Furthermore, N_r gases can form aerosols which affect the radiation balance of the earth. The contribution of aerosol biosphere-atmosphere exchange to N deposition and aerosol production/loss within canopies is required to calculate N_r budgets and NGE. Similarly, interactions with ecosystem functioning and biodiversity must be considered in order to understand the observed responses of the net greenhouse gas exchange (NGE) to global change drivers.

Spatial variability: The nitrogen cascade is a sequence of effects occurring in different phases (air, soil and water) in response to N loadings and concentrations with a large spatial variability. There is thus a need to integrate the analysis of N_r and GHG at linked field-, farm- and landscape-scales, including the consideration of spatial interactions with NH_3 emissions and NO_3^- leaching, requiring unique modelling approaches and techniques. This is in particular relevant when trying to determine a comprehensive N budget for a region, hence trying to upscale from a local, detailed, often plot-based method to landscapes and regions, at the same time accounting for the 'historic' burden of N still in the system from past agricultural activities.

There are presently several estimates of European-scale land use related emissions of NH_3, NO_x, N_2O and CH_4, and of the N budget, focusing on nitrate leaching and runoff to surface waters (e.g. Bouwman et al., 1997). However, these estimates are all based on a coarse approximation (e.g. country statistics or data at 0.5 by 0.5 degree resolution) of the required inputs (N fertiliser use, animal manure inputs etc) and IPCC-like emission factor approaches (Bouwman et al., 1997) or simple empirical models. Much of the information required for an adequate derivation of N_r and GHG emissions from agriculture is not included in current European databases compiled on a regular basis. There are currently ecosystem models available that provide process-level descriptions that can be applied to derive spatial N and GHG fluxes at regional scale (e.g. Butterbach-Bahl et al., 2004), but the up-scaling is based on crude assumptions regarding model inputs and results are not yet validated. Also, the different sources of error have not been specified, which is crucial to improve and understand the results and possible biases. As a result, studies on the responses of N_r and GHG emissions to European-scale land-use and land-cover changes are still lacking.

To overcome this, datasets on NH_3, N_2O and CH_4 measurements obtained within e.g. the NEU project and from the literature have to be used in combination with detailed ecosystem models for daily NH_3, N_2O, CH_4 and CO_2 emissions (Li, 2000; Li et al., 2000), to derive simplified process-based and empirical models in an integrated multi-sector, multi-component model. Both detailed and simplified bottom-up process-based modelling approaches are applied to develop an integrated approach to estimate the past, present and future N_r and GHG emissions and sinks in response to various scenarios reflecting: (i) past and present land use changes and land management decisions and (ii) various policies and actions that affect N_r emissions in interaction with GHG emissions. In NEU, these estimates will be based on a linkage of: (i) detailed GIS-based assessment of environmental data (land use, soil type, average climatic situation, altitude, etc.) and farming data (farm types and agricultural management) and (ii) detailed reconstructions of land use changes in the period 1970-2000 and projections for the period 2000-2030 with both detailed process-based models and the integrated multi-sector multi-component framework. To exploit the full potential of available farming data, information obtained from networks, national surveys and farm scale questionnaires will be used to downscale the regional statistics using appropriate disaggregation techniques. Together with these advances, the uncertainties in estimates of European emissions of N_r and GHG as produced by the bottom-up GIS-based results will be quantified, including verification against independent measurements and a comparison with results from inverse modelling.

3. MODELLING APPROACHES

3.1. Covering spatial scales – local to global

With the nitrogen cascade having its origin on the plot scale, applying manure and industrial fertilisers on farmland, and then being dispersed through air, water and soil towards regional watersheds, rivers and finally coastal zones and oceans, any comprehensive modelling approach needs to address this aspect.

In the case of air quality modelling, nesting approaches have been established for the purpose of assessing chemical transformation and dispersion of air pollutants with increasing spatial resolution. Mainly one-way nesting from global/hemispheric models down to region and local applications is applied, for instance using the European EMEP (Co-operative programme for monitoring and evaluation of the long-range transmissions of air pollutants in Europe) Unified Model (http://www.emep.int/index_model.html). While the regional application runs on a grid with 50×50 km resolution, national/local nests are applied with 5×5 resp. 1×1 km resolutions currently, and hemispheric modelling is conducted on an even larger scale. Nesting methods have been applied in integrated assessment models as well (e.g. Oxley and ApSimon, 2007). While in theory the resolution of 1×1 km could be run on a regional scale as well, computing time is a limiting factor. In addition to that, input data (e.g. emission files, meteorological parameters etc.) with such high resolution are often not readily available.

In order to model the nitrogen cascade, it is as well relevant to develop robust up-scaling approaches, which are capable of capturing the dispersion of nitrogen fluxes from the application on plot scale downstream. While a number of models is available and has been thoroughly tested for high spatial and temporal resolution on the plot scale (e.g. DNDC http://www.dndc.sr.unh.edu/, PASIM see e.g. Calanca et al. 2007, SUNDIAL see e.g. Smith et al., (1996) etc.), scaling their results up from individual plots to landscapes and finally regions is not straightforward. Among problems of data availability, the heterogeneity of plots with regard to soil, fertiliser application, agricultural practise etc. is a main challenge (see for instance Dragosits et al. 2002, Theobald et al. 2005 and van Oijen et al. 2005).

3.2. Integrating across temporal scales

Different species of reactive nitrogen have quite distinctively different lifetimes. Depending on the chemical transformation and their dispersion through air, water and soil, models need to address time steps from minutes to days to years.

This is not only limited to the emission of substances, deposition as well as effects on ecosystems can vary significantly with regard to their time frame. Finally, for some aspects of ecosystem impacts and their recovery, dynamic modelling approaches have recently been discussed in the *Working Group on Effects* (WGE) of the CLRTAP. This means that models or model families have to consider both the time scale of emission, transport and deposition of N_r, and the time scale of the effect and (potential) recovery of the ecosystems affected.

When taking into account transport, chemical transformation and deposition of air pollutants, and also effects of the N deposition, the temporal domain becomes even more difficult to handle. While atmospheric dispersion models typically run at time steps in minutes to hours, hydrological and water-soil models often calculate the accumulation of concentrations during decades and even millennia. Hence, a fully integrated model covering all environmental sectors needs to be capable of harmonising its overall time steps and temporal coverage across this whole scale.

3.3. Linking multiple causes and effects

The complication of dealing with a multi-pollutant multi-effect problem lies not only in the different spatial and temporal scales on/in which these occur. In addition, control options to tackle some of the problems arising from the release of N_r into the atmosphere are subject to explicit trade-offs where reducing one problem increases others. This has been addressed in some specialist models in order to deal with for instance the issue of nitrate leaching vs. ammonia emissions. Similar aspects related to synergies or trade-offs, when reducing air pollutant and greenhouse gas emissions have been the main driver for the development of the GAINS model from its predecessor (see section 4.1).

4. CONCEPTUAL MODEL DEVELOPMENT

Two main paradigms for model development have emerged in recent years where complex environmental problems are under investigation.

On the one hand, increasingly complex, integrated models have been developed, which aim to incorporate all relevant physical, chemical and systems aspects into one model. By setting clear priorities, different aspects are often implemented with varying degree of detail and complexity, reflecting the main purposes for which the specific model has been built. As an example for this branch of modelling concepts, the RAINS/GAINS model developed by the *International Institute of Applied Systems Analysis* (IIASA) will be introduced in 4.1. Increasingly complex models are, however, difficult to validate, and often the interpretation of results becomes a cumbersome task due to a variety of parameters determining the results at the same time and the lack of data. A different development path that has been taken in the view of this realisation, is to model each individual problem using a specialist model, developed and applied to only a well defined part of the problem, while several models are linked to exchange data, parameters, even dynamically. This allows for the individual verification and validation of specialist models, however, the overall uncertainty and validity of the combined results need yet to be assessed. Within this branch, the Open Modelling Interface and Environment (OpenMI, http://www.openmi.org/) community has established a leading role in the development of standards and guidelines how to link/couple models. In section 4.2, the conceptual design of the INTEGRATOR model will be briefly described, which is following the OpenMI philosophy and while it integrates core aspects of the nitrogen cycle, the linking to other models is vital for its operation.

4.1. RAINS/GAINS

The RAINS integrated assessment model has been developed at the *International Institute for Applied Systems Analysis* (IIASA), Austria primarily to model cost-effective emission control strategies for transboundary air pollutants in the frame of the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP). Initially this covered emissions, control options and abatement costs, as well as – in a limited fashion – effects on human health, agricultural crops and ecosystems, for SO_2, NO_x, NH_3 and NMVOCs of ground level ozone, acidification and eutrophication (see *Figure 1*). In the context of a growing awareness with regard to the synergies and trade-offs between emissions of air pollutants on the one hand and greenhouse gases on the other hand, this integrated assessment modelling system evolved further to include CO_2, N_2O and CH_4. At the same time, some paradigms in the modelling of emission control options were adapted to take a more systematic approach to the complex interrelationships between sectors and technologies. The new model system is now termed GAINS (*Greenhouse Gas and Air Pollution Interactions and Synergies*).

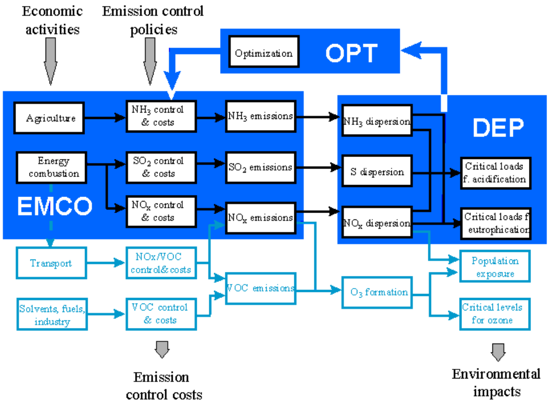

Figure 1. Conceptual overview over the RAINS model (Source: www.iiasa.ac.at/Research/TAP/rains_europe/intro.html)

From a modelling perspective, it is interesting to note that GAINS is further developed to integrate a process-oriented module to address agricultural emissions. The concept chosen for this is similar to that taken in INTEGRATOR.

RAINS/GAINS in particular face the challenge of any integrated, multi-pollutant multi-effect assessment model, in that it is becoming increasingly difficult to define a set of targets and priorities for the optimisation. In addition to that, interpreting the results in a context that allows identifying the relationships between mitigation options selected and their effect on environmental pressures is also more and more difficult.

4.2. INTEGRATOR

The *Integrated European multi-sector and multi-component model* (INTEGRATOR), a core task within the NitroEurope Integrated Project, aims to assess at a European scale:

- Present atmospheric nitrogen (NH_3, NO_x) and GHG fluxes (CH_4, N_2O and CO_2) from and to terrestrial systems.
- The interaction between C and N and between agricultural and (semi) natural ecosystems
- Past and future N and GHG emissions and sinks in response to various scenarios reflecting: (i) past and present land cover changes and land management decisions and (ii) policies and actions that affect nitrogen emissions in interaction to greenhouse gas emissions and climate change.

The approach followed in the development of INTEGRATOR is to link various modules, calculating N and GHG emissions from: (i) industrial sources, (ii) farms: housing and manure storage systems, (iii) agricultural soils, (iv) non-agricultural soils and (v) surface waters (indirect emissions), while accounting for the interaction between agricultural and non-agricultural soils through an (vi) emission-deposition model for N compounds (NH_3 and NO_x), as illustrated in *Figure 2*.

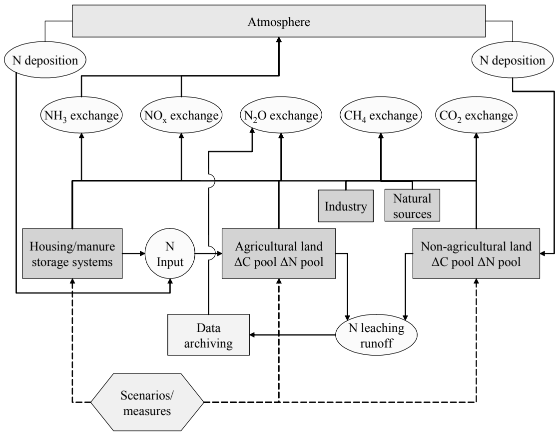

Figure 2.The INTEGRATOR concept

To assess the impact of scenarios and policies on future N and GHG emissions, INTEGRATOR has to be coupled with models that predict changes in land cover and agricultural management, and the resulting impacts on climate and N deposition in response to such scenarios and policies. The embedding of INTEGRATOR into a suite of different modelling systems is a necessity to deliver fully integrated answers to the complex modelling tasks. While the concept of INTEGRATOR has been developed and some of the modules are currently implemented, a full documentation of the model approach is in preparation (DeVries et al. 2007).

4.3. Comparative analysis

A casual comparison of the conceptual design of both RAINS/GAINS and the development of INTEGRATOR does not seem to reveal crucial differences. Even though their development has originated in the view of different tasks, a convergence into a similar direction can be observed (i.e. in the integration of process based models with a focus on agricultural activities). Nevertheless, there are various differences between (the ultimate version of) INTEGRATOR and RAINS/GAINS in that the former includes:

- Much more detailed level of model inputs (combinations of land use, soil type, altitude etc instead of e.g. national average values).
- Process-based descriptions of N and C fluxes and budgets in terrestrial and aquatic ecosystems (RAINS focuses on the IPCC-like emission factor approach)
- Dynamic aspects, specifically in view of changes of C pools in soils and biomass (RAINS uses a steady-state approach).
- A much more spatially detailed evaluation of the effect of changes in land use, climate and management on N and GHG fluxes from terrestrial ecosystems.

Another difference between INTEGRATOR and RAINS/GAINS is that the latter model searches for the optimal emission policy, in terms of costs and benefits, on a country basis, whereas INTEGRATOR evaluates the consequences of scenarios and measures without any optimization. For RAINS/GAINS, the legacy of its initial development steps makes it particularly difficult to embrace new modelling concepts and follow the scientific developments timely. In this respect, INTEGRATOR, as being developed within a scientific research project, will find it easier to embrace “best scientific knowledge” and conduct substantial experiments prior to applying the modelling framework in a policy making context. RAINS/GAINS has been relied upon by decision makers in the UNECE CLRTAP context and the European Commission environmental policy process (for instance developing the *Clean Air for Europe* strategy).

5. SUMMARY AND CONCLUSIONS

Current models have achieved a significant degree of integration, in spite of quite different starting points of their development. Some key challenges for a comprehensive modelling of the nitrogen cycle have yet to be addressed, in particular in the view of the complexity of the problem (McIntosh et al, 2005). Significant progress has been made in recent years in understanding the fundamental challenges of modelling multi-media effects across environmental compartments and in laying the foundations for the development of models capable of integrating process-based modules for some of the most relevant areas. Most modelling concepts see as a vital first step of integration the coverage of multiple sectors, pollutants and effects, mainly dominated by the air pathway. In addition to the work on the models briefly described above, a significant amount of research has been conducted on the integrated modelling of watersheds, where a portfolio of models exists (e.g. Grizetti 2003, Lowrance 2000, Wade 2002). Thus, a strong driving force for the OpenMI development has been coming from hydrology related research.

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