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Implications of different spatial (and temporal) resolutions for integrated assessment modelling on the regional to local scale – nesting, coupling, or model integration?

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Abstract: Integrated assessment modelling (IAM) in general is currently applied to a range of environmental problems addressing aspects of air pollution and climate change, water pollution and many more. While different branches have emerged from applications within different disciplines, they share a similar view of the core features of IAM, i.e. multi-disciplinary approaches, integration across environmental compartments, and the application of models with the aim to provide decision support for complex problems. Examples of IAMs on a regional scale are the RAINS/GAINS model suite (International Institute for Applied Systems Analysis, IIASA), with versions for Europe and Asia. On a national scale, several European countries are currently developing and applying IAMs for policy development, in some cases using special adaptations of the IIASA RAINS/GAINS model (e.g. Italy), or own models (UK, Germany).

IAMs have been extensively used in the preparation of the Multi-Effect Protocol (United Nations Convention on Long-Range Transboundary Air Pollution, CLRTAP) and the European Clean Air For Europe (CAFE) strategy. In these applications, target setting included a mixture of health and ecosystem related indicators. State-of-the-art IAMs are typically operating on rigid spatial scales, and in most cases do not take into account the temporal patterns of emissions and effects in their assessment approaches. IAM results are typically provided on national or regional level (e.g. control measures, costs, benefits due to reduced environmental and health impacts) and for annual indicators (e.g. critical load exceedances or morbidity/mortality effects. However, scientific evidence is today capable of providing a better foundation to identify major aspects for uncertainties in these larger scale assessments, for instance investigating the distinct temporal patterns of air quality throughout the year and the detailed modelling and mapping of human exposure to air pollutants beyond statistical average exposures on total population level. This requires a more advanced and flexible design of IAMs to better model the temporal and spatial domains which are of relevance for the key issues to be assessed.

First steps towards bridging the gap between regional and national, respectively national and local scale models for integrated assessments have taken the route to derive parameters for e.g. the urban differential in ambient air quality outside of the models regular domain and integrate these parametric values into the IAMs assessments. While this approach is moderately labour intensive, the major flaw is the integration of static values into an intrinsically dynamic model. In other words, if input datasets and external drivers (e.g. meteorology, atmospheric composition and chemistry) change, all other parameters have to be recalculated and re-integrated. This paper will discuss emerging trends for IAMs with a specific focus on spatial and temporal aspects and aims to elaborate on the policy context which is a key driver for the development of IAMs. The growing understanding of how complex interactions e.g. between/within the nitrogen and carbon cycles, where both management options and effects arise/occur on different spatial scales and with different time scales, both feeds into and requires the development of next generation IAMs, which are capable of tackling these problems.

Keywords: *integrated assessment modelling (IAM), impact assessment, spatio-temporal aspects*

1. INTRODUCTION

The term Integrated Assessment (Modelling), in short, IA(M), is widely used, but in different contexts and within a variety of scientific disciplines and policy applications. For the purpose of this paper, we will use the CIESIN (1995) definition of integrated assessment:

An assessment is integrated when it presents a broader set of information than is normally derived from a standard research activity. Because integrated assessments bring together and summarise information from diverse fields of study, they are often used as tools to help decision makers understand very complex environmental problems.

With regard to the modelling aspect, CIESIN (1995) further defines:

Integrated assessment modelling is a tool for conducting an integrated assessment. The two activities, however, are not identical even though the terms are often confused and used interchangeably. Integrated assessment models (IAMs) are mathematical computer models based on explicit assumptions about how the modeled system behaves. The strength of an IAM is its ability to calculate the consequences of different assumptions and to interrelate may factors simultaneously, but an IAM is constrained by the quality and character of the assumptions and data that underlie the model.

There are other definitions around, but the above terminology is widely applicable and serves us well for the purpose of the following discussion.

This paper aims to provide an initial discussion of the current challenges IA(M) is facing, with an emphasis on the implications of spatio-temporal aspects of the modelling conducted for a variety of purposes. The models described and experiences are mainly drawing from examples in Europe and regarding the application of IA(M) on aspects of controlling emissions of air pollutants and greenhouse gases into the air. The conclusions made, however, are applicable to a wider range of models and applications. The paper cannot provide solutions to all the problems and issues highlighted, but will hopefully stimulate the discussion nevertheless.

2. STATE-OF-THE-ART – WHERE ARE WE WITH INTEGRATED ASSESSMENT MODELLING?

Within the scope of this paper, it would be futile to even attempt a comprehensive overview of integrated assessment (modelling) approaches and activities, even if it was just limited to Europe. The concept is widely used in policy decision support and spans a wide range of applications and topics. These can, for instance, be distinguished by their spatial coverage, by environmental compartment, by topic and so on:

- Global climate change modelling (e.g. IMAGE, ICAM[1], MERGE[2], IGSM[3])
- European air pollution control and greenhouse gas reduction strategies (e.g. RAINS/GAINS, see Höglund-Isaksson L. and Mechler R., 2005; Klaassen et al., 2005; Tohka et al., 2005; Winiwarter et al., 2005; Hordijk, L. and Amann, M., 2007)
- National modelling of air pollution control and greenhouse gas emission reductions (e.g. UKIAM for the UK, MINNI for Italy)
- Models for integrated assessment of water resource allocation and contamination (e.g. Letcher et al., 2007)

Furthermore, we can distinguish between models developed aiming at policy decision support primarily (applied, operational) and models for scientific research (often process based, technical). While the latter are marked by knowledge-driven developments, the former are more demand driven and it is not always straightforward to migrate a fully developed model suite from its scientific development stage to an operational, applied stage.

As indicated above, the abundance of different models does not allow to make general statements for the whole domain of IAM, yet, a few common trends can be observed:

[1] http://hdgc.epp.cmu.edu/models-icam/models-icam.html

[2] http://www.stanford.edu/group/MERGE/

[3] http://globalchange.mit.edu/igsm/

1) Many models have evolved to extend their scope, e.g. incorporating additional topics *(air quality based models extending to climate change, multimedia models covering air, water, soils and working across compartments)*
2) Spatial integration, both up- and downscaling and/or nesting is frequently being conducted *(e.g. regional models downscaling to national/local applications)*
3) Both increasingly complex stand-alone models and extended coupling/linking of specialised models takes place (e.g. the integration of process-based agricultural models into RAINS/GAINS vs. the OpenMI concept of model coupling using wrappers)

These developments reflect the growing understanding of the complex connections between a variety of environmental problems on local to global scale and represent a trend towards a systems approach to problem solving, in contrast to the single-problem, one-purpose strategies that had marked the initial stage of (environmental) research and policy development.

3. EMERGING CHALLENGES

The aforementioned development trends are mainly driven by the evolution of the main scientific and policy questions of this time, especially global environmental change, biodiversity and global warming. The global aspect of current policy discussions leads to an increased development pressure on hemispheric or global climate and earth system models to provide underpinning scientific evidence. An example for the complexity of this class of problems is given in Figure 1, using the nitrogen cycle and cascade for illustration purposes.

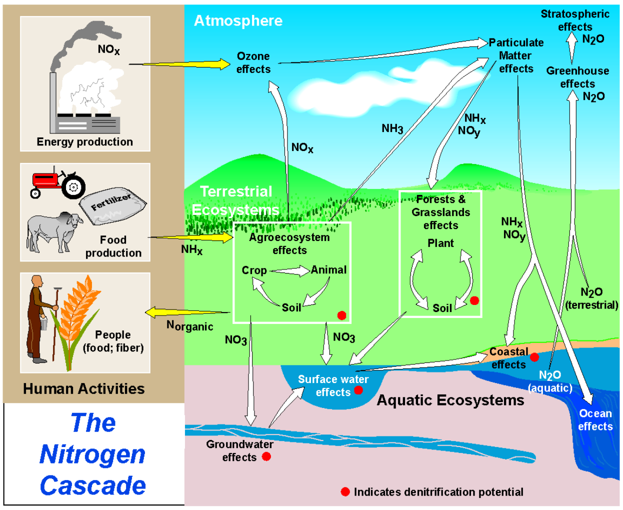


Figure 1. The nitrogen cascade concept based on Galloway et al. (2003), illustrating how different nitrogen species are released into the environment and making their way through a cascade of environmental media and compartments. The chemical transformation and transport through air, water and soil can take place over significant spatial distances and take long periods of time. Hence, management options to reduce harmful effects of the nitrogen cycle at any stage of the cascade requires modelling across the whole spatiotemporal domain.

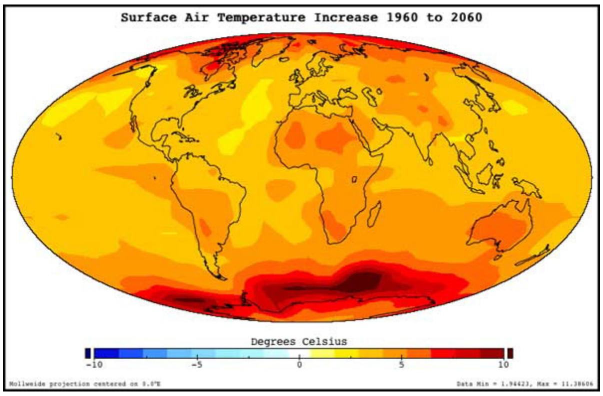
In the same way, the spatial and temporal domains for challenges like global warming (where policy measures implemented now will see benefits in the distant future), the perturbation of the global N cycle (measures can be taken at different stages of the nitrogen cascade, and positive and negative (side) effects may occur both with a significant time lag and at different locations than the measure application) or for instance the accumulation of heavy metals emitted as air pollutants, which deposit and accumulate in soils over long time frames, require models to be capable of modelling across time and space.

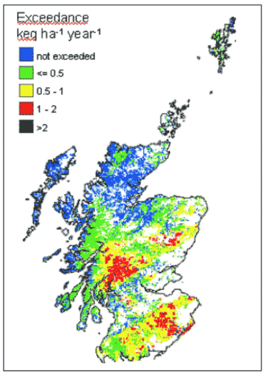
On the other end of the spectrum, regional or national policies are often implemented at the local scale and compliance monitoring e.g. of air quality limit values is often done where the problems occur, i.e. on street level or – more generally – in urban areas. This means, that regional or national IAMs need to incorporate local scale effects to conduct a robust cost-effectiveness or cost-benefit assessment of policy measures taken on the national scale. Here, again, the spatio-temporal aspects - for instance emission sources and receptors moving within the modelling domain - present formidable challenges for modellers to capture.

Last, but not least, with the complexity as well as the spatio-temporal scope of the modelling required to support policy development, it is not always feasible to apply optimisation algorithms to derive “optimal” solutions for pre-defined policy questions. This is the case not only because the interdependency of problems, the often recursive aspects of policy measures taken changing the basis on which projections of future situations have been made or the sheer demand of computing time. In some cases, providing a robust tool to aid the policy development process by assessing different scenario (*“What if…?”*) impacts to policy makers is the preferred option to – comparatively more complex, black-box-type calculations to derive – a set of policy measures that would deliver an optimised solution.

4. CURRENT APPROACHES

Again, it is not feasible to deliver a comprehensive discussion of the current approaches model developers are taking to implement aspects to address the challenges elaborated on in the previous section. The integration of local scale effects in street canyons into a national IAM and the linking of process-based models to incorporate all aspects of the nitrogen cycle will serve as examples.





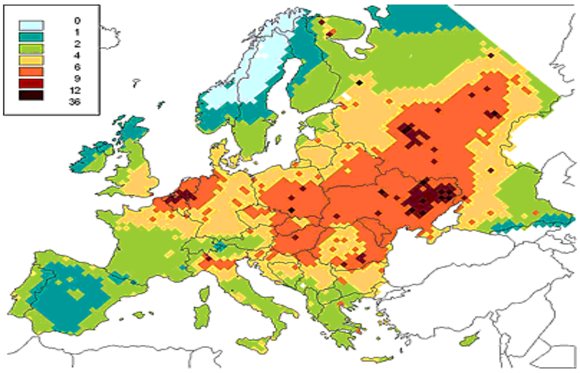


Figure 2. Illustration of the spatial scope of environmental problems addressed in IAMs, ranging from global scale (upper left) for climate change, regional scale (lower left) for instance assessing increased mortality due to exposure to ambient concentrations of PM2.5, or national scale (above) to assess the exceedance of critical loads in ecosystems.

(Sources: NASA, IIASA and Scottish Government)

4.1. Integrating across spatio-temporal domains

Oxley and ApSimon (2007) discuss the need for integration of IAM's from the global scale down to the local scale, and describe a framework for addressing the many issues arising from integration across spatio-temporal domains. In this context – requiring higher resolution modelling of urban areas such as London – the BRUTAL model has been developed to capture the impacts of road transport in urban areas (Oxley et al., 2009). The BRUTAL model has been integrated with the national scale UK Integrated Assessment Model (UKIAM) to provide the necessary spatial resolution to model NO_2 and PM_{10} concentrations in urban areas and assess different abatement strategies in relation to Air Quality Limit Values.

During development, the focus has been upon scenarios for road transport up to 2020, and the effectiveness of both technical measures aimed at reducing exhaust emissions, and non-technical measures influencing behavioural changes to reduce traffic volumes (and thus also emissions from tyre and brake wear). Similar approaches are being applied to capture local non-traffic emissions and energy use such as combined heat and power (CHP) and space heating systems.

The BRUTAL model estimates emissions and road-side concentrations for the whole UK road network, using data assembled on traffic flows and speeds and the fleet composition (vehicle & fuel types, emissions technologies, etc.) combined with emission factors underlying the National Atmospheric Emissions Inventory (NAEI). The concentrations required for comparison with air quality limit values include road-side enhancements to capture the effect of urban street canyons, non-transport contributions calculated by the UKIAM and transboundary contributions by ASAM (Oxley & ApSimon, 2007). The model has already been adapted to calculate CO_2 and N_2O emissions so that the effects of policies on greenhouse gas emissions are also taken into account.

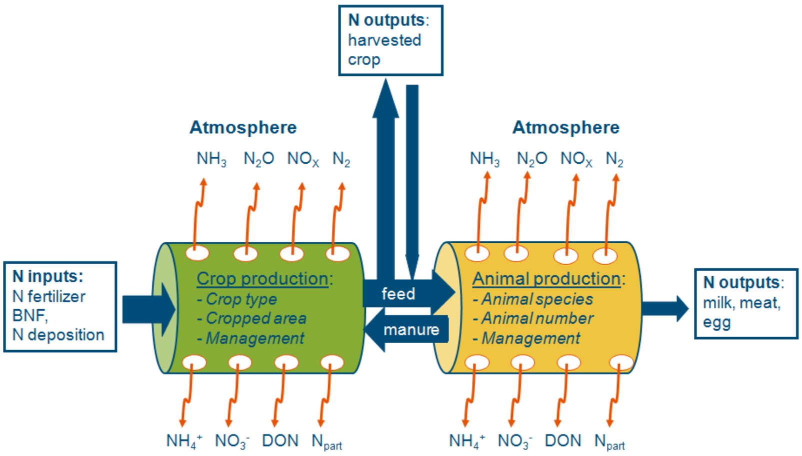
This integration of models across spatial scales facilitates development of national policy scenarios which capture technologies (eg. Euro Standards) to reduce vehicle emissions, and promote local behavioural changes affecting traffic volumes, all within the context of projected transboundary changes in 2020 (such as towards the EU's Thematic Strategy on Air Pollution) and aspired changes towards 2050 currently being discussed in UN/ECE fora.

In a similar fashion, ongoing work at the EC Joint Research Centre is investigating options to assess the impact of present and future global air quality on human health in an integrated approach (see van Dingenen et al., 2008). In this context, an urban increment is modelled within the global atmospheric dispersion model to account for the high population exposures in urban areas.

4.2. Modelling the Nitrogen cycle

Modelling the complexity of mitigation options in relation to the nitrogen cycle (see Figure 1) presents another case where a series of developments has been undertaken recently. One example is the MITERRA model described in detail by Velthof et al. (2009). MITERRA is a comparatively simple, rapid tool for the integrated assessment of N (C and P) emissions from agriculture in the EU-27 at Member State and regional levels. And as Figure 3 illustrates, modelling the complex interactions requires the model to cover not only air emissions, but equally leaching to water and soil and the N flows products as inputs and outputs of the sectoral production.

Figure 3. Conceptual illustration of the major N flows for the subsector agricultural production in the MITERRA model. Emissions to the atmosphere (↑) and leaching into groundwater (↓) of different species is the focus of environmental impacts analysed.



The challenges presented by modelling management options for nitrogen flows - not only, but particularly relevant for agricultural production – are marked by the spatiotemporal aspects of dealing with sources and receptors which are often separated by time and space. Furthermore, individual measures that have been historically taken to reduce the impact of one (for instance atmospheric) pollutant on the environment have led to adverse effects (e.g. on water or soils) in other locations or environmental compartments. Mitigation of NH_3 emissions to the air and the resulting impact on increased N leaching into groundwater and freshwater ecosystems is just one example. In a similar way, reducing NH_3 emissions may lead to increased N_2O emissions later in time from the same soil area.

Similar approaches for the agricultural sector have been taken in the CAPRI *(Common Agricultural Policy Regional Impact Analysis)* modelling system (http://www.capri-model.org/index.htm) and a process-based sub-model is currently integrated into the IAM system RAINS/GAINS to better reflect the effect of emission control measures on the N cycle on a European scale.

5. GAPS, CAVEATS AND UNCERTAINTIES

5.1. Spatial integrity of nested modelling systems

Nesting approaches to increase the resolution for specific areas of a domain under investigation require steps to ensure, that input data used at each level of the model application are consistent. This includes, but is not limited to, avoiding double counting, for instance when building emission inventories e.g. on a European, national and local scale. On the other hand, in the case of atmospheric modelling for instance, boundary conditions on the larger scale have to provide the necessary primers to run models on the next, more highly resolved, level.

This presents a potential source of uncertainties, as it is not always straightforward to quantify the quality of the datasets thus generated. In addition to that, a mixture of top-down and bottom-up approaches to derive spatially or temporally explicit emissions can lead to inconsistencies, as underlying statistics (e.g. total national fuel consumption vs. detailed modelling of vehicle fleets and annual mileage) may be based on quite different datasets.

5.2. Discounting and modelling across time

Discounting of environmental effects has been recognised as a challenge for some time (see for instance Hanley and Spash, 1993) and is especially relevant in the case of modelling aspects of global climate change or the accumulation of heavy metals or other toxic substances over time. While mitigation measures and related costs occur at this point in time, effects of these measures (and thus benefits) may only be observed tens or hundreds of years later.

A different, but related, issue is the increased uncertainties associated with input data based on future projections. In particular when looking at a time horizon of 100 or more years ahead, even input data that are deemed accurate and prone to low uncertainties today can vary by orders of magnitude in the future. Lastly, when modelling for instance global climate change, future effects on, for example, air quality, are significantly influenced by meteorological drivers, which in turn heavily depend on the magnitude and the nature of changes in global and regional climates.

5.3. Model coupling vs. model integration

Finally, modelling complex aspects as described above requires selecting a paradigm for the development of models that have the capability of assessing the full scale of the problem. Currently, different trends can be observed in this realm; on the one hand, increasingly complex models are being developed with the aim to integrate all processes and interactions required into one model. On the other hand, concepts to link or couple advanced specialist models (e.g. OpenMI, http://www.openmi.org) have been successfully applied.

Both approaches have advantages and disadvantages and the main difference can be seen in the level of complexity of the resulting model frameworks. Fully integrated models, with a large number of parameters and variables, are often not easily accessible and or applicable by experts other than those developing the models. They can thus be perceived as a kind of “black-box” where the interpretation of results and the setting of initial conditions and system parameters can be a task of a complexity similar to the original modelling task. In contrast, the challenge for coupled modelling systems lies in the expertise and experience required with all specialist models involved to ensure that data streams and links are well understood and correctly interpreted.

6. DISCUSSION AND CONCLUSIONS

This paper aims at giving a general overview on the current situation in IAMs. To achieve this, the main aspects of the challenges IAM development and application is currently facing have been briefly introduced and evaluated.

Obviously, it is beyond the scope of this paper to evaluate the capability of individual models or model families in detail. However, it can be stated that models currently applied for policy decision support have achieved a substantial level of maturity. A growing understanding of the complexity of the systems modelled, applying systems theory and control theory in model design and development, as well as carefully choosing the level of ambition and precision required have led to an evolution of IAMs that are capable of providing robust scientific underpinning of policy decision making.

However, one caveat that needs discussion is an often observed mismatch regarding the nature of (scientific) model results and the expectations/demands of policy makers. While current IAMs are generally well capable of identifying ranges of options and compare different measures *ceteris paribus*, decision makers are often expecting an accurate representation of reality in models and results that pinpoint individual options or deliver an exact number (e.g. for costs, reduction targets, future levels of ambient concentrations etc.). This is not a trivial problem to overcome, but improvements in communication between model developers and users can significantly reduce this problem.

Finally, the development of more complex IAMs will benefit from embracing approaches applied e.g. in Earth Systems Modelling and further integration across scientific disciplines that are currently evolving along similar, but different lines. A further integration of modelling approaches from local to global scale, across different time scales and environmental compartments is essential to provide modelling support for complex problems such as global environmental change (Burton et al, 2008; Turnpenny, 2008).

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