Global-scale modelling of flows and impacts of nitrogen use:

Modelling approaches, Linkages and Scenarios

Towards the INMS

International Nitrogen Management System

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About INMS:

The International Nitrogen Management System (INMS) is a global science-support system for international nitrogen policy development established as a joint activity of the United Nations Environment Programme (UNEP) and the International Nitrogen Initiative (INI). It is supported with funding through the Global Environment Facility (GEF) and around 80 project partners through the 'Towards INMS' project (2016-2022).

INMS provides a cross-cutting contribution to multiple programmes and intergovernmental conventions relevant for the nitrogen challenge. These include the Global Partnership on Nutrient Management (GPNM) and the Global Waste Water Initiative (GWWI) under the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA), the UNECE Convention on Long-Range Transboundary Air Pollution (Air Convention), through its Task Force on Reactive Nitrogen (TFRN), the UN Convention on Biological Diversity (CBD), the UN Framework Convention on Climate Change (UNFCCC), the Vienna Convention for the Protection of the Ozone Layer, and many regional agreements, such as the Black Sea Commission, the Lake Victoria Basin Commission, the Partnership for Environmental Management for the Seas of East Asia (PEMSEA) and the South Asian Cooperative Environment Programme (SACEP).

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Nitrogen for Life is the motif of UN Nitrogen Campaign launch, held in Colombo, Sri Lanka on 23-24 October 2019

Global-scale modelling of flows and impacts of nitrogen use:

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Abstract

In this report document, we discuss the approach to a global integrated nitrogen assessment model chain allowing to evaluate the consequences of different socio-economic drivers (scenarios) and N mitigation management in terms of: (i) benefits, including food, feed, fibre (wood) and energy production and (ii) threats, including pollutant and greenhouse gas emissions, affecting the quality of air, soil and water and related climate, human health and biodiversity impacts and (iii) cost- effectiveness. This is done by addressing:

- The overall modelling approach, including (i) the type of models that are needed to simulate nitrogen benefits and threats and (ii) the model linkages needed to enable a consistent multi-model approach in response to a consistent set of scenarios of drivers (population development, income etc.) and N mitigation measures.

- The modelling practice including (i) the modelling approaches, distinguishing between empirical and process-based models, and (ii) the available models that would serve an integrated global scale nitrogen assessment, considering the variety of impacts and scales.

- A modelling protocol of the involved models including information on: (i) the models involved, (ii) basic agreements on base year (2010), spatial extent and resolution, temporal extent and resolution, (iii) scenarios, (iv) model outputs and (v) model linkages.

- A database platform for the INMS model inputs and outputs.

Keywords: modelling, nitrogen flows, nitrogen impacts: modelling approaches, scenarios, global scale

Contents

Foreword

For too long there has been insufficient attention given to bringing together the multiple ways in which humans have been altering the global nitrogen cycle, with the multiple impacts of this alteration on environment, health and economy.

Past efforts have typically examined only parts of the problem. Agricultural researchers have primarily focused on food and feed production and the economic benefits for farmers. In parallel, other researchers have assessed how agricultural activities and wastewater lead to leaching and run-off of nitrogen compounds, contributing with other nutrients to freshwater and coastal pollution. Even if much remains to be known, these issues have been intensively studied and informed matching policy development.

The same applies to air pollution. Nitrogen compounds such as nitrogen oxides (NO_x) and ammonia (NH_3) are being emitted by human activities into the air, leading to increased concentrations of nitrogen dioxide (NO_2) and NH_3, exacerbating formation of fine particulate matter ($PM_{2.5}$) and tropospheric ozone. Together with increased deposition of nitrogen compounds from the atmosphere, these are leading to major impacts on human health and ecosystems.

Again, the same human activities – transport, combustion, agriculture and wider land-use change – are leading to emissions of the greenhouse gas nitrous oxide (N_2O), which contributes to stratospheric ozone depletion in addition to its substantial warming effect on climate. These are specialist areas in their own right, while not enough attention has been given to addressing the close interconnection between these threats.

Other issues could be mentioned, but this basket of nitrogen pollutants and effects is already sufficient to show that nitrogen presents humanity with a special challenge. Whereas past efforts of environmental research and policy have typically focused on individual threats (water, air, climate, biodiversity, food etc.), with nitrogen we find that these dimensions must be brought together if humanity is to make real progress towards sustainability.

This is especially the case when it comes to examining the barriers-to-change. It is fair to say that progress in reducing these nitrogen-related threats over the past 30 years has been extremely limited. At the heart of the approach being developed by the International Nitrogen Management System (INMS) is the hypothesis that a joined-up approach for nitrogen will strengthen the case for taking action by offering multiple win-wins: for transboundary pollution of water and air, for climate, biodiversity, human health and economy. By counting the co-benefits, maximizing the synergies and minimizing the trade-offs, there is the opportunity for action on nitrogen to be transformational in working toward the Sustainable Development Goals (SDGs).

One of the starting points for implementing this vision must be to increase the capability of the scientific community to work across traditional disciplinary boundaries. It means that we need to develop a more integrated approach to assessing the multiple benefits and threats of nitrogen use, which can then provide the foundation for examining how nitrogen-focused solutions could help many of the SDGs.

With this document, we start a new series of reports as outputs from the "Towards INMS" project supported by the Global Environment Facility (GEF) through the United Nations Environment Programme (UNEP). It is highly appropriate that this first report in the series focuses on developing the global scale system of nitrogen models. As such, it provides a foundation for other products to follow, including examination of future scenarios, development of guidance on assessment and examination of barriers and solutions.

These inputs will be critical as INMS works with the United Nations and its Member States to mobilize a more-coordinated international response on nitrogen. The support of the GEF/UNEP 'Towards INMS' project has already been decisive in catalysing adoption of the Resolution on Sustainable Nitrogen Management adopted at the fourth UN Environment Assembly (UNEP/EA.4/Res.14). The resulting mandate is now mobilizing development of the first global intergovernmental process on nitrogen, the Interconvention Nitrogen Coordination Mechanism (INCOM). Under the UNEP Nitrogen Working Group, this activity is bringing together Member States to strengthen cooperation between the main intergovernmental conventions and programmes, with support from the science community.

The approach as described in this report will be critical to help move this process forward. It provides the methods needed to underpin the first International Nitrogen Assessment, offering UN Member States and Conventions the tools they need.

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Summary

The GEF/UNEP project Entitled "Targeted Research for improving understanding of the global nitrogen cycle towards the establishment of an International Nitrogen Management System" project, referred to as "Toward INMS," aims to bring together the science community to consider evidence that can support policy development and management to mitigate environmental problems stemming from nitrogen pollution. An important overall goal is to establish a framework for a global integrated nitrogen modelling approach that enables to understand the past and to explore possible future developments and to assess the benefits and costs of feasible improvements in global and regional nitrogen management, in terms of improved food, goods and energy production, reduced pollution and climate threats.

The intended nitrogen integrated modelling approach aims to provide policy makers with an option space of possible interventions and to explore the outcomes for key sustainable development goals (SDGs) and environmental indicators, including a cost-benefit analysis. It further aims to contribute to the optimization of nitrogen management in the context of food, goods and energy production and other ecosystem services at the global scale, with a focus on aquatic impacts. In addition, the opportunities for regional scale assessments are considered, particularly where this is supported by detailed regional data. The modelling approach is multi-sectoral with a strong focus on agricultural N management (including NH_3, N_2O and N_2 emissions and nitrate leaching), but also including N losses in wastewater and NO_x emissions related to energy production and industrial N uses. Where necessary through the coupling and interactions of element cycles, INMS also considers other nutrients (like phosphorus) or elements (like carbon).

In this background document, we discuss the approach to a global integrated nitrogen assessment model chain allowing to evaluate the consequences of different socio-economic drivers (scenarios) and N mitigation management in terms of: (i) benefits, including food, feed, fibre (wood) and energy production and (ii) threats, including pollutant and greenhouse gas emissions, affecting the quality of air, soil and water and related climate, human health and biodiversity impacts and (iii) cost-effectiveness. This is done below by addressing:

- The overall modelling approach, including (i) the type of models that are needed to simulate nitrogen benefits and threats and (ii) the model linkages needed (outputs from model 'x' as input to model 'y') to enable a consistent multi-model approach in response to a consistent set of scenarios of drivers (population development, income etc.) and N mitigation measures.
- The modelling practice, including (i) the modelling approaches, distinguishing between empirical and process-based models, and (ii) the available models that would serve an integrated global scale nitrogen assessment, considering the variety of impacts and scales.
- A modelling protocol of the involved models including information on: (i) the models involved, (ii) basic agreements on base year (2010), spatial extent and resolution, temporal extent and resolution, (iii) scenarios, (iv) model outputs and (v) model linkages.
- A database platform for the INMS model inputs and outputs.

The report also includes three annexes with an overview of characteristics of identified relevant global scale scenario (Integrated Assessment) models, quality models and impact models for potential use within INMS.

1 Background of the modelling approach

Rationale

The GEF/UNEP project Entitled "Targeted Research for improving understanding of the global nitrogen cycle towards the establishment of an International Nitrogen Management System" project, referred to as "Toward INMS," aims to bring together the science community to consider evidence that can support policy development and management to mitigate environmental problems stemming from nitrogen pollution. An important overall goal is to establish a framework for a global integrated nitrogen modelling approach that enables to understand the past and to explore possible future developments and to assess the benefits and costs of feasible improvements in global and regional nitrogen management, in terms of improved food, goods and energy production, reduced pollution and climate threats. The modelling approach is multi-sectoral with a strong focus on agricultural N management (including NH_3, N_2O and N_2 emissions and nitrate leaching), but also including N losses in wastewater and NO_x emissions related to energy production and industrial N uses. Where necessary through the coupling and interactions of element cycles, INMS also considers other nutrients (like phosphorus) or elements (like carbon).

Multiple sector model-based assessment at global scale, and where possible in defined INMS regions, is a key element of such an "Integrated Nitrogen Management System" (INMS). It provides a resource to inform policy makers on the multiple co-benefits of improved nitrogen management, and allows analysis of scenarios, incorporating cost-benefit assessment. The nitrogen integrated modelling approach aims to provide policy makers with an option space of possible interventions and to explore the outcomes for key sustainable development goals (SDGs) and environmental indicators, including a cost-benefit analysis. It further aims to contribute to the optimization of nitrogen management in the context of food, goods and energy production and other ecosystem services at the global scale, with a focus on aquatic impacts. In addition, the opportunities for regional scale assessments will be considered, particularly where this is supported by detailed regional data.

Modelling consensus

In April 2015, a pre-meeting on modelling took place in Edinburgh, in view of the so-called INMS-pump priming project, including the principle question "How different compartments of the nitrogen cycle should be linked when formulating global nitrogen integrated assessment models". This principle question was split into four sub-questions:

1. Which effects, both benefits and threats, should be included in the modelling framework?
2. Should a detailed modelling framework be used, for an elaborated evaluation of impacts of N management measures, or a simplified system to do economic-optimization?
3. What global scale models are available, what are criteria to evaluate them for their potential use and which aspects are currently missing?
4. How can collaboration be organized between the various modelling groups?

A summary of results of that meeting is given below.

1. Measures and effects to be included in the modelling framework

It was agreed that the modelling framework should consist of:

1. Linkages between consumption-production (food, feed, industrial N products, bioenergy etc.)- pollution (quality of water, air and soil)-impacts (human health, climate and biodiversity),
2. Options to evaluate measures related to mitigation (linked to consumption-production) and adaptation (linked to impacts or possibly pollution).

2. Impacts versus optimization modelling frameworks

It was agreed that to evaluate impacts of scenarios including N management measures, we should focus on a comprehensive modelling framework, using multiple indicators, including (co-)benefits and adverse impacts of nitrogen and costs. Such an approach would allow us to assess cost-effectiveness and economic - welfare optimization, with targets in terms of reduced threats or improved benefits or a combination of them. Cost-effectiveness is useful for selecting the most efficient measures, whereas a broader economic optimization aims to find the balance between societal costs and benefits. A simplified system (e.g., limited to the assessment of air, soil and water quality without further use of impact models but using/assessing critical levels and critical loads) could be worthwhile for cost-optimization, although the variation in circumstances/valuation makes a global cost-optimization very difficult.

3 Criteria to evaluate the potential use of available global scale models

It was decided to evaluate the potential of available models by various criteria, while distinguishing:

1. Driver (Scenario) -Pressure models enabling the linkage between scenarios, consumption-production and nutrient inputs/air emissions with linkage mitigation and possible cost-benefit optimization
2. Pressure-State models (air, soil and water quality): including loads and concentrations of nitrogen compounds (and where relevant other elements) in air soil and water.
3. State- Impact models (including human health, biodiversity and productivity of agricultural and terrestrial systems).

The criteria that were mentioned to evaluate the potential of the models were:

- Model aim/Functionality,
- Inputs considered: drivers of change,
- Outputs considered: e.g., N forms, other elements etc.,
- Biophysical representation,
- Steady state versus dynamic models,
- Data needs,
- Validity status,
- Spatially resolution; Temporal resolution (and extent),
- Linkage to scenarios/measures,
- Operational status, accessibility.

4 Collaboration between various modelling groups

The consensus was that we should form an N modelling community, focusing on:

1. Model improvement and data exchange
   - We focus on improving available models and rather than on development of new models or upscaling country/European scale models to the world unless a certain aspect is missing.
   - Data and system knowledge exchange is a crucial issue within the group.

2. Model use
   - The output of integrated assessment models (here denoted as scenario models), which are able to translate scenario information into drivers of N use and related pressures on the system, are used by models predicting impacts on air, soil or water quality (denoted as quality models) and related impact on human health or biodiversity (denoted as impact models).
   - The idea is to apply several models of scenarios, quality and impact to enable model intercomparisons.

Aim and content this document

In this document, we discuss the approach to a global integrated nitrogen assessment model chain allowing to evaluate the consequences of different socio-economic drivers (scenarios) and N mitigation management in terms of: (i) benefits, including food, feed, fibre (wood) and energy production and (ii) threats, including pollutant and greenhouse gas emissions, affecting the quality of air, soil and water and related climate, human health and biodiversity impacts and (iii) cost-effectiveness. This is done below by addressing:

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- The modelling practice, including: (i) the modelling approaches, distinguishing between empirical and process-based models, and (ii) the available models that would serve an integrated global scale nitrogen assessment, considering the variety of impacts and scales (Chapter 3).
- A modelling protocol of the involved models including information on: (i) the models involved, (ii) basic agreements on base year (2010), spatial extent and resolution, temporal extent and resolution, (iii) scenarios, (iv) model outputs and (v) model linkages (Chapter 4).
- A database platform for the INMS model inputs and outputs (Chapter 5).

This report also includes three annexes with an overview of characteristics of identified relevant global scale scenario (Integrated Assessment) models (Annex 1), quality models (Annex 2) and impact models (Annex 3) which may be used within INMS.

2 Approach and model linkages to assess benefits and threats of nitrogen use in response to scenarios

2.1 Overall approach

The global integrated nitrogen assessment model chain to be developed aims to include all aspects of the so called DPSIR (Driver- Pressure-State-Impact-Response) diagram as illustrated in Figure 1.

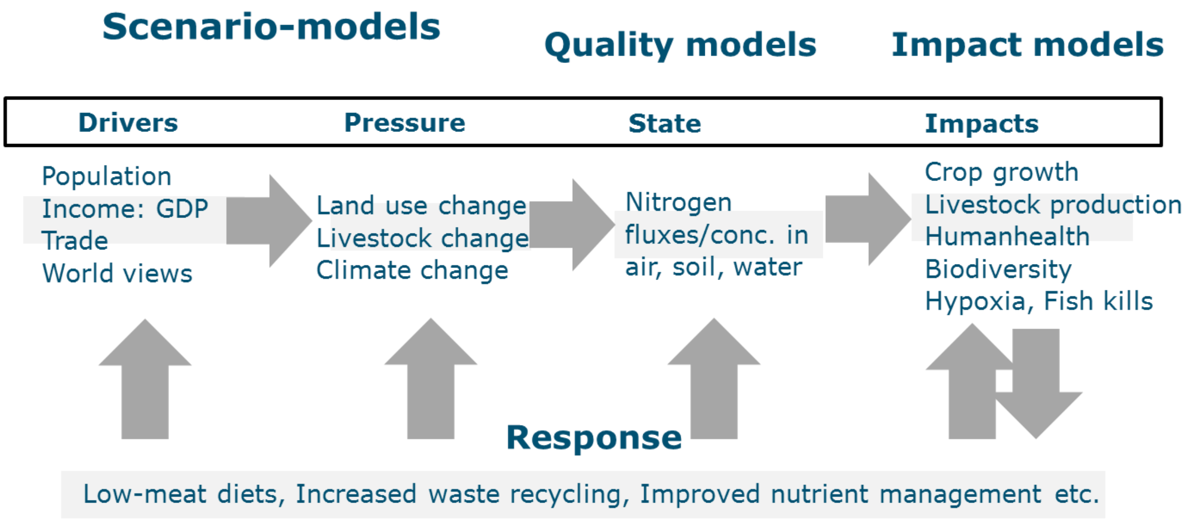

Figure 1. *Aspects of- and models to be included in- global integrated N assessment model chain.*

We may consider also a more simplified model chain that ends with quality models, predicting fluxes and concentrations of N, which are then evaluated with impact based critical limits and loads, such as regional boundaries for N (see also De Vries et al., 2013; Steffen et al., 2015). Such a chain can be useful when applying cost optimization.

A full model chain, however, should include: (i) models that are able to evaluate scenarios, i.e. effects of changes in drivers (population development, income etc.) on food, feed and energy demand and related land allocation, nutrient and greenhouse gas emissions, followed by (ii) quality models and (iii) impact models that are able to assess the impacts of those changes on benefits and threats. The quality models should enable the prediction of the quality of air, soil and water in response to nutrient and greenhouse gas emissions. The impact models should be able to predict food and feed, i.e. crop and livestock, production (benefits), and associated environmental impacts (climate, human health and biodiversity, in response to changes in soil, air and water quality). In this context, it is relevant to the sustainable development goals (SDGs), as illustrated in Figure 2.

Interactions between cycles of nitrogen and those of other elements in relation to different environmental issues require specific attention. Examples of important interactions when considering soil quality and productivity include N, P, and other macro- and micronutrients as well as water availability; N and C in relation to climate; N and S in relation to air quality; N, P and Si when considering water quality.

Figure 2. *Linkage between N use and sustainable development goals denoted with a circle.*

2.2 Scenarios and nitrogen mitigation measures and interventions

The models to be linked for 'Towards INMS' should enable assessment and quantification of the global effects of nitrogen management linked to socioeconomic factors determining (i) food consumption and production, including population growth, trade, dietary change and (ii) agricultural practices (including the availability of infrastructure and technologies), while accounting for differences in site factors (climate, soil, crop). The main idea is to compare impacts related to a business as usual or baseline scenario, driven by population, Gross Domestic Product (GDP) and demands for energy and food; versus exploring impacts of interventions and adaptation in N management. Regarding the baseline, INMS can fully connect to established shared socioeconomic pathways (SSP) storylines where SSP2 is generally used as the baseline (Kriegler et al., 2014) or any other established scenario "family", whereas the interventions and adaptations in N management should comprise a set of potential improvements, depending on the area.

We thus need to agree on storylines, being qualitative overarching scenarios, that can be used to integrate assumptions of all model (chains) at all scales. To provide assessments of the different components of nitrogen losses, recycling and nitrogen use efficiency, agreements are also needed on which major mitigation and management options have to be considered. This is important as identification of different mitigation options has implications for the modelling requirements.

Efforts should be made to make the INMS scenarios as consistent as possible with existing scenarios (e.g. the Shared Socioeconomic Pathways) to ensure comparability. The main idea of the INMS contribution is to focus on N needs and losses associated with various scenarios of food and energy demand. We may need, however, to include nitrogen mitigation measures in those story lines, including (i) improved farm (crop and livestock) management, (ii) increased waste (crop residues, animal manure, human waste) recycling and (iii) reduced food waste. Furthermore, dietary change may be included, by adapting existing global scenarios.

2.3 Modelling impacts of scenarios on global nitrogen requirements

Rationale

A global economic model should form the front of the model chain to provide welfare-optimal production patterns, and simulate major dynamics of the agricultural sector, including land allocation, while accounting for the scarcity of suitable land, water and economic resources, trade and technological progress. Such economic models (typically, partial equilibrium models) are the basis for any land N management system and should allow to estimate how per-capita requirements of N will change with economic development in relation to different management and development pathways and mitigation strategies that all influence the nitrogen cycle. The principle approach of such an economic model is illustrated in Figure 3.

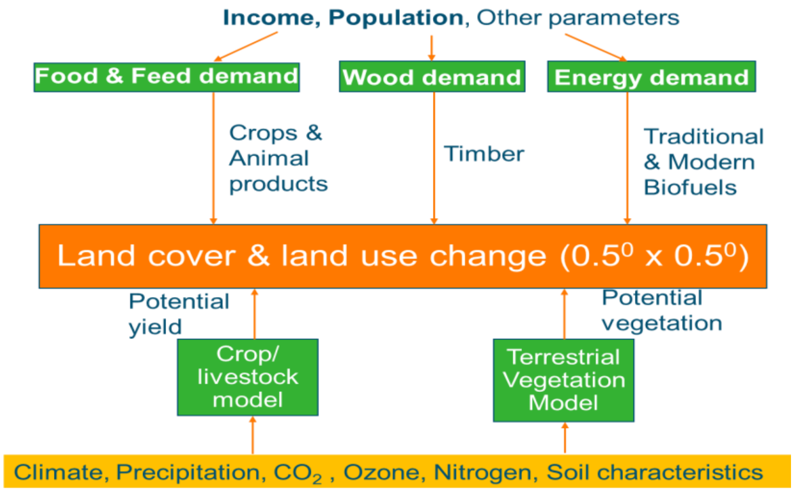

Figure 3. *Basic approach of a scenario model, predicting changes in food, feed and energy demand and related changes in land cover/land use, crop and nitrogen requirements, as used in IMAGE.*

These models thus predict N requirements to produce food and goods and N emissions in view of energy demand under physical constraints of resource availability (including water and land) and considering international trade. This can then be compared with the current availability of N and other elements, and the extent in which the yield gap (difference between potential and actual production) in regions can be reduced by proper agricultural management. Global economic models also allow to balance costs and benefits at different with societal well-being. While general equilibrium models will cover all economic sectors, we expect to apply better resolved partial equilibrium models focussing on the agriculture and forestry sectors.

Modelling

Economic models to assess and allocate production (=supply) to satisfy the demand in a given scenario and year under resource limitations are the basis for an overall integrated global scale modelling of N flows and N impacts. Examples of integrated assessment models, that include economic models to allow such predictions, possibly after adaptation, include IMAGE 3.0, MAgPIE (Model of Agricultural Production and its Impact on the Environment) and GLOBIOM (see below). It is anticipated that such economic models should ultimately enable the:

- Assessment of food and feed demand and required crop and grass production for future changes in population growth, dietary patterns and bioenergy/biofuel production (assuming a baseline scenario and variations on it).

- Assessment of goods and energy demand and required industrial N uses from industrially fixed nitrogen and emitted NO_x for future changes in population growth and ongoing wealthy society, resulting especially urban air pollution.
- Comparison of the food and feed demand with the current crop (food) and grass (feed) production based on the current use / presence of natural resources (current availability of water, fertility of land and supply of fertilizers, biological nitrogen fixation and fixation via NO_x, taking into account climate change (supply).
- Evaluation of the extent in which the yield gap (difference between potential and actual production) in regions could be reduced to fulfil the demand.
- Evaluation of the possibilities to alleviate the difference in food supply and demand by changing nitrogen management, including interactions with irrigation and fertilization with other nutrients, also given the finiteness of water and phosphate resources and limited transportation options, particularly in parts of Africa and Asia.

2.4 Modelling impacts of nitrogen management on food and feed production

Rationale

To assess the consequences of N management on future crop production and thus on the global food and feed system and the environment, it is important to consider the impacts of the availability of other major nutrients, i.e. phosphorus (P) and potassium (K), and of carbon and water – all under the constraint of land limitation and competition for land. Water availability and the associated distribution of water is essential for improved food security, particularly in areas where crop production and livestock systems are vulnerable to changing physical conditions (water availability), socio-economic developments and anticipated climate change, such as Southeast Asia, North Africa and Sub-Saharan Africa, the savannah regions in South America and the semi-arid regions in Latin America, and Southern Europe (Foresight, 2011). A study in Nature (Mueller et al., 2012) shows spatially explicit results where the current yield gaps are mainly caused by either water shortages or nutrient deficiencies. This study does not show, however, whether the yield gaps can be eliminated, because a comparison with resource availability and the costs to exploit them is lacking. Other analyses suggest that a future shortage of irrigation water will form a threat to food production where the extraction of fresh water is reaching its limits (Biemans, 2012). The influence of nitrogen (nutrient) and water management on agricultural production needs modelling at global scale, distinguishing relevant subscales (watersheds/ landscapes, country/regions), acknowledging the fact that many decisions leading to agricultural N pollution are actually made at the field-scale. There is also an important interaction between nitrogen and water use efficiencies (NUE and WUE). A recent study indicates how NUE and WUE could be enhanced simultaneously in regions with water scarcity (Quemada & Gabriel, 2016). This integrated approach requires a combination of agronomic expertise on the response of crops to water and nutrients with basic knowledge of hydrology and soil chemistry. A typical expression of the scale dependence and context of N optimization is the N yield response curve (net economic result per hectare as a function of N input). A major driver for N losses to water is overuse of N which is driven by overestimation of N response and risk avoidance at farm level. The efficiency of nitrogen use is also affected by interactions with other nutrients such as phosphorus and potassium. Where phosphorus or potassium is limiting, addition of nitrogen is less effective and may lead to low NUE.

Analysis of the global nitrogen cycle has shown that about 75-80% of harvested nitrogen from agricultural activities goes to feed livestock, with only 20% going to feed people directly (Sutton et al., 2013). This points to the critical importance of livestock as being the major consumer of agricultural products (including crops and managed grassland). Moreover, livestock diets are generally richer in protein than human diets resulting in a higher share on nitrogen of the total crop production when compared to other indicators such as calories or dry matter. The total amount of nitrogen annually excreted in livestock systems is even higher than the total industrial fixation by the Haber-Bosch process. Any modelling of the global nitrogen cycle therefore needs to consider nitrogen inputs in the form of manure, as a basis for investigating alternative scenarios (management, mitigation, supply and demand) that link food and feed production. Similarly, with the increasing global transition to reduce the use of fossil fuels, increasing amounts of biomass produced by agriculture and forestry) are used as bioenergy resources. These activities play an important and growing role in the global nitrogen cycle and also generate new claims on land, water and nutrients in addition to food and feed production.

The amount of N globally traded embedded in agricultural commodities (particularly in the form of feed) has progressively increased during the last 50 years and nowadays ca. one third of the nitrogen in agricultural production is internationally traded (Lassaletta et al., 2014b). On the other hand, the nitrogen use efficiency (NUE) has also evolved differently during the same period (Lassaletta et al., 2014a; Lassaletta et al., 2016) and policies and management can lead to significant reductions of N emission to the environment. Even with a significant improvement in NUEs, some countries have still an unacceptable level of N surpluses per ha that have to be considered when comparing sustainable agricultural practices. Thus, any global N model needs to be able to evaluate the effect of global trade considering the regional diversity of the NUEs, N surpluses, yield gaps and land availability as well as to estimate the potential effect of different alternative evolution of NUEs and also of the intensification or extensification of production underlying the international exchanges.

An evaluation of the effects of the changing nitrogen (nutrient) and water management on environmental quality requires various models, distinguishing spatially explicit N models and global N management models to assess N (and other element) demands and needed management changes from the more detailed models on hydrology, soil chemistry and crop growth. While the N models used to analyse scenarios with different management options s often have a regional to global scale, the specialized models are mostly used to simulate processes at field, farm or landscape scales.

Modelling

Addressing these challenges would require linkage to or inclusion of the following types of models:

- *Hydrological models* focusing on water availability and water balances (inputs, evapotranspiration, discharge) are needed for the characterization of the amount of water and the prediction of the effects of adapted management of groundwater and surface water resources during drought periods.
- *Agricultural soil quality models* are needed for predictions of the change in soil quality in response to agricultural management.
- *Crop and grass growth models* are needed to assess the response in crop and grass production (including food, feed and bioenergy) to changes in nitrogen, water and other elements.

- *Livestock growth models* are needed to assess the needs of livestock production and the manure generated in relation to different management and mitigation strategies that influence the nitrogen cycle.

2.5 Modelling impacts of nitrogen management on water and air quality, climate, ecosystems and human health

Rationale

A healthy economic planning and development requires not only an improvement of the food production but also maintenance or improvement of ecosystem services, such as to provide cleaner air, cleaner waters, carbon sequestration and biodiversity conservation. These require a reduction in all forms of nitrogen pollution. For example, protection of human health from particulate matter requires the reduction in emissions of nitrogen oxides (NO_x) from combustion sources and agricultural soils, and of ammonia (NH_3) from livestock management, fertilizers and biomass burning. Reduction of ammonia is also necessary because of its negative impacts on terrestrial biodiversity. In parallel the leaching and runoff of nitrogen (especially nitrates, NO_3^-) leads to eutrophication of surface waters (including fresh and coastal waters) with an associated loss of biodiversity in aquatic systems. Similarly, nitrous oxide (N_2O) emissions from agriculture, transport and industrial activities contribute as a powerful greenhouse gas and ozone depleting substance. Lastly, although emission of di-nitrogen (N_2) are environmentally irrelevant, they represent a significant wastage of global energy use, and are also likely to be associated with N_2O emissions. All these effects are included in the term "nitrogen cascade". Together measures that promote nitrogen use efficiency, including better recycling of all available N pools (e.g. industry, agriculture, waste water) across 'nitrogen green economy', can be expected to contribute to more efficient production while reducing environmental pollution threats at the same time (Sutton et al., 2013).

Both the availability and quality of external N sources (fertilizer, biological nitrogen fixation, NO_x deposition) and their recirculation within the system through organic manures and crop residues play a central role in the assessment of their fate and effects on the environment. Regarding the agricultural sector, there is quite some experience on modelling the N surplus, being equal to the difference between N inputs, needed for production and N harvested in the final products. For the high-income regions with high N inputs, N surpluses are relatively easy to quantify with a reasonable reliability, but there are challenges for modelling N surplus for low N regions and future low N input scenarios. Also, the allocation of the N surpluses to different N loss terms is much more difficult and large variations exist due to differences in climate, soil, crops, slope etc. Therefore, modelling NUE and N losses at different scales (from global scale to field scale), including the involvement of other factors that change the NUE, such as the interaction with P, K and water, should be a key issue. Combining this knowledge is essential for the development of climate-robust agricultural production with simultaneous an increased productivity and profitability and a reduced environmental footprint.

Modelling effects on water and air quality (quality models)

An evaluation of the effects of the changing nitrogen and water management (including interactions with other elements) on environmental quality requires various models, including:

- *Emission models:* are needed to assess the future exchange (release or sequestration) of greenhouse gases (especially N_2O, CH_4 and CO_2) and NH_3 and NO_x emissions from agricultural systems in response to agricultural management, as well as from biomass burning and other sources.
- *Air quality (atmospheric transport) models:* are needed to assess impacts on air quality, in terms of exposure (concentrations) of NH_3 and NO_x, ozone (O_3) and particulate matter ($PM_{2.5}$ and PM_{10}) and N deposition, in response to changes in NH_3 and NO_x emissions.
- *Water quality models:* are needed to quantify N and P concentrations in surface waters in response to N and P management. This does not only include pollution loads in (or at the mouth of) rivers, but also an assessment of impacts and fate of nitrogen in coastal and marine systems.

Modelling effects on climate, ecosystem health and human health (impact models).

A useful and easy tool to assess impacts of scenarios is to compare the concentrations in or fluxes from air, soil and water with critical levels and critical loads in view of impacts on ecosystems, climate or humans. This approach is applicable to all exposure-impact relationships and implies that specific impact models are not required. It offers a relevant short-cut for fast evaluations.

A specific evaluation of the effects of the changes in air, soil and water quality on ecosystem health, human health and climate, which is crucial in a cost-benefit assessment, requires, however, various impact models, including:

- *Earth System models/Terrestrial productivity models:* such models are needed for predictions of the change in carbon uptake and also N_2O emissions (greenhouse gas emissions) in response to N deposition, in interaction with climate and air quality of non- agricultural systems. Some models also include agricultural systems but compared to global crop models the level of detail is limited, also in view of the limited role of agricultural systems in carbon sequestration.
- *Human health impact models*: such models are needed to estimate human impacts, such as the loss of Disability Adjusted Life Years (DALY's) and Quality Adjusted Life Years (QALY's).
- *Biodiversity impact models:* these models are needed for predictions of impacts of deposition, soil and water quality on terrestrial and aquatic biodiversity.

2.6 Needed model linkages to enable a consistent modelling approach

Suggested model linkages to assess global scale impacts of changing N and water management on food production, greenhouse gas emissions, the quality of air, soil and water and impacts on human health and biodiversity on a global scale are illustrated in figure 4. The model linkages are not complete, but aim to illustrate the linkages between various models. Several models already integrate several of the above components. For example, LPJmL combines a crop growth and vegetation model with a hydrology model. Moreover, modelling frameworks like IMAGE or PIAM (REMIND-MAgPIE-LPJmL-MAGICC) (Kriegler et al., 2017) do already couple several of the above models. One integrated modelling approach that includes nearly all aspects at global scale is IMAGE (Integrated Model to Assess the Global Environment), being a modelling framework that started some 25 years ago as IMAGE1.0 (Rotmans, 1990), being continually updated since then, including IMAGE 2.0 (Alcamo, 1994), IMAGE 2.1 (Alcamo et al., 1998), IMAGE 2.4 (Bouwman et al., 2006) and most recently IMAGE 3.0 modelling framework (Stehfest et al., 2014).

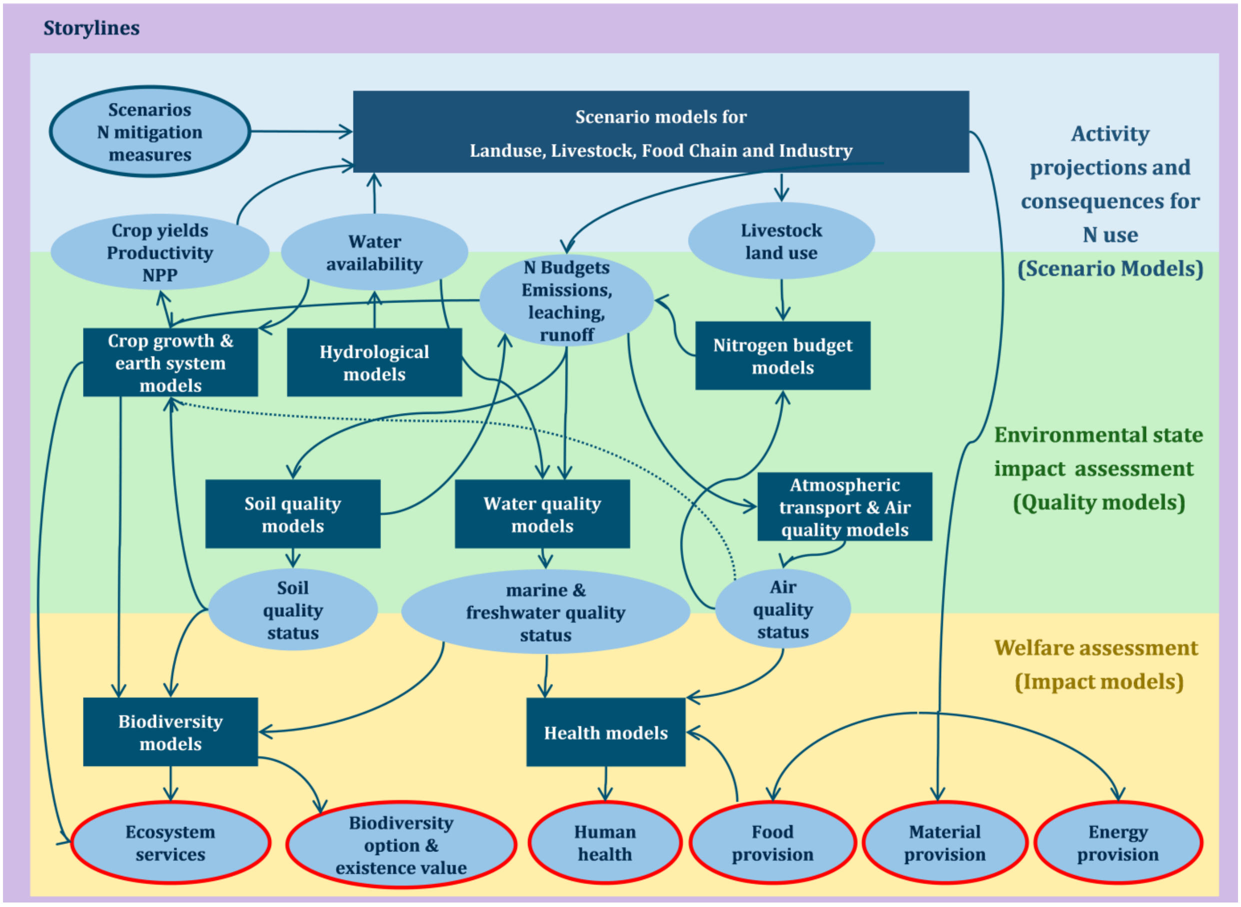

Figure 4. *Suggested types of models and model linkages to assess global scale impacts of nitrogen on food production, greenhouse gas emissions and the quality of air, soil and water. The interaction with water availability is also included. Note that the figure is limited in that it does not specifically show the link from scenario models to hydrology models, nor specifically includes livestock-manure models nor "Cost-benefit models" nor potential feedback loops that would require iterative running of the models.*

3 Practices and available models for a global integrated nitrogen assessment

3.1 Modelling practices

There are various possible modelling practices. Apart from empirical approaches, based on either experimental results or detailed model approaches (called meta-models), more detailed process-based model approaches may be relevant, for example to include interactions between N, water and other nutrients. Furthermore, a distinction can be made in steady-state models, such as emission models reacting directly on changes in activities, or dynamic models, such as soil models assessing long-term changes in soil element pools and availability in response to management. In choosing a model approach, and answering the question which approach is most appropriate, we need to balance the required model complexity (and inherent needed data) and available data.

In general, considering the coarse spatial resolution of global modelling approaches, it can be argued that parsimonious approaches based on experimental results are important in view of their limited data demands. Examples of approaches that could be used in an integrated modelling approach are:

- Emissions factor approaches for ammonia and nitrous oxide emissions, such as the IPCC (IPCC, 2006), GAINS (Amann et al., 2011), MITERRA (Velthof *et al.*, 2007; 2009), INTEGRATOR (De Vries et al., 2011; Velthof et al., 2007; 2009) and IMAGE- Global Nutrient Model (GNM) (Bouwman et al., 2013) approaches, accounting for differences in crops, soil types, climate etc.
- Process-based models for simulating air quality, specifically regarding the impact of N compounds (NO_x, NH_3) on atmospheric concentrations of ozone and PM. Relevant models include the EMEP model (Simpson et al., 2012), the Transport Model TM5 (Dentener et al., 2006) and LOTOS-Euros (Schaap et al., 2008).
- Empirical relationships in models for *water quality*, with the dose being N and P inputs by diffuse and point sources and response the N and P concentrations in rivers, including the Global NEWS approach (Global NEWS approach; Mayorga et al., 2010), the process-based IMAGE- Global Nutrient Model (GNM) approach with spiralling concept (Beusen et al., 2015; Beusen et al., 2016) and the mechanistic RIVE model (Garnier et al., 2002) coupled to IMAGE-GNM. IMAGE-GNM is part of the IMAGE3.0 framework. It uses the hydrology from the PCR-GLOBWB model to simulate in-stream biogeochemistry. IMAGE 3.0 also includes LPJ-ml to simulate water availability.
- Dose-response approaches for *crop growth*, with the dose being N inputs and response the crop growth with response curves per crop and region accounting for the impacts of differences in water, and other element availability (Quefts approach; Janssen et al., 1990; Sattari et al., 2014) versus a process-based modelling approach, as used in e.g. LPJml (Bondeau et al., 2007).
- Dose-response approaches for *forest growth and related tree carbon sequestration*, with the dose being e.g. N deposition and response being forest growth with response curves per tree type and region (boreal, temperate, tropical) accounting for the impacts of differences in soil quality, climate and ozone exposure (EUgrow approach; De Vries & Posch, 2011) versus process-based approaches in earth system models such as CLM (Lombardozzi et al., 2013; Thornton & Zimmermann, 2007) and OCN (Zaehle & Friend, 2010; Zaehle et al., 2011).
- Dose-response approaches for *human health*, with the dose e.g. being population density weighted Nr emissions or air and water pollution and response being the human

life year loss (increased incidence of disease, loss of DALY's and QALy's) or the critical N level exceedances for health impacts.
- Dose-response approaches for *biodiversity*, with the dose being e.g. N deposition and response being the mean species abundance or the use of critical N load exceedances for biodiversity impacts (Globio approach; Alkemade et al., 2009), versus models for simulating the impact of nitrogen and phosphorus on hypoxia and harmful algal blooms in coastal marine ecosystems (using outputs from the GEF project "Global foundations for reducing nutrient enrichment and oxygen depletion from land based pollution, in support of Global Nutrient Cycle"; GNC project).
- Critical N-input approaches using inverse-modelling approaches to assess critical N-inputs to agriculture and non-agricultural systems based on critical limits for N compounds in air, soil and water.

3.2 Available global scale models

Models that are available at global scale and their use in evaluating impacts of scenarios on: (i) future N demand/production in view of energy and food demand (scenario analysis, cost-benefit analysis) and their effects, including improved N management on (ii) the N cycle (quality models) and (iii) N impacts (impact models) are listed below.
Scenario (Driver-pressure) models, allowing integrated scenario and cost-benefit analysis):
- IMAGE (Integrated Model to Assess the Global Environment) 3.0 (Stehfest et al., 2014) including a link to a Modular Applied General Equilibrium Tool (MAGNET; earlier GTAP/LEITAP; Van Meijl et al., 2006),
- GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model (publicly available for key regions: Europe, South Asia, East Asia, while implemented for all regions globally: Amann et al., 2011),
- MAgPIE (Model of Agricultural Production and its Impact on the Environment) (MAgPIE; Bodirsky et al., 2014; Lotze-Campen et al., 2008).
- GLOBIOM (Global Biosphere Management Model) (Havlík et al., 2014).
- CAPRI (Common Agricultural Policy Regionalised Impact) model (Britz, 2005; Britz et al., 2005).

Quality (Pressure-state) models for water availability and air, soil and water quality
- Hydrological models predicting water fluxes/ availability in response to meteorology, being key for the assessment of leaching and runoff of N, such as LPJml (Biemans, 2012) (part of IMAGE 3.0), PCR-GLOBWB (Van Beek et al., 2011) (coupled to IMAGE-GNM because of its landscape and riverscape features relevant to biogeochemistry) and WBM (Fekete et al., 2010).
- Emission models, including: (i) empirical models, such as EDGAR (Van Aardenne et al., 2009; Van Aardenne, 2002), IMAGE- Global Nutrient Model (GNM) ((Bouwman et al., 2013), MITERRA Global; an extension of MITERRA Europe (Velthof *et al.*, 2007; 2009) and IPCC approaches (Syakila & Kroeze, 2011), MAgPIE (Bodirsky et al., 2014) and (ii) process-based models, such as as ForestDNDC (Werner et al., 2007) or LandscapeDNDC (Haas et al., 2013).
- Air quality (atmospheric transport) models predicting N air concentrations and N deposition, such as TM5-FASST (Dentener et al., 2006) and EMEP4 Earth (Vieno et. al 2016a,b).
- Soil quality models predicting changes in soil organic carbon, nitrogen and phosphorous contents and soil pH. Models that can calculate changes in soil organic carbon contents in agriculture worldwide include IMAGE coupled to LPJml (Bondeau et al., 2007), EPIC/GEPIC (Liu et al., 2007) and MITERRA-Global. Furthermore, IMAGE-S World can

also calculate worldwide changes in soil phosphorous contents in agricultural soils (Zhang et al., 2017). The other models could be combined with P models such as DPPS (Sattari et al., 2012; Wolf et al., 1987) and INITIATOR P (Van der Salm et al., 2016) to allow the calculation of such changes and with VSD+ (Bonten et al., 2016) to allow calculation of pH, which is not yet included in any of the models.
- Water quality models predicting N (DIN, DON, PN) runoff to rivers and oceans in response to point and diffuse N sources, such as Global NEWS (Mayorga et al., 2010), IMAGE- Global Nutrient Model (GNM) using a spiralling approach (Beusen et al., 2015; Beusen et al., 2016) and RIVE, the biogeochemistry part of Riverstrahler (Garnier et al., 2002), now coupled to PCR-GLOBWB and IMAGE.

Impact (State-impact) models for impacts on productivity, human health and biodiversity
- Crop growth models predicting crop growth in response to N inputs and other crop requirements. This includes process-based global scale crop growth models, such as LPJml (Bondeau et al., 2007; Müller et al., 2016; Müller et al., 2017) which is part of the IMAGE framework, EPIC/GEPIC (Liu et al., 2007), being part of GLOBIOM (Havlík et al., 2014), and continental scale models, such as WOFOST (Boogaard et al., 2013) and SIMPLACE (Gaiser et al., 2013) and empirical local scale models such as QUEFTS (Janssen et al., 1990; Sattari et al., 2014).
- Earth system models/terrestrial productivity/vegetation models predicting NPP of terrestrial ecosystems in response to N deposition, ozone exposure, CO_2 and climate, including process-based models such as LPJ guess (Sitch et al., 2003; Smith et al., 2014), LPJ-ml (part of IMAGE 3.0), CLM (Lombardozzi et al., 2013; Thornton & Zimmermann, 2007), OCN (Zaehle & Friend, 2010; Zaehle et al., 2011) and Jules (Mercado et al., 2009) and empirical response models, such as stoichiometric scaling models (De Vries et al., 2014), being an extension of response models at European scale (EUGROW; De Vries & Posch, 2011).
- Human health models predicting human health due to exposure to ozone and fine particulate matter ($PM_{2.5}$) being influenced by N emissions, such as ITHIM (Woodcock et al., 2009), DYNAMO-HIA (Lhachimi et al., 2012) and IMAGE-GISMO (Stehfest et al., 2014).
- Terrestrial biodiversity models predicting plant species diversity/abundance in response to N deposition and other drivers, such as GLOBIO (Schipper et al., 2019) , being part of the IMAGE framework (Alkemade et al., 2009).
- Aquatic biodiversity predicting aquatic species diversity/abundance in response to N inputs and other drivers, such as GLOBIO-Aquatic (Janse et al., 2015), part of the IMAGE framework (Stehfest et al., 2014).

It is crucial in any global N management model chain to include scenario models. These are needed to evaluate impacts of scenarios and nitrogen management measures on nitrogen fixation/use through impacts on food and energy demand/production and land demand/land use. This is the basis for all subsequent quality models and impact models, evaluating nitrogen management measures in terms of environmental and human health in the context of those scenarios for integrated assessment models, developing cost-benefit and economic optimization is also a key issue. Data requirements for such analyses may differ between models. For example, the GAINS model performs its optimization using certain environmental criteria (critical loads, human health indicators) for which further input is collected elsewhere. This approach does not require linked detailed impact sub-models (compare IMAGE3.0) and a discussion is needed which approach is most favourable here.

A meta-description of the Scenario (Driver-pressure) models, Quality (Pressure-state) and Impact models participating in INMS is given in Annexes 1, 2 and 3, respectively.

4 Modelling protocol for the INMS global modelling effort

4.1 Approach and models involved

The goal of the INMS global modelling effort is a multi-model evaluation of various scenarios involving different types of models. The main model types are integrated assessment models (scenario models in Figure 5) that translate scenario information to provide outputs that can be used by other models, further down the effect chain. The approach and the models that are involved are illustrated below.

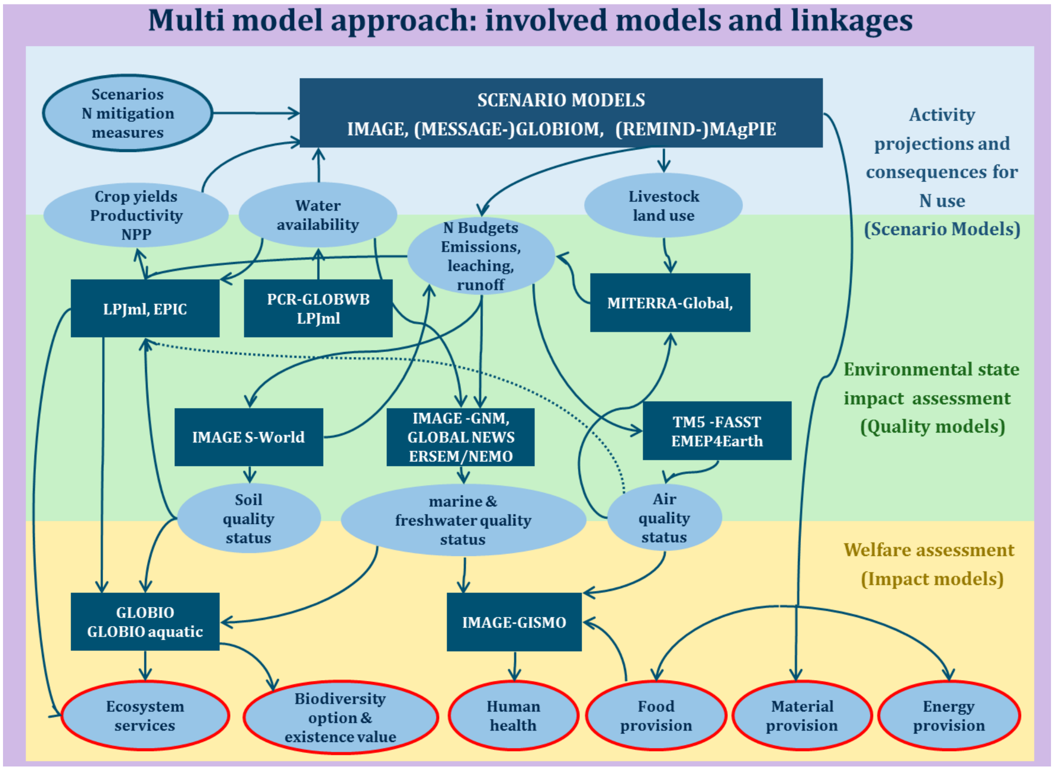

Figure 5. *Overview of models involved in the multi-model comparison and their linkage*

The models that are involved and their principle contact persons:

- IMAGE (with PCR-GLOBWB, GNM, GLOBIO and GLOBIO aquatic): Lex Bouwman, Arthur Beusen
- MADRAT/MAgPIE: Benjamin Bodirsky
- GLOBIOM (with EPIC): David Leclère, Petr Havlík
- GAINS: Wilfried Winiwarter
- CAPRI: Adrian Leip (European Focus)
- EDGAR: Greet Maenhout, Marilena Muntean
- MITERRA-Global: Jan Peter Lesschen
- TM5-FASST: Rita van Dingenen
- EMEP4Earth: Massimo Vieno
- LPJml: Christoph Muller
- Global NEWS (includes VIC): Carolien Kroeze
- ERSEM/NEMO: Icarus Allan/Jason Holt (Focus on specific regions)
- DLEM: Tian Hanqin

4.2 Basic agreements

Models involved in the global intercomparison share the following characteristics:
- Base year: 2010,
- Spatial extent: World,
- Spatial resolution: Continental pre-defined regions, 0.5° by 0.5° degrees and (sub)basins,
- Temporal extent: At least past 1970-2010 and future 2010-2050. Most model up to 2070 and even some to 2100,
- Temporal resolution: periods 1970, 1990, 2010 in the past and 2030, 2050 and 2070 in future. Some models (and the scenario guidance) will extend to 2100. Those fixed years on maps. (NB models have their own temporal resolution and every year would be useful for presentation of trends).

Spatial resolution
For common presentation of all global scale model outputs, the idea is to use continental regions (AGMIP regions and INMS demonstration regions) as given in Section 6.2. At more-detailed levels, the idea is to use:
1. 0.5° by 0.5° degrees in all integrated assessment models (common resolution, i.e. in IMAGE, MAGPIE/MADRAT, GLOBIOM/GAINS; see Table 1),
2. Furthermore, each model can use its own resolution (e.g. countries, NUTS regions, other resolution grids, catchments as used in e.g. CAPRI, MITERRA, EDGAR and Global NEWS, respectively).

Temporal extent and resolution
For common presentation of all model outputs (intercomparison):
1. 1970-2070 (only possible for IMAGE and MADRAT/ MAgPIE). GLOBIOM from 2000 onwards and GAINS between 1990 and 2070. Some models can be used from 2010 onwards (e.g. Global NEWS), some generate snap shots (individual years),
2. model-internal, finer resolution may be presented (see Table 1).

Table 1 *Spatial and temporal resolution/extent in integrated assessment/activity models*

Sources	IMAGE	MADRAT/ MAgPIE	GLOBIOM	GAINS	CAPRI
Spatial resolution	0.5 x 0.5 degree[1]	0.5 x 0.5 degree	0.5 x 0.5 degree[1]	0.5 x 0.5 degree[2]	countries (77) and country blocks (40)[3]
Temporal extent/ resolution	1970-2050 (2100 for selected output) (5 yr)	1965-2100 (5 yr)	2000-2100 (10 yr)	1990-2070 (5 yr)	2012, 2030, 2050

[1] Also a version on 5 by 5 minutes

[2] GAINS uses country scale data but will provide explicit emission reduction formulations to models like GLOBIOM such that finely resolved results are possible

[3] CAPRI will focus on Europe and the model is not meant for use in the global intercomparison

4.3 Scenarios and N policy story lines

Modellers have been requested to cover at minimum four and at maximum six combinations of scenarios and N policy story lines, i.e. (see Table 2):
- Three Shared Socioeconomic Pathway (SSP) scenarios with related Representative Concentration Pathway (RCP) scenarios:
  - A scenario with no/low environmental ambition, i.e. SSP5 “Fossil fuelled development – taking the highway” in combination with RCP8.5.

- Scenarios with intermediate ambition: SSP2 (middle of the road; typically business as usual) combined with RCP4.5.
- A scenario with high environmental ambition, i.e. SSP1 "Sustainability – taking the green road" in combination with (i) RCP4.5, with reduced N and P inputs compared to the current situation and (ii) RCP2.6, a scenario with a high climate ambition possibly being much less environmental friendly for N and P due to intense biofuel use.

- N policy storylines (N measure/ambition combinations) to be superimposed onto the selected scenarios with different N mitigation policy ambitions. The idea is to have specifically diverse N policy ambitions for the SSP2 scenario (see Table 2), while the other scenarios will have connected ambition levels in line with the SSP storyline. We will identify N policies with (i) a high ambition level, (ii) intermediate ambition level and (iii) low ambition levels for preservation of nitrogen compounds. The idea is to have region specific ambitions related to:
  - Food waste (losses in food by producers and consumers),
  - Waste (animal, crop and human) recycling,
  - Waste (water) treatment and reuse of nutrients (linked to recycling),
  - Increases in soil-crop NUE (applying 4 R strategy improvements) and crop-livestock NUE (applying improved feeding strategies).

Table 2: *Selected SSP-RCP-N scenario combinations for model evaluation. The suggested minimum four scenarios are given in bold (Source: Kanter et al., 2018)*

Scenario	Climate	Development	Land-use	Diet	N policy
Business-as-usual[1]	**No mitigation (RCP 8.5)**	**Fossil-fuel driven (SSP 5)**	**Medium regulation; high productivity**	**Meat & dairy-rich**	**Low ambition**
Low N regulation	**Moderate mitigation (RCP 4.5)**	**Historical trends (SSP 2)**	**Medium regulation; medium productivity**	**Medium meat & dairy**	**Low ambition**
Medium N regulation	**Moderate mitigation (RCP 4.5)**	**Historical trends (SSP 2)**	**Medium regulation; medium productivity**	**Medium meat & dairy**	**Moderate ambition**
High N regulation	**Moderate mitigation (RCP 4.5)**	**Historical trends (SSP 2)**	**Medium regulation; medium productivity**	**Medium meat & dairy**	**High ambition**
Best-case	**Moderate mitigation (RCP 4.5)**	**Sustainable development (SSP 1)**	**Strong regulation; high productivity**	**Low meat & dairy**	**High ambition**
Best-case +[2]	Moderate mitigation (RCP 4.5)	Sustainable development (SSP 1)	Strong regulation; high productivity	Ambitious diet shift and food loss/waste reductions	High ambition
Bioenergy	High mitigation (RCP 2.6)	Sustainable development (SSP 1)	Strong regulation; high productivity	Low meat & dairy	High ambition

[1] Scenario with expected highest N flows/N emissions

[2] Scenario with expected lowest N flows/N emissions

The included narratives of N abatement given in Table 3. The integrated modellers will take guidance from recommendations provided in Table 3 (with support of the "scenario" Activity) but will use their own algorithms to adjust model parameters accordingly.

4.4 Deliverables/model outputs

The combination of SSPs and RCPs leads to changes in:

- land cover (forests, semi-natural vegetation, grassland, crop land): affecting N and P runoff from non-agricultural vs agricultural regions,

- land use (type of crops): affecting N and P budgets from crop lands,
- climate, i.e. changes in precipitation (patterns): affecting particulate N and P flows by erosion and dissolved N and P runoff.

The climate change impacts on spatial patterns of temperature and precipitation in response to the different RCPs will be based on the results of the HADCM2 GCM model. Model output of the various models given in Table 4.

Table 3: *Narratives of N abatement.*

		N policy ambition levels			
Sector & country group		High	Medium	Low	Indicators
Crops[1]	OECD	Target NUE by 2030	Target NUE by 2050	Current NUE remains constant	Crop NUE (%) N surplus (kg N ha^{-1})
	Non-OECD/High N	Target NUE in 10 years after catch-up with OECD countries	Target NUE in 30 years after catch-up with OECD countries	NUE trends from past 10 years continue if positive, otherwise NUE remains constant	
	Non-OECD/Low N	Target NUE in 30 years by avoiding historical trajectory	NUE follows historical trajectory towards high N/low NUE over 30 years, before improving	Current decreasing NUE trends continue akin to countries with similar socioeconomic status	
Livestock manure excretion[2]	OECD	10% reduction by 2030, 30% reduction by 2050	10% reduction by 2050, 30% reduction by 2070	Current rates remain constant to 2050	N excretion per unit animal (kg N LSU^{-1} yr^{-1}) N excretion per unit animal product (kg N kg^{-1} meat, milk, eggs)
	Non-OECD/High N	N excretion rates same as OECD in 10 years after catch-up	N excretion rates same as OECD in 30 years after catch-up	Current trends continue if positive, otherwise remain constant	
	Non-OECD/Low N	30% reduction for new livestock production after 2030	30% reduction for new livestock production after 2050	Current trends continue or remains constant	
Manure recycling[2]	OECD	90% recycling by 2030	90% recycling by 2050	Current rates remain constant to 2050	Excreted manure collected, properly stored and recycled (%)
	Non-OECD/High N	50% increase in recycling by 2030; 100% increase by 2050	50% increase in recycling by 2050; 100% increase by 2070	Current trends continue if positive, otherwise remain constant	
	Non-OECD/Low N	90% recycling by 2030	90% recycling by 2050	Current trends continue or remain constant	
Air Pollution[3]	OECD	70% of technically feasible measures by 2030, all measures by 2050	Current legislation (CLE) by 2030, 70% of technically feasible in 2050 increasing to all measures by 2100	CLE reached by 2040, further improvements slow	NO_x emissions (t N yr^{-1}) NH_3 emissions (t N yr^{-1})
	Non-OECD/High-Med income	Same as OECD in 10 years after catch-up	Delayed catch-up with OECD (CLE achieved by 2050), 70% of technical feasible reductions achieved by 2100	CLE reached by 2040, further improvements slow	
	Non-OECD/Low income	CLE by 2030, OECD CLE by 2050, gradual improvement towards 70% technical feasible measures	OECD CLE achieved by 2100	CLE reached 2050, further improvements negligible	

Sector & country group		N policy ambition levels High	Medium	Low	Indicators
Waste water[4]	OECD	>99% wastewater treated; 100% N and P recycling from new installations from 2020	>95% wastewater treated 100% N and P recycling from new installations from 2030	>90% wastewater treated	Secondary treatment rate (%) Sludge recycling (%) Organic recycling (%)
	Non-OECD/High N	>80% wastewater treated; Recycling same as OECD in 10 years after catch-up	>70% wastewater treated Recycling same as OECD in 30 years after catch-up	>60% wastewater treated	
	Non-OECD/Low N	>70% wastewater treated	>50% wastewater treated	>30% wastewater treated	

Notes: LSU is livestock unit.

Table 4. *Model outputs to be sent to CEH for uploading in the CEH database[1]*

Model outputs	IMAGE	MAG-PIE	GLO-BIOM	MI-TERRA	CAPRI	GAINS [3]	EDGAR	EMEP4 Earth/ TM5-FASST	Global NEWS	ERSEM NEMO[4]
Drivers of N sources/N fate										
Energy emissions	X				X	X	X			
cropping patterns/ crop areas;	X	X	X		X					
herd size/animal numbers	X		X		X					
Crop production, livestock production	X	X	X		X					
Climate parameters (rainfall, temperature)	X				X					
N sources and withdrawal										
N fertilizer and N manure input	X	X	X		X					
Biological N fixation	X	X	X		X					
Atmospheric deposition	X	X	X		X					
Point N sources	X	X								
Aquaculture	X	X								
Livestock production	X									
Crop N withdrawal	X	X	X	X						
Growth/NPP	X	X								
crop yield	X[2]									
NPP/forest yield	X[2]									
N fate agricultural land										
N (NH_3, N_2O, NO_x, N_2) emissions	X	X	X	X						
N leaching and N runoff	X	X	X	X						
Air quality indicators										
N deposition	X					X		X		
AOT40, POD	X					X		X		
N- PM2.5, N- PM10	X					X		X		
Water quality indicators										
N (P) river export	X								X	
ICEP index	X								X	
Biodiversity indicators										
Terrestrial diversity index	X									
Aquatic diversity index	X									
Marine impacts (Algal Blooms)										x
Health indicators										
DALY						X				

[1] DLEM is not yet included (focuses on global N export to rivers) as funding is not yet secured

[2] Crop production is calculated with LPJml in IMAGE and MAgPIE and with EPIC in GLOBIOM.

[3] Limited to areas that have GAINS source-receptor matrices implemented (currently Europe and East Asia)

[4] Not planned for use at global scale

Data delivery and exchange

The “scenario modelling group” agreed on a data exchange format, including a detailed description of the various outputs. The data exchange will be done by (i) csv files of a specific format for continental regions and (ii) NetCDF files for global scale at 0.5*0.5°. Deliverables to be send and uploaded in the a shared-access database by CEH are:

- model input and output data,
- accompanying meta data text describing the data.

4.5 Model linkages and number of multi-model evaluations

The N sources that can be produced by the integrated assessment models (IMAGE, MADRAT/MAgPIE, GLOBIOM) in response to scenarios are given in Table 5.

Table 5. *N Sources produced by the integrated assessment in response to scenario inputs*

Sources	IMAGE	MADRAT/MAgPIE	GLOBIOM
Agriculture	x	x/x	x
Sewage/waste	x	x/x	x
Combustion, Industry	x	x/-	-
Natural	x	x/x	-

Outputs from the integrated assessment models (IMAGE, MAgPIE, GLOBIOM) that is relevant as input to other flow and impacts models include:

Land use (main outputs):

- cropping patterns/crop areas and crop yields,
- herd size/animal numbers.

N sources (main outputs):

- N fertilizer and N manure input to crop land and pasture,
- N uptake by crop land and pasture,
- N (NH_3, N_2O, NO_x, N_2) air emissions,
- N leaching and N runoff,
- N input to non-agricultural systems,
- Point N sources.

Output from IMAGE, MAgPIE and GLOBIOM is input to:

- ***1 Air quality models:***
  - IMAGE- N emission scaling to Air quality model ensemble,
  - TM5-FASST using results of MAgPIE (and CAPRI for Europe),
  - EMEP4Earth using results of IMAGE or MAgPIE/MADRAT,

Output
  - NO_y deposition, NH_x deposition (currently in IMAGE),
  - Ozone exposure (AOT40, POD),
  - $PM_{2.5}$, PM_{10} (N components),
- ***2 Water quality models, i.e.***

GLOBAL NEWS/Marina: Output
  - N (and P loads) to river mouths,
  - ICEP index,

IMAGE-GNM: output
  - Spatially explicit nutrient delivery, retention and export,
  - N:P ratios, ICEP,

IMAGE-GLOBIO aquatic: output
  - Mean species abundance,

• ***3 Terrestrial biodiversity models, i.e.***

IMAGE-GLOBIO: Output

- Species diversity index (linked to N deposition from IMAGE scaling procedure).

It should be noted that vegetation and crop models are intrinsically linked to scenario models (LPJmL gives crop yields, carbon stocks, which drives land use change, management and N fertilization in MAgPIE and IMAGE, while the same holds for EPIC and GLOBIOM.

Model linkages thus include:

1. ***Integrated assessment models to atmospheric transport models:***
   - IMAGE - N emission scaling procedure wit N deposition results of an air quality model ensemble (no specific link to air quality model),
   - IMAGE or MADRAT/MAGPie - EMEP4Earth,
   - MADRAT/MAGPie - TM5-FASST,

   Further linkages
   - CAPRI-TM5/FASST for Europe.
2. ***Scenario models to nutrient export models:***
   - IMAGE-MITERRA GLOBAL,
   - IMAGE and/or MAgPIE and/or GLOBIOM-Global NEWS.

Agreements on linkages and outcomes

1. ***Integrated assessment models included:***
   - Idea is that we have 3 Scenario-models predicting scenario impacts on (factors affecting) N sources, i.e. IMAGE, MADRAT/MAgPIE and GLOBIOM/GAINS,
   - CAPRI is too broad in resolution but used in internal link with TM5-FASST (including links to EDGAR).
2. ***Number of multi-model evaluations:***
   - N sources: IMAGE, MADRAT/MAgPIE and GLOBIOM/GAINS (3 outcomes),
   - N budgets: IMAGE, MADRAT/MAgPIE, GLOBIOM/GAINS and MITERRA Global (4 outcomes),
   - Air quality: EMEP4Earth and TM5-FASST (using results of MAgPIE/ MADRAT) (2 outcomes),
   - Water quality: IMAGE-GNM; Global NEWS linked to at least to one of the models GLOBIOM, IMAGE and/or MAgPIE,
   - Terrestrial and Aquatic Biodiversity: IMAGE (1 outcome of each),
   - Marine Biodiversity: ERSEM-NEMO coupled to river input from IMAGE-GNM focusing on NW Europe, SE Asia and E Africa.
3. ***Linkage air quality to crop yields/NPP:***
   - There is currently no linkage between deposition/air quality outputs to crop growth models (LPJml, EPIC) nor to the Net Primary production in IMAGE-Magpie,
4. Linkage Global-NEWS to at least one of the models GLOBIOM/GAINS, IMAGE and/or MADRAT/MAgPIE,
   - Global NEWS has been developed on the basis of IMAGE and WBM plus input data; the model will be updated for the year 2010, with new input data from an IAM and hydrology from the VIC model. Global NEWS will be linked to at least one of the models GLOBIOM (at least for SSP2 and its alternative scenarios for N policies), IMAGE and/or MAgPIE (depends on the availability of 0.5° data from IMAGE and MAgPIE),
5. Human health impact by air quality is currently not sufficiently covered – efforts to extend model suite are ongoing.

4.6 INMS Study regions

The suggested INMS study regions are adapted from the AgMIP study, by including the INMS regions, as given in Table 6 and depicted in Figure 6.

Table 6 *INMS Study regions: codes and corresponding AGMIP regions*

Study Code	Description	AgMIP region
Level 1		
ANZ	Australia, New Zealand	AgMIP region ANZ
EUR	Europe	AgMIP region EUR
FSU	Former Soviet Union	AgMIP region FSU
MEN	Middle East and Northern Africa	AgMIP region MEN
SAS	South Asia	AgMIP regions OAS & IND
SAM	South America	AgMIP regions OSA & BRA
EAS	East Asia	AgMIP regions SEA & CHN
SSA	Sub-Saharan Africa	AgMIP region SSA
NAM	Northern America	AgMIP regions USA & NAM
Level 2 (Split for case study regions)		
ANZ_ALL	Australia, New Zealand	AgMIP region ANZ
EUR_OTH	Europe other than European Atlantic Seaboard case study region	AgMIP region EUR – INMS study region EUR_XAS
FSU_OTH	Former Soviet Union other than Eastern Europe case study region	AgMIP region FSU - INMS study region EUR_XEE
MEN_ALL	Middle East and Northern Africa	AgMIP region MEN
OAS_OTH	South Asia other than East Asia case study region	AgMIP region OAS & IND - INMS case study region SAS_XSA
SAM_OTH	South America other than La Plata River Catchment case study region	AgMIP region – INMS case study region SAM_XPR
EAS_OTH	East Asia other than East Asia case study region	AgMIP region SEA & CHN – INMS case study region SEA_XEA
SSA_OTH	Sub-Saharan Africa other than	AgMIP region SSA - INMS case study region SSA_XLV
EUR_XAS	European Atlantic Seaboard case study region	INMS Case study region
EAS_XEA	East Asia case study region	INMS Case study region
FSU_XEE	East Europe case study region	INMS Case study region
SSA_XLV	East Africa Lake Victoria case study region	INMS Case study region
NAM_ALL	North America case study region	INMS Case study region
SAM_XPR	La Plata River catchment case study region	INMS Case study region
SAS_XSA	South Asia case study region	INMS Case study region

The clustering of countries into INMS regions is given in an excel file

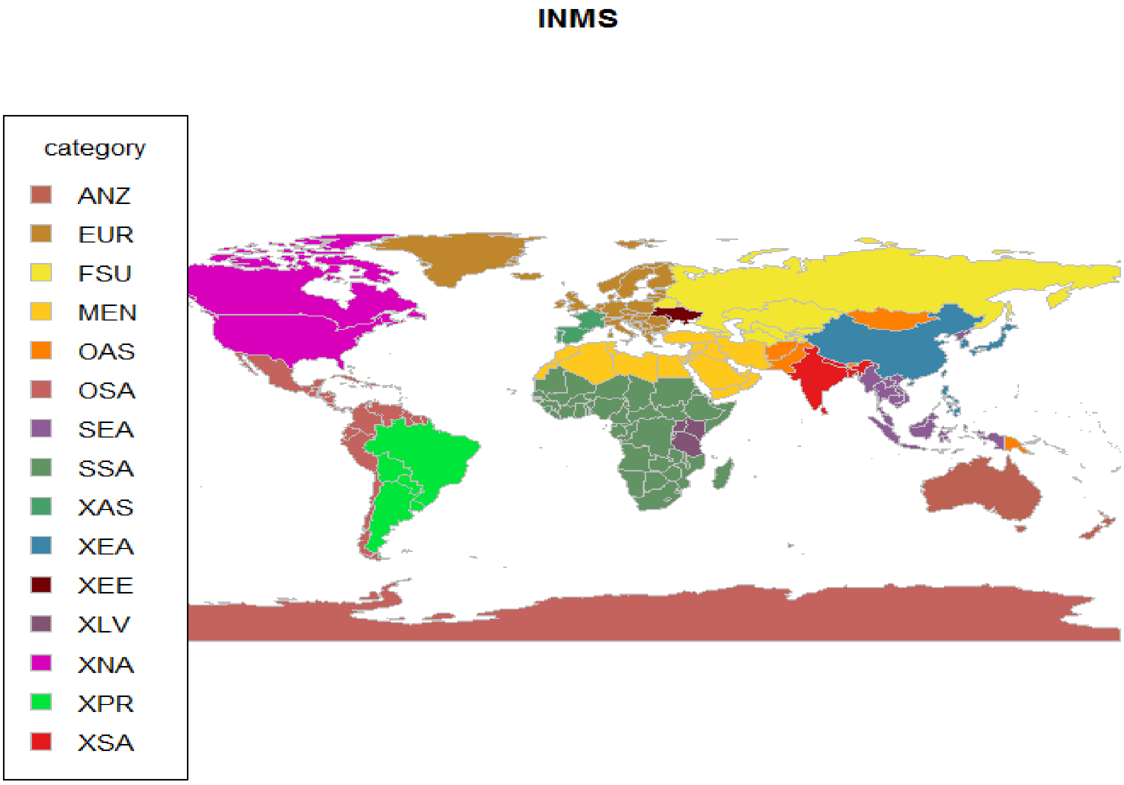

Figure 6. *Overview of the study regions*

5 Database Platform for the INMS model inputs and outputs

5.1 Aims

The aim of the INMS Database Platform is to allow searchable access to datasets and model records used in the INMs project. This will include, for example, access to nitrogen inventories, key input data to models and sharing of output model results. The users of this information will be those in the INMS community who are looking to improve harmonization and coordination of data and models within the nitrogen cycle. The main users will likely be modellers of the nitrogen cycle, but also those interested in impact assessment methodologies – measuring, modelling, and monitoring approaches - in support of regional and global assessment processes. Within the INMS project, the database system will act as a key knowledgebase system to the demonstration regions.

5.2 Scope

The scope of the database platform within INMS is to provide a system to provide ready access to data based on two main data types– namely dataset records (both input data to models and output results from models) and model meta-data records. Regarding model outputs, the first use is for the modellers and consequently these results will initially only be open to the A1.5/A2.1 modelling community. The system will be searchable via keywords and also by filtering records using tagged keywords. Datasets generated under the INMS activities will be downloadable from the INMS system while external datasets (e.g. model input data) will be referenced/signposted to where they are stored externally (e.g. external data centres). Some datasets can be presented as a web map service and datasets created from the INMS project will have their own DOI (digital object identifier) and will be citable.

5.2.1 Database System Approach

The INMS database platform will use existing technologies developed by NERC-CEH for their Environmental Information Data Centre (EIDC eidc.ceh.ac.uk). The EIDC provides discovery metadata on dataset records containing information about a dataset or model that enables prospective users to find it using simple search tools and to determine if the data is suitable for their needs. Discovery metadata contains simple information such as:

- A title,
- A short description of the dataset,
- A list of those who created the dataset (authors),
- Brief information about how the data were created/processed,
- Geographical location,
- how to access (download) the dataset,
- the terms and conditions regarding its use and how others using it should acknowledge & cite the data.

The production of effective use of metadata throughout the life-time of the INMS project will ensure effective utilisation of the data during and after the project has finished.

5.2.2 Types of data

The INMS system uses metadata standards GEMINI (which is based on INSPIRE) to provide common terms, definitions, and structure to ensure consistency in our dataset documentation.
The INMS platform will collect two main types of data:

- Model meta-data records providing a brief description of the model, authors with links to external pages, description of key input and output data, and spatial domain and resolution.
- Dataset records which can be for:
  - important model input datasets that we would like to share within the INMS community. They will not be stored in the INMS system but have a dataset record that points to where they are stored (e.g. an external data centre).
  - output model datasets or any dataset produced from INMS activities. These datasets will be stored in the system.

Spatial datasets can also be served to users as a Web Map Service (WMS), which provides a georeferenced map image returned as a jpeg or png that can be displayed in a web browser (see Figure 7 for an example). Additionally, images can be returned as transparent so that different layers from different datasets can be combined together to create overlaid maps that display more information.

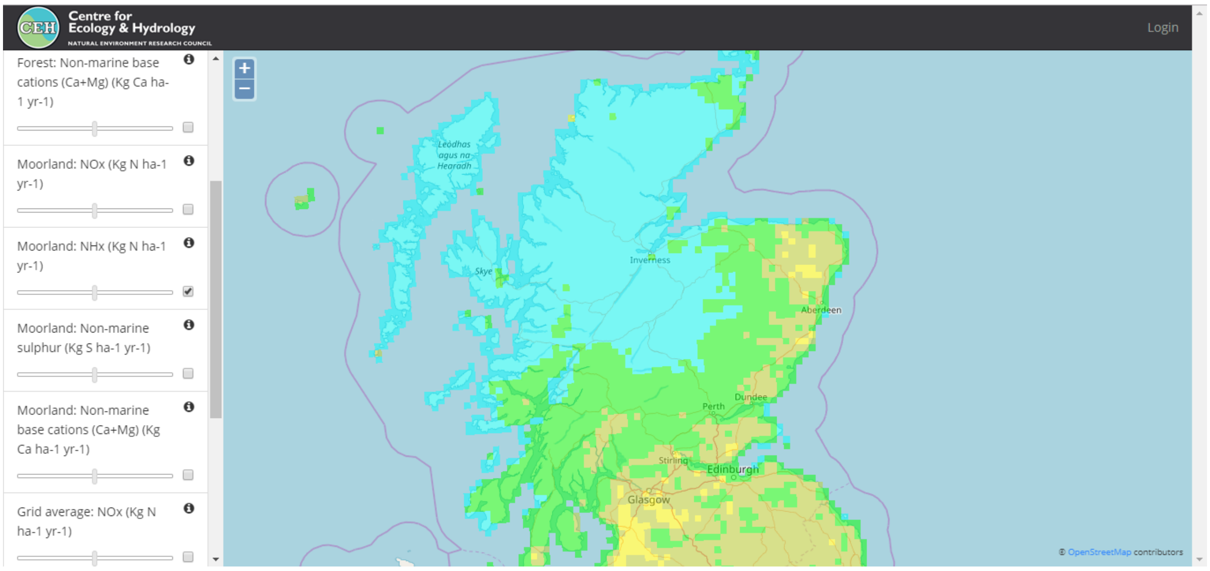

Figure 7: *Web map service for N deposition to the UK using overlay maps*

Model Records -15 global models have been chosen for supporting the INMS scenario activities.
Outputs from Integrated models using scenario information are used by other models down the effects chain. The models and key contacts that are involved in INMS are given in Table 7.

5.2.3 Information/harmonization of databases

The various models use (different) global datasets on e.g.:

- Fertilizer inputs,
- Livestock numbers,
- Meteorology/climate,

- Land use/crop yields,
- Soils,
- Relief/slope,
- Etc.

There is a need for information and possible harmonization of global datasets used by the different models. The key/current global datasets by each model will be added in the database catalogue. When available, an overview will be made to see the possible (in)consistencies.

Table 7: *INMS models and key contacts*

#	Model	Contact person/e-mail	Institute
1	IMAGE	Lex Bouwman lex.bouwman@pbl.nl	PBL
2	PCR-GLOBWB	Lex Bouwman lex.bouwman@pbl.nl	PBL
3	MAGPIE	Benjamin Bodirsky bodirsky@pik-potsdam.de	PIK
4	LPJml	Christoph Muller Christoph.Mueller@pik-potsdam.de	PIK
5	GAINS	Wilfried Winiwarter winiwart@iiasa.ac.at	IIASA
6	GLOBIOM	David Leclere leclere@iiasa.ac.at	IIASA
7	EPIC	Juraj Balkovič/Petr Havlík balkovic@iiasa.ac.at	IIASA
8	CAPRI	Adrian Leip Adrian.Leip@ec.europa.eu	JRC
9	EDGAR	Greet Maenhout greet.maenhout@ec.europa.eu	JRC
10	TM5-FASST	Rita van Dingenen rita.van-dingenen@ec.europa.eu	JRC
11	EMEP4Earth	Massimo Vienno mvi@ceh.ac.uk	CEH
12	MITERRA Global	Jan Peter Lesschen Janpeter.lesschen@wur.nl	WUR
13	GLOBAL NEWS	Carolien Kroeze Carolien.Kroeze@wur.nl	WUR
14	WBM/VIC	Carolien Kroeze Carolien.Kroeze@wur.nl	WUR
15	ERSEM/NEMO	Icarus Allen; jia@pml.ac.uk Jason Holt: jholt@noc.ac.uk	PML, NOC
16	GLOBIO: GLOBIO-aquatic	Aafke Schipper, Aafke.Schipper@pbl.nl Jan Janse, Jan.Janse@pbl.nl	PBL

5.2.4 How INMS data cited?

Details of the citation and acknowledgement that should be used for INMS data are set out on the metadata page of each dataset. Citations can be imported into most popular reference management software (for example EndNote or Zotero). Simply click on the 'RIS' or 'BibTeX' icons to download the citation in that format and import the file into the management software. (see Figure 8).

5.2.5 Search filters

You can narrow a search by using the filters in the left-hand menu or the simple search bar at the top where as you type, records that contain your search terms are displayed (see Figure 9).

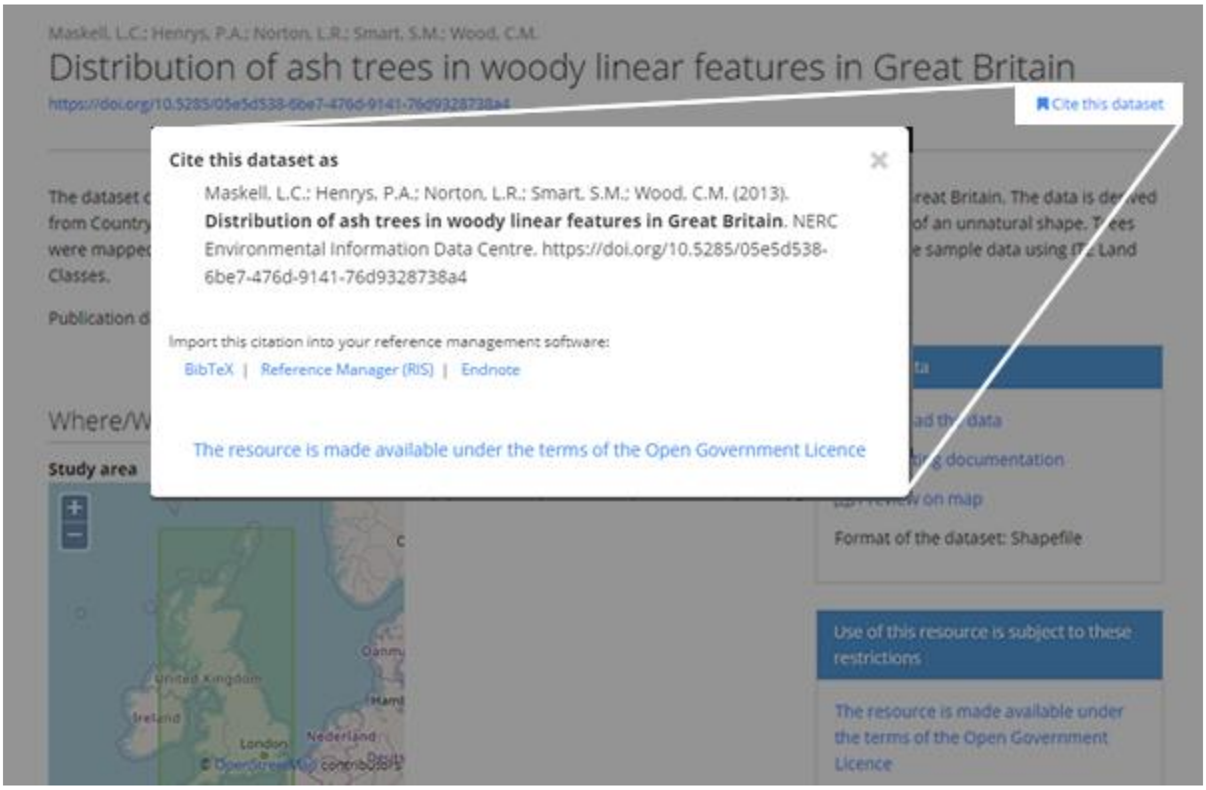

Figure 8: *Citing datasets and DOI URL together with links for importing to reference mangers.*

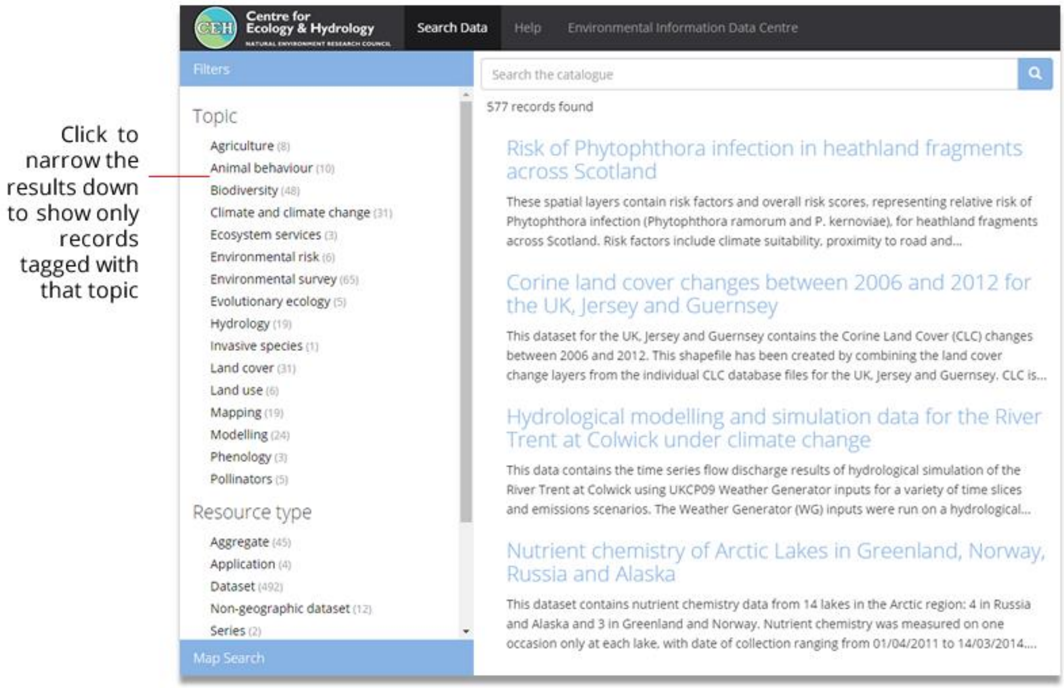

Figure 9: *Search filters in left-hand sidebar*

5.2.6 Data Collection and Validation

Standardised and consistent methods will be used to collect and record data. During data collection, researchers must ensure that the data recorded reflect the actual facts, responses, observations and events. Quality control methods during all stages of data collection and entry are important to ensure validity of data.

5.2.7 Downloading data

Having found a data resource that is of interest, you can download a copy (See Figure 10). If a dataset in catalogue is available to order, a "Download the data" link will be present in the detailed view for that record. The relevant Terms & Conditions of use of the data will be shown and you will be asked to confirm your acceptance.

Depending on the dataset, you may be prompted to make a number of choices in order to customise the download to your requirements. For example, in the case of a spatial dataset, this might include clipping out an area from a map, deciding which coordinate reference system to use, and selecting your preferred file format. If you proceed, your data will be prepared and after a short while you will receive an email which contains a download link. To download your data simply click on the link in the email.

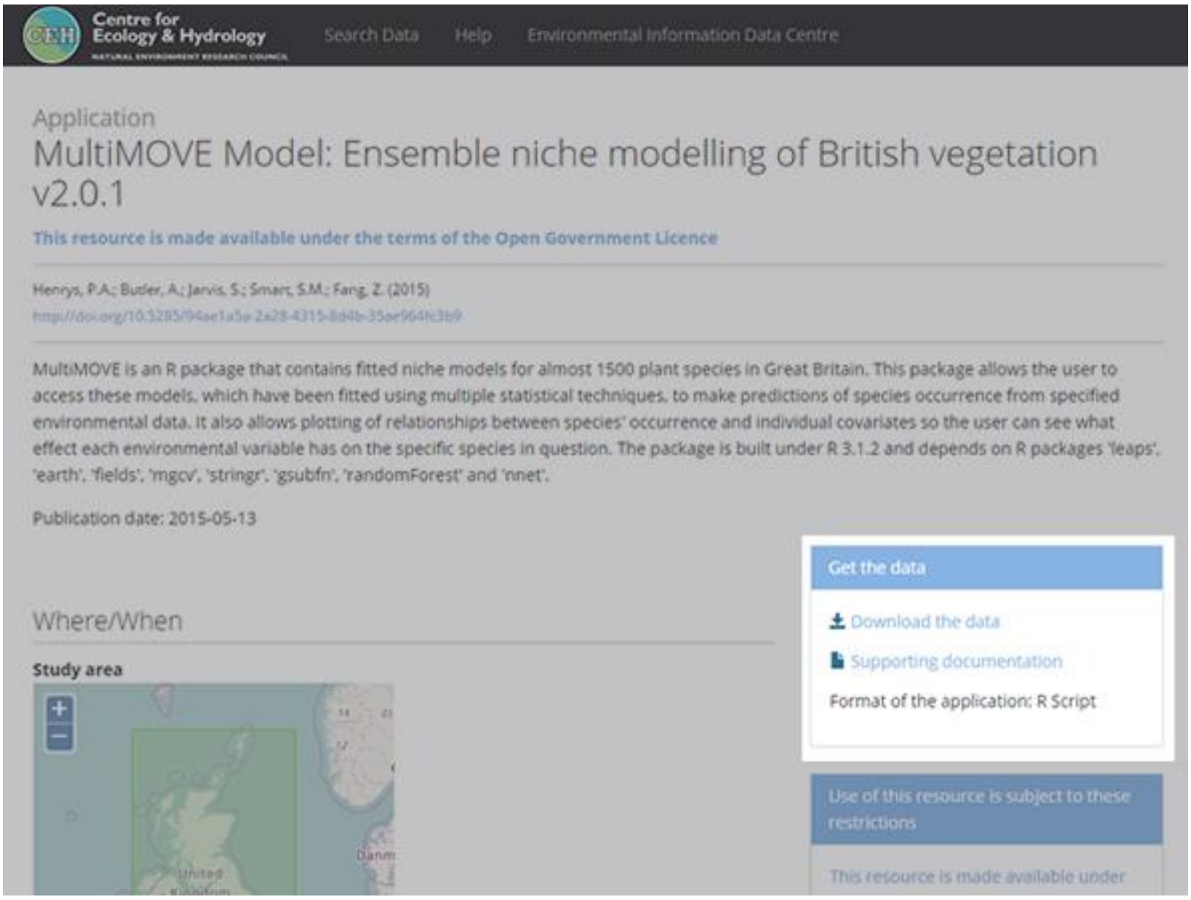

Figure 10: *How to 'Get the data' - downloading link*

5.2.8 Licensing/Terms & Conditions

For downloading data created by the INMS project you agree to abide by a set of licensing terms and conditions that regulate their reuse. These, and any other restrictions, are clearly displayed in the catalogue record for the dataset. By accessing the data, you consent to be bound by the agreement and all the conditions therein. Such

conditions cover the use, distribution and transmission of the data as well as the exploitation of products and services derived from the data. You must always ensure that the data you use is appropriately cited together with the DOI.
See Annex 1 for suggested Licence text.

5.2.9 Next steps

- Input model meta-data records to the system with external signposting to relevant input datasets
- Further development of INMS data vocabulary for tagging dataset records
- Be ready for capturing dataset outputs from modelling activities

References

Alcamo, J., R. Leemans & E. Kreileman (Eds.), 1998. *Global Change Scenarios of the 21st Century: Results from the IMAGE 2.1 Model.* Oxford, Elsevier Science.

Alcamo, J., (Ed.), 1994. *IMAGE 2.0. Integrated modeling of global climate change.* Water Air Soil Pollut. 76 (1-2), 1-318.

Alkemade, R., M. van Oorschot, L. Miles, C. Nellemann, M. Bakkenes & B. ten Brink, 2009. *GLOBIO3: A Framework to Investigate Options for Reducing Global Terrestrial Biodiversity Loss.* Ecosystems 12 (3), 374-390.

Amann, M., I. Bertok, J. Borken-Kleefeld, J. Cofala, C. Heyes, L. Höglund-Isaksson, Z. Klimont, B. Nguyen, M. Posch, P. Rafaj, R. Sandler, W. Schöpp, F. Wagner & W. Winiwarter, 2011. *Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications.* Environ. Model. Softw. 26 (12), 1489-1501.

Beusen, A.H.W., L.P.H. van Beek, A.F. Bouwman, J.M. Mogollón & J.J. Middelburg, 2015. *Coupling global models for hydrology and nutrient loading to simulate nitrogen and phosphorus retention in surface water - description of IMAGE-GNM and analysis of performance.* Geosci. Model Dev. 8 (12), 4045-4067.

Beusen, A.H.W., A.F. Bouwman, L.P.H. Van Beek, J.M. Mogollón & J.J. Middelburg, 2016. *Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum.* Biogeosciences 13, 2441-2451.

Biemans, H., 2012. *Water constraints on future food production.* Wageningen university.

Bodirsky, B.L., A. Popp, H. Lotze-Campen, J.P. Dietrich, S. Rolinski, I. Weindl, C. Schmitz, C. Müller, M. Bonsch, F. Humpenöder, A. Biewald & M. Stevanovic, 2014. *Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution.* Nat. Commun. 5, 3858.

Bondeau, A., P.C. Smith, S. Zaehle, S. Schaphoff, W. Lucht, W. Cramer, D. Gerten, H. Lotze-Campen, C. Müller, M. Reichstein & B. Smith, 2007. *Modelling the role of agriculture for the 20th century global terrestrial carbon balance.* Glob. Change Biol. 13 (3), 679-706.

Bonten, L.T.C., G.J. Reinds & M. Posch, 2016. *A model to calculate effects of atmospheric deposition on soil acidification, eutrophication and carbon sequestration.* Environ. Model. Softw. 79, 75-84.

Boogaard, H., J. Wolf, I. Supit, S. Niemeyer & M. van Ittersum, 2013. *A regional implementation of WOFOST for calculating yield gaps of autumn-sown wheat across the European Union.* Field Crops Research 143 (1), 130-142.

Bouwman, A.F., T. Kram & K. Klein Goldewijk (Eds.), 2006. *Integrated modelling of global environmental change. An Overview of IMAGE 2.4.* Bilthoven, The Netherlands, Netherlands Environmental Assessment Agency (MNP).

Bouwman, A.F., K. Klein Goldewijk, K.W. van Der Hoek, A.H.W. Beusen, D.P. van Vuuren, J. Willems, M.C. Rufino & E. Stehfest, 2013. *Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900-2050 period.* Proc. Natl. Acad. Sci. USA 110 (52), 20882–20887.

Britz, W. (Ed.) 2005. *CAPRI Modelling System Documentation. Common Agricultural Policy Regional Impact Analysis. "Development of a regionalised EU-wide operational model to assess the impact of current Common Agricultural Policy on farming sustainability".* Bonn, J05/30/2004 - Deliverable 1.

Britz, W., T. Heckelei & M. Kempen, 2005. *Description of the CAPRI Modeling System. Final report of the CAPRI-DynaSpat Project.* Bonn, Germany, Institute for Food and Resource Econommics, University of Bonn.

De Vries, W., A. Leip, G.J. Reinds, J. Kros, J.P. Lesschen & A.F. Bouwman, 2011. *Comparison of land nitrogen budgets for European agriculture by various modeling approaches.* Environ. Pollut. 159 (11), 3254-3268.

De Vries, W. & M. Posch, 2011. *Modelling the impact of nitrogen deposition, climate change and nutrient limitations on tree carbon sequestration in Europe for the period 1900-2050.* Environ. Pollut. 159 (10), 2289-2299.

De Vries, W., J. Kros, C. Kroeze & S.P. Seitzinger, 2013. *Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts.* Curr. Opin. Environ. Sustainability 5 (3-4), 392–402.

De Vries, W., E. Du & K. Butterbach-Bahl, 2014. *Short and long-term impacts of nitrogen deposition on carbon sequestration by forest ecosystems.* Curr. Opin. Environ. Sustainability 9-10, 90–104.

Dentener, F., J. Drevet, J.F. Lamarque, I. Bey, B. Eickhout, A.M. Fiore, D. Hauglustaine, L.W. Horowitz, M. Krol, U.C. Kulshrestha, M. Lawrence, C. Galy-Lacaux, S. Rast, D. Shindell, D. Stevenson, T. Van Noije, C. Atherton, N. Bell, D. Bergman, T. Butler, J. Cofala, B. Collins, R. Doherty, K. Ellingsen, J. Galloway, M. Gauss, V. Montanaro, J.F. Müller, G. Pitari, J. Rodriguez, M. Sanderson, F. Solmon, S. Strahan, M. Schultz, K. Sudo, S. Szopa & O. Wild, 2006. *Nitrogen and sulfur deposition on regional and global scales: A multimodel evaluation.* Glob. Biogeochem. Cycles 20, GB4003.

Fekete, B.M., D. Wisser, C. Kroeze, E. Mayorga, L. Bouwman, W.M. Wollheim & C. Vörösmarty, 2010. *Millennium Ecosystem Assessment scenario drivers (1970-2050): Climate and hydrological alterations.* Glob. Biogeochem. Cycles 24, GB0A12.

Foresight, 2011. *The Future of Food and Farming.* London, The Government Office for Science. Final Project Report.

Gaiser, T., U. Perkons, P.M. Küpper, T. Kautz, D. Uteau-Puschmann, F. Ewert, A. Enders & G. Krauss, 2013. *Modeling biopore effects on root growth and biomass production on soils with pronounced sub-soil clay accumulation.* Ecol. Model. 256, 6-15.

Garnier, J., G. Billen, E. Hannon, S. Fonbonne, Y. Videnina & M. Soulie, 2002. *Modelling the transfer and retention of nutrients in the drainage network of the Danube River.* Estuar. Coast. Shelf Sci. 54 (3), 285.

Haas, E., S. Klatt, F. A., P. Kraft, C. Werner, R. Kiese, R. Grote, L. Breuer & K. Butterbach-Bahl, 2013. *LandscapeDNDC: a process model for simulation of biosphere-atmosphere-hydrosphere exchange processes at site and regional scale.* Landscape Ecol. 28 (4), 615-636.

Havlík, P., H. Valin, M. Herrero, M. Obersteiner, E. Schmid, M.C. Rufino, A. Mosnier, P.K. Thornton, H. Böttcher, R.T. Conant, S. Frank, S. Fritz, S. Fuss, F. Kraxner & A. Notenbaert, 2014. *Climate change mitigation through livestock system transitions.* Proceedings of the National Academy of Sciences 111 (10), 3709-3714.

IPCC, 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*. IGES, Japan.

Janse, J.H., J.J. Kuiper, M.J. Weijters, E.P. Westerbeek, M. Jeuken, M. Bakkenes, R. Alkemade, W.M. Mooij & J.T.A. Verhoeven, 2015. *GLOBIO-Aquatic, a global model of human impact on the biodiversity of inland aquatic ecosystems.* Env. Sci. Pol. 48, 99–114.

Janssen, B.H., F.C.T. Guiking, D. van der Eijk, E.M.A. Smaling, J. Wolf & H. van Reuler, 1990. *A system for quantitative evaluation of the fertility of tropical soils (QUEFTS).* Geoderma 46 (4), 299-318.

Kriegler, E., J. Edmonds, S. Hallegatte, K.L. Ebi, T. Kram, K. Riahi, H. Winkler & D.P. van Vuuren, 2014. *A new scenario framework for climate change research: The concept of shared climate policy assumptions.* Clim. Chang. 122 (3), 401-14.

Kriegler, E., N. Bauer, A. Popp, F. Humpenöder, M. Leimbach, J. Strefler, L. Baumstark, B.L. Bodirsky, J. Hilaire, D. Klein, I. Mouratiadou, I. Weindl, C. Bertram, J.-P. Dietrich, G. Luderer, M. Pehl, R. Pietzcker, F. Piontek, H. Lotze-Campen, A. Biewald, M. Bonsch, A. Giannousakis, U. Kreidenweis, C. Müller, S. Rolinski, A. Schultes, J. Schwanitz, M. Stevanovic, K. Calvin, J. Emmerling, S. Fujimori & O. Edenhofer, 2017. *Fossil-Fueled Development (SSP5): An Energy and Resource Intensive Scenario for the 21st Century.* Global Environ. Chang. 42, 297–315.

Lassaletta, L., G. Billen, B. Grizzetti, J. Anglade & J. Garnier, 2014a. *50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland.* Environ. Res. Lett. 9, 105011.

Lassaletta, L., G. Billen, B. Grizzetti, J. Garnier, A.M. Leach & J.N. Galloway, 2014b. *Food and feed trade as a driver in the global nitrogen cycle: 50-year trends.* Biogeochem. 118 (1-3), 225-241.

Lassaletta, L., G. Billen, J. Garnier, L. Bouwman, E. Velazquez, N.D. Mueller & J.S. Gerber, 2016. *Nitrogen use in the global food system: past trends and future trajectories of agronomic performance, pollution, trade, and dietary demand.* Environ. Res. Lett. 11 (9), 095007.

Lhachimi, S.K., W.J. Nusselder, H.A. Smit, P. van Baal, P. Baili, K. Bennett, E. Fernández, M.C. Kulik, T. Lobstein, J. Pomerleau, J.P. Mackenbach & H.C. Boshuizen, 2012. *DYNAMO-HIA–A Dynamic Modeling Tool for Generic Health Impact Assessments.* Plos One 7 (5), e33317.

Liu, J., A.J.B. Zehnder & H. Yang, 2007. *GEPIC—modeling wheat yield and crop water productivity with high resolution on a global scale.* Agricult. Sys. 94 (2), 478-493.

Lombardozzi, D., J.P. Sparks & G. Bonan, 2013. *Integrating O_3 influences on terrestrial processes: photosynthetic and stomatal response data available for regional and global modeling.* Biogeosciences 10 (11), 6815-6831.

Lotze-Campen, H., C. Müller, A. Bondeau, S. Rost, A. Popp & W. Lucht, 2008. *Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach.* Agr Econ-Blackwell 39, 325-338.

Mayorga, E., S.P. Seitzinger, J.A. Harrison, E. Dumont, A.H.W. Beusen, A.F. Bouwman, B.M. Fekete, C. Kroeze & G. van Drecht, 2010. *Global Nutrient Export from WaterSheds 2 (NEWS 2): Model development and implementation.* Environ Modell Softw 25 (7), 837-853.

Mercado, L.M., N. Bellouin, S. Sitch, O. Boucher, C. Huntingford, M. Wild & P.M. Cox, 2009. *Impact of changes in diffuse radiation on the global land carbon sink.* Nature (458), 1014-1017.

Mueller, N.D., J.S. Gerber, M. Johnston, D.K. Ray, N. Ramankutty & J.A. Foley, 2012. *Closing yield gaps through nutrient and water management.* Nature 490, 254-257.

Müller, C., E. Stehfest, J.G. van Minnen, B. Strengers, W. von Bloh, A.H.W. Beusen, S. Schaphoff, T. Kram & W. Lucht, 2016. *Drivers and patterns of land biosphere carbon balance reversal.* Environ. Res. Lett. 11, 044002.

Müller, C., J. Elliott, J. Chryssanthacopoulos, A. Arneth, J. Balkovic, P. Ciais, D. Deryng, C. Folberth, M. Glotter, S. Hoek, T. Iizumi, R.C. Izaurralde, C. Jones, N. Khabarov, P. Lawrence, W. Liu, S. Olin, T.A.M. Pugh, D.K. Ray, A. Reddy, C. Rosenzweig, A.C. Ruane, G. Sakurai, E. Schmid, R. Skalsky, C.X. Song, X. Wang, W. de, A. & H. Yang, 2017. *Global gridded crop model evaluation: benchmarking, skills, deficiencies and implications.* Geosci. Model Dev. 10, 1403-1422.

Quemada, M. & J.L. Gabriel, 2016. *Approaches for increasing nitrogen and water use efficiency simultaneously.* Global Food Security 9, 29-35.

Rotmans, J., 1990. *IMAGE. An integrated model to assess the greenhouse effect*. Dordrecht, Kluwer Academic Publishers.

Sattari, S.Z., A.F. Bouwman, K.E. Giller & M.K. van Ittersum, 2012. *Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle.* Proc. Natl. Acad. Sci. USA 109 (16), 6348–6353.

Sattari, S.Z., M.K. van Ittersum, A.F. Bouwman, A.L. Smit & B.H. Janssen, 2014. *Crop yield response to soil fertility and N, P, K inputs in different environments: Testing and improving the QUEFTS model.* Field Crops Research 157, 35-46.

Schaap, M., R.M.A. Timmermans, M. Roemer, G.A.C. Boersen & P.J.H. Builtjes, 2008. *The LOTOS–EUROS model: description, validation and latest developments.* Int. J. Environment and Pollution 32 (2), 270-290.

Schipper, A., J. Hilbers, J. Meijer, L. Antão, A. Benítez-López, M. De Jonge, L. Leemans, E. Scheper, R. Alkemade, J. Doelman, S. Mylius, E. Stehfest, D. Van Vuuren, W. Van Zeist & M. Huijbregts, 2019. *Projecting terrestrial biodiversity intactness with GLOBIO 4.* Glob. Change Biol. 00, 1-12.

Simpson, D., A. Benedictow, H. Berge, R. Bergström, L.D. Emberson, H. Fagerli, C.R. Flechard, G.D. Hayman, M. Gauss, J.E. Jonson, M.E. Jenkin, A. Nyiri, C. Richter, V.S. Semeena, S. Tsyro, J.-P. Tuovinen, A. Valdebenito & P. Wind, 2012. *The EMEP MSC-W chemical transport model -- technical description.* Atmos. Chem. Phys. 12, 7825-7865.

Sitch, S., B. Smith, I.C. Prentice, A. Arneth, A. Bondeau, W. Cramer, J.O. Kaplan, S. Levis, W. Lucht, M.T. Sykes, K. Thonicke & S. Venevsky, 2003. *Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model.* Glob. Change Biol. 9 (2), 161-185.

Smith, B., D. Warlind, A. Arneth, T. Hickler, P. Leadley, J. Siltberg & S. Zaehle, 2014. *Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model.* Biogeosciences 11, 2027-2054.

Steffen, W., K. Richardson, J. Rockström, S. Cornell, I. Fetzer, E. Bennett, R. Biggs, S.R. Carpenter, W. de Vries, C.A. de Wit, D. Gerten, J. Heinke, C. Folke, G. Mace, L.M. Persson, V. Ramanathan, B. Reyers & S. Sörlin, 2015. *Planetary Boundaries: Guiding human development on a changing planet.* Science 347 (6223), 1259855.

Stehfest, E., D. van Vuuren, T. Kram, L. Bouwman, R. Alkemade, M. Bakkenes, H. Biemans, A. Bouwman, M. den Elzen, J. Janse, P. Lucas, J. van Minnen, M. Müller & A. Prins, 2014. *Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications.* The Hague, PBL Netherlands Environmental Assessment Agency. PBL publication number: 735.

Sutton, M.A., A. Bleeker, C.M. Howard, M. Bekunda, B. Grizzetti, W. de Vries, H.J.M. van Grinsven, Y.P. Abrol, T.K. Adhya, G. Billen, E.A. Davidson, A. Datta, R. Diaz, J.W. Erisman, X.J. Liu, O. Oenema, C. Palm, N.

Raghuram, S. Reis, R.W. Scholz, T. Sims, H. Westhoek & F.S. Zhang, 2013. *Our Nutrient World: The challenge to produce more food and energy with less pollution. Global Overview of Nutrient Management*. Nairobi, Centre for Ecology and Hydrology, Edinburgh & United Nations Environment Programme.

Syakila, A. & C. Kroeze, 2011. *The global nitrous oxide budget revisited.* Greenhouse Gas Measurement & Management 1 (1), 17-26.

Thornton, P.E. & N.E. Zimmermann, 2007. *An improved canopy integration scheme for a land surface model with prognostic canopy structure.* J. Climate 20 (15), 3902-3923.

Van Aardenne, J., U. Doering, S. Monni, V. Pagliari, L. Orlandini & F. SanMartin., 2009. *Emission Inventory for period 1990-2005 on 0.1x0.1 grid. Report to the Sixth Framework Programme Project No. 036961-CIRCE, 23 January 2009*.

Van Aardenne, J.A., 2002. *Uncertainties in emission inventories.* PhD thesis, Wageningen, Wageningen University.

Van Beek, L.P.H., Y. Wada & M.F.P. Bierkens, 2011. *Global monthly water stress: 1. Water balance and water availability.* Water Resour. Res. 47 (7), W07517.

Van der Salm, C., J. Kros & W. de Vries, 2016. *Evaluation of different approaches to describe the sorption and desorption of phosphorus in soils on experimental data.* Sci. Tot. Environ. 571, 292-306.

Van Meijl, H., T. Van Rheenen, A. Tabeau & B. Eickhout, 2006. *The impact of different policy environments on agricultural land use in Europe.* Agric. Ecosyst. Environ. 114 (1), 21-38.

Velthof, G.L., D. Oudendag & O. Oenema, 2007. *Development and application of the integrated nitrogen model MITERRA-EUROPE. Task 1 Service contract "Integrated measures in agriculture to reduce ammonia emissions".* Wageningen, The Netherlands, Alterra. Alterra report 1663.1.

Velthof, G.L., D.A. Oudendag, H.P. Witzke, W.A.H. Asman, Z. Klimont & O. Oenema, 2009. *Integrated assessment of nitrogen emission losses from agriculture in EU-27 using MITERRA-EUROPE.* J. Environ. Qual. 38 (2), 1-16.

Werner, C., K. Butterbach-Bahl, E. Haas & R. Kiese, 2007. *A global inventory of N_2O emissions from tropical rainforest soils using a detailed biogeochemical model.* Glob. Biogeochem. Cycles 21 (3), GB3010.

Wolf, J., C.T. de Wit, B.H. Janssen & D.J. Lathwell, 1987. *Modeling Long-Term Crop Response to Fertilizer Phosphorus. 1. The Model.* Agron. J. 79 (3), 445-451.

Woodcock, J., P. Edwards, C. Tonne, B.G. Armstrong, O. Ashiru, D. Banister, S. Beevers, Z. Chalabi, Z. Chowdhury, A. Cohen, O.H. Franco, A. Haines, R. Hickman, G. Lindsay, I. Mittal, D. Mohan, G. Tiwari, A. Woodward & I. Roberts, 2009. *Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport.* Lancet 374, 1930-1943.

Zaehle, S. & A.D. Friend, 2010. *Carbon and nitrogen cycle dynamics in the O-CN land surface model: 1. Model description, site-scale evaluation, and sensitivity to parameter estimates.* Glob. Biogeochem. Cycles 24, GB1005, doi:10.1029/2009GB003521.

Zaehle, S., P. Ciais, A.D. Friend & V. Prieur, 2011. *Carbon benefits of anthropogenic reactive nitrogen offset by nitrous oxide emissions.* Nat. Geosci. 4, 601-605.

Zhang, J., A.H.W. Beusen, D.F. van Apeldoorn, J.M. Mogollón, C. Yu & A.F. Bouwman, 2017. *Spatiotemporal dynamics of soil phosphorus and crop uptake in global cropland during the 20th century.* Biogeosciences 14, 2055-2068.

Annex 1 Meta-description of scenario (Drivers – pressures) models.

Criterion/Model Name	IMAGE 3.0 Global Nutrient Model	MAGPIE1	GLOBIOM
Contact Person	Lex Bouwman lex.bouwman@pbl.nl	Benjamin Bodirsky bodirsky@pik-potsdam.de	Peter Havlik; David Leclère havlikpt@iiasa.ac.at; leclere@iiasa.ac.at
Model aim/ Functionality	IMAGE is an ecological-environmental model framework that simulates the environmental consequences of human activities worldwide. The objective of the IMAGE model is to explore the long- term dynamics and impacts of global changes that result. It integrates a range of sectors, ecosystems and indicators. The future development of the agricultural economy can be calculated using the agro-economic model MAGNET. The Global Nutrient Model (GNM) is part of IMAGE and computes emissions of greenhouse gases, ozone precursors and acidifying compounds, nutrients in wastewater discharge to surface water, nutrient release from aquaculture, and agricultural and natural soil nutrient budgets.	The integrated assessment modelling framework REMIND-MAgPIE can create long-term scenarios for greenhouse gases, aerosols and nitrogen-related pollutants. Within the agricultural sector, MAgPIE captures all major nitrogen flows from a cropland soil budget, over crop and livestock production, trade, up to the consumer, household waste and sewage. Finally, it captures crop- and livestock nitrogen surplus, as well as emissions into the environment. Within the energy and industry sector, REMIND captures the relevant nitrogen emissions.	GLOBIOM is a global economic bottom-up agricultural and forest sector model. The model is based on a detailed spatially explicit grid and estimates economic and environmental impacts, incl. nutrient balances, tightly linked with bio-physical process-based models like EPIC. The model is typically used for scenario analysis in medium (2030), long (2050), and very long (2100) time horizon.
Inputs/ Drivers of change	The ultimate drivers of change are income and population change, which lead to changes in diets, trade and domestic production, but also to land use changes, agricultural projection, fertilizer use and so on.	Drivers of change are income and population change, policy assumptions on trade and land-protection policies, climate change impacts, and technological development.	Population, GDP growth, dietary preferences, policies (bioenergy, biodiversity,…), technological progress
Outputs	Grid-based land use as well as gas emissions to air of all greenhouse gases, aerosols, ozone precursors and acidifying gas compounds from energy, industry and agricultural sectors and natural ecosystems including oceans; gridded soil nutrient budgets including input terms (fertilizer, manure, biological N fixation, atmospheric deposition, weathering (P)), and outputs (crop and grass withdrawal, surface runoff, denitrification and leaching); further gridded inputs to surface water include allochthones vegetation inputs to surface water, aquaculture and wastewater, grid-based retention of N and P, export to coastal seas of TN and TP.	(A) Regional nitrogen budgets for croplands and pastures that can be downscaled to 0.5° grid. Inputs including fertilizer, manure, crop residues, belowground crop residues, biological N fixation, deposition, soil organic matter loss. Withdrawals include harvested crops and crop residues, and losses by volatilization, leaching and denitrification. (B) Regional nitrogen budgets for the agricultural supply chain, ranging from crop production, international trade, processing, use for livestock feed, food or material use, animal waste management, food waste and sewage. (C) Nitrogen pollution (total losses, N_2O, leaching, volatilization) on croplands, pastures, animal waste management systems, household consumption,	Regional activity levels for agricultural and forestry sector; related environmental impact (fertilizer use, GHG emissions, nutrient cycle, land use and land use changes, irrigation water). Emissions cover CO_2 and non-CO_2 sources from the AFOLU sector. The regional output can be downscaled to a grid. Demand quantities, bilateral trade flows, commodity prices are also model outputs.

		industry, traffic, energy combustion. (D) Non-nitrogen indicators like gridded dynamic land-use (multiple cropland activities, pasture, forest, natural vegetation), agricultural production, agricultural water use and co-limitation, phosphorus consumption, non-nitrogenous air pollutants (BC, OC, S,…), greenhouse gases, energy usage ect.	
Biophysical representation	IMAGE uses climate data for the past and calculates future climate to account for changes in the hydrology relevant to the cycling of N; uses soil and geological information. IMAGE-GNM includes the hydrological model PCR-GLOBWB for computing runoff and flooding.	MAgPIE uses outputs of the process-based LPJmL vegetation model to estimate climate-induced 0.5°-gridded crop productivity patterns, irrigation water availability and carbon stocks of different crop types and landuse types. Nitrogen-flows are estimated within MAgPIE based on a budgeting approach. The biophysical constraints (land availability, water availability, nutrient availability, carbon storage) influence the endogenous socio-economic dynamics within MAgPIE. REMIND uses emission factors to relate emissions relevant activity (e.g. energy usage or traffic) into emissions.	Biophysical models (i.e. EPIC for the crop sector, RUMINANT for livestock parameters) estimate relevant input parameters (i.e. productivities, fertilizer requirements, feed requirements, irrigation water environmental impacts) for different production systems and sectors (crop-, livestock and forest sector) at pixel level (Simulation Units).
Technology representation	Technology improvement is possible on all kind of key parameters.	Technology includes key productivity parameters (yields, feed conversion efficiencies, nitrogen uptake efficiency, animal waste management), which are partly endogenously, partly scenario parameters. Additionally, marginal abatement cost curves can be used for GHG abatement.	Leontief production functions for a comprehensive set of management activities at the grid level (crop- and livestock sector).
Data needs	FAOSTAT country data on food, feed and fodder crop production, livestock production, land use, inputs; equivalent subnational data for USA, China, India; IEA data on energy use; emission factors from EDGAR. Fertilizer use by crop from IFA.	Climate Data, FAOSTAT, IFA, IEA, EDGAR, Population and GDP projections.	FAOSTAT country data on agricultural production, demand, areas, prices. GLC2000 land cover map. Parameters for the different management systems are provided from biophysical models. Energy projections from energy models (e.g., PRIMES, POLES, IEA).
Validation status	IMAGE is validated with respect to the global carbon cycle for the historical period. Air emissions are consistent with EDGAR. IMAGE-GNM is not calibrated. Nutrient budgets have been validated with OECD published nutrient budgets at the country scale. River nutrient export has been validated with measurement data for Europe, USA and large world rivers; all comparisons are satisfactory for a global model.	REMIND-MAgPIE-LPJ has participated and is participating in several model-intercomparison projects (AgMIP, ISIMIP, SSP, ROSE). Outputs are validated against past trends (e.g. FAO). Nutrient budgets have been validated against literature of current budgets and future scenarios.	Input data is harmonized with FAO statistics. GLOBIOM participated in various impact assessments for EC but also US EPA, Brazil (INPE) and others, where it undergoes review by country experts, scientific committees and various other stakeholders. The model also participated in the Agricultural Model Intercomparison and Improvement Project (AgMIP) and its performance can be compared to the top peers.
Spatial resolution	0.5 by 0.5 degree and 5 by 5 minutes; IMAGE is flexible with regard to spatial resolution and	MAgPIE: Clustered 0.5° by 0.5° degrees. REMIND: 11 world regions. Downscaling to 0.5° resolution shall be possible in	Input data: Simulation Units based on biophysical characteristics; 5 by 5 minutes up to 0.5 by 0.5 degree. This

	can be easily focused to smaller regions.	the near future. LPJ runs usually on 0.5° grid, but can be run on any resolution when input data on climate and soils is available.	resolution used by biophysical models. Economic model usually run at 2 degree plus country boundaries and agro-ecological zone. Downscaling available.
Temporal resolution	1 year	MAgPIE/Remind: 5 year LPJ: daily	10 year periods
Linkage to scenarios and mitigation / measures	IMAGE is especially designed for scenario analysis. Mitigation of greenhouse gases, ozone precursors and acidifying compounds is part of the model framework. The wastewater model includes several options to improve sewage connection and wastewater treatment. The nutrient model can deal with several measures such as incorporation of manure, reduce emissions from animal houses, substitution of fertilizer by manure, integration of livestock and crop systems, increased efficiency in livestock and crop systems, as well as recycling of human excreta to substitute fertilizers	MAgPIE is able to simulate the SRES and SSP scenarios, as well as customized scenarios. Scenario drivers include for example population and GDP growth assumptions on dietary dynamics, policies (trade, land-use, climate), or technological development (some technological development is also estimated endogenously). In regard to nitrogen, the mitigation measures that can be simulated cover the demand-side (lower livestock consumption, less food waste) and the supply side (efficient fertilization, efficient livestock management) and integrated measures (recycling of manure, household waste or sewage).	GLOBIOM is designed to analyse economic and environmental impacts and trade-offs of different policies, socio-economic or climatic developments on the land use sectors. It forms with the MESSAGE model, the core of the IIASA Integrated Assessment Framework. Has been used recently to develop the SSP-RCP scenarios, OECD long-term agricultural outlook, and is being extensively used for scenario work in EU research projects. Mitigation options cover the crop-, livestock- and forestry sector. Two groups can be distinguished: 1. Technological options (e.g. digesters), 2. Structural change (e.g. switch between production systems or change in international trade patterns).
Mitigation costs and co-benefits	Mitigation costs and co-benefits are included for greenhouse gases, ozone precursors and acidifying compounds. No costs or benefits are computed for nutrients in agriculture.	Co-benefits of mitigation can be simulated for many mitigation measures. Production side-measures can be related to costs. Improving this processes is an ongoing activity.	While the costing of technological mitigation options for the agricultural sector is explicit and based on EPA (2008), the cost of most of the structural mitigation options incl. REDD+ is calculated endogenously based on opportunity cost.
Operationality	Fully operational	Fully operational.	Fully operational
Accessibility/ links	PC version is available for public. The GNM model is online available with one year of input data.	Open-Source model will become public this year	Model shared on a case by case basis.
Literature sources	Stehfest et al. (2014b); Morée et al. (2013); Bouwman et al. (2013g); Bouwman et al. (2013f); Bouwman et al. (2013e); Bouwman et al. (2013c); Bouwman et al. (2013a); Beusen et al. (2015); Beusen et al. (2016);	Bodirsky et al (2012,2014,2015) Lotze-Campen et al (2008) Popp et al (2010) Strefler et al (2014) Klein et al (2013) Humpenöder et al (2015)	Havlík et al., 2014

1 MAgPIE: Global socio-economic agriculture and land-use model, cost-optimization model, recursive dynamic. REMIND: global intertemporal optimization model of the macro-economy and the energy sector. LPJmL: Dynamic Global Vegetation Model (DGVM)

Scenario (Drivers –pressures) models: continued

Criterion/Model Name	GAINS Global	DLEM	CAPRI
Contact Person	Wilfried Winiwarter winiwart@iiasa.ac.at	Hanqin Tian tianhan@auburn.edu	Adrian Leip Adrian.Leip@ec.europa.eu
Model aim/ Functionality	GAINS estimates emissions of air pollutants and greenhouse gases in future scenarios based on (1) projections of activity data and (2) rate of implementation of emission reducing technologies. An optimization algorithm allows to minimize costs of measures when intending to arrive at a given ecological "endpoint" (human health, biodiversity, GHG level etc.)	DLEM (Dynamic Land Ecosystem Model) is a process-based terrestrial ecosystem/land surface model that simulates daily carbon, water and nitrogen cycles in land ecosystems, GHG emissions from agricultural and natural soils, and carbon and nitrogen loading and export from watershed to oceans, driven by changes in atmospheric chemistry including ozone, nitrogen deposition, CO_2 concentration, climate, land-use and land-cover types, land management practices and disturbances (i.e., fire, hurricane, and harvest).	The Common Agricultural Policy Regional Impact Analysis (CAPRI) modelling system is a large-scale comparative-static, global multi-commodity, partial equilibrium model for the agricultural sector. It has been developed for policy impact assessment of the European Common Agricultural Policy (CAP) and other policies affecting agriculture from global to regional and farm type scale, focusing on Europe (Britz et al., 2006; Britz & Witzke, 2014) CAPRI simulates changes in global agricultural trade and EU supply of agricultural commodities under given technological, economic and policy constraints. Strengths of CAPRI include the possibility of good representation of EU policies, the detailed description of farm management in EU supply models, and the bio-physical approach based on nutrient mass-flow approach, including life-cycle assessment with regard to GHGs (operational) and nitrogen (operational end 2017) for agricultural commodities.
Inputs/ Drivers of change	Energy consumption/projection, agricultural production/projection	Driving factors- Climate (temperature, precipitation, solar radiation, and relative humidity), atmospheric composition (CO_2, O_3, and nitrogen deposition), land use (deforestation, urbanization, harvest, nitrogen fertilizer application, manure application, and irrigation), and other disturbance (wildfire, climate extremes) Controlling factors- Soil (physical and chemical properties, and soil depth), geomorphology (elevation, slope, and aspect), river network (flow direction, accumulation area, river slope, river length, and river width), vegetation functional types, and cropping system	Population growth, demographic changes, changes in demand, GDP growth, market power and trade agreements, specific policies between EU and other countries, EU policies (CAP and others), technological changes
Outputs	Country-level anthropogenic emissions to air of greenhouse gases and air pollutants (CO_2, CH_4, N_2O, F-gases, SO_2, NO_x, NH_3, VOC, PM-coarse, PM-fine, BC, OC), Abatement costs by technology, for "current legislation", "maximum reduction" and pre-	Grid-level/country-level carbon and nitrogen fluxes including: Ecosystem production (GPP, NPP, NEP) and crop yield Greenhouse gases (CO_2, CH_4, N_2O) *Nitrogen pollutant (*NH_3) Riverine Fluxes: Carbon (DOC, POC and DIC) and Nitrogen (DON, DIN, TN)	Global: supply, final demand, feed processing, prices (consumer/producer) trade flows EU: Agricultural supply (crop areas, heard sizes, yield); agricultural management (farm inputs), gross value added

	defined policy scenario (optimized)	Water fluxes: ET, Runoff, discharge	Post-model processing indicators: yield response, farm income indicators, welfare analysis, CAP budget/ instruments, GHG and Nr emissions, N,P,K balances, energy use in EU agriculture, representative diets. Indicators following spatial downscaling to pixel-level: biodiversity friendly farming practices, potential soil losses by water erosion, landscape indicators.
Biophysical representation	Biophysical relationships parametrized from specialized models: Source-receptor relationships (matrices) from CTM's; "endpoints" as plant damage, human health effects, biodiversity from effect models	The biophysical component includes the instantaneous exchanges of energy, water, and momentum with the atmosphere, which involves micrometeorology, canopy structure, soil physics, radiative transfer, water and energy flow, and momentum movement.	Biophysical representation of flows of biomass and nutrients (N,P,K). Detailed representation of land.
Technology representation	More than 200 individual abatement technologies and abatement costs individually defined and implemented in connection with specific "target" emitted compound, interference with other compounds considered	DLEM-Agricultural version (AG) incorporates the representation of technology improvement through parameterization.	Technology improvements possible for large number of parameters.
Data needs	Energy projections and costs as well as industry projections from energy models (e.g., PRIMES, POLES, IEA); agricultural projections from like models (e.g., CAPRI, FAO). Source-receptor matrices require multiple CTM runs (available for EMEP-Europe, East Asia, South Asia), link to "endpoints" requires effect models to be run	At the global scale, climate data are derived from CRUNCEP 6-hourly climate datasets. Atmospheric CO_2 concentration data was obtained from a spline fit of the Law Dome before 1959, and from NOAA during 1959-2016. Monthly atmospheric ozone concentration was represented by AOT 40. Atmospheric nitrogen deposition data was obtained from ISIMIP. The global nitrogen fertilizer use data was from Lu et al., 2017-ESSD. The global manure application data was from Zhang et al., 2017-ESSD. The basic soil physical and chemical properties, such as soil texture, bulk density, soil pH etc., were obtained from Harmonized World Soil Database (HWSD). Cropland distribution was derived from the 5-arc minute resolution HYDE v3.1 data and aggregated to half-degree.	FAOSTAT, EUROSTAT, IFA
Validation status	Input data and emission output validated with country experts in national consultations	The DLEM simulation results have been extensively validated against a large number of field observations and measurements at site level (Lu & Tian, 2013; Ren et al., 2011; Tao et al., 2013; Tian et al., 2010; Tian et al., 2011). The DLEM-estimated fluxes and storages of water, carbon and nutrients are also compared with estimates from other approaches, such as statistical-based empirical	Model results are scrutinized annually when preparing a new 'baseline' for use at DG AGRI. CAPRI participates to the AgMIP project. Data base (national and regional) are checked on consistency and data gap, which are corrected if necessary (CoCo = consistent and complete database).

		modelling, top-down inversion or other process-based modelling approaches at regional, continental and global scale	
Spatial resolution	Country scale; urban effects considered separately, also 0.5°x0.5° downscaling is available globally.	Global scale - 0.5°x0.5° Regional scale (Asia - 0.25°x0.25°, North America - 0.125°x0.125°)	CAPRI consists of a global market model and a regional supply model which run interactively. The global model is split into 77 countries and 40 country blocks, while the supply model runs at NUTS 2 level in the EU. The link between the supply and market modules is based on an iterative procedure until an equilibrium is obtained
Temporal resolution	1 year	Daily	1 year
Linkage to scenarios and mitigation / measures	Emission reduction measures are the core of the GAINS methodology – cost-optimizing such measures is the central idea. Scenarios need to be developed externally.	Scenario drivers include climate change, elevated CO_2 concentration, change in ozone concentration, land use types, nitrogen fertilizer application, manure application, and atmospheric nitrogen deposition. With respect to nitrogen, the mitigation measures that can be simulated cover the demand-side (lower livestock consumption, lower fertilizer application, less greenhouse gas emission, less nitrogen loading to the river) and the supply side (efficient fertilization, efficient livestock management).	CAPRI is designed to run counter-factual scenarios around base line scenarios, which are linked to / consistent with other models, such as AgLink (for short-to-medium term outlook) and GLOBIOM (e.g. for SSP scenarios).
Mitigation costs and co-benefits	Costs are computed as a function of investments, interest rates and country specific labour/energy/ commodity costs; co-benefits can be integrated in cost factors (e.g. negative energy costs)	Mitigation strategies to reduce the GHG emissions, reduce the N loading to the inland water (hypoxia), as well as maintain the food production.	Several technological GHG mitigation options are ‘endogenous’ in thet CAPRI supply model cost function in order to simulate the most cost-efficient mitigation strategy, capturing also structural and leakage effects. The options include both livestock and crop measures and cover also NH_3 mitigation options. Reduction potentials costs are taken, amongst others, from the GAINS database. CAPRI has an extensive list of economic an denvironmental indicators to evaluate co-benefits.
Operationality	Stated features are fully operational	Fully operational	Fully operational
Accessibility/ links	The GAINS online tool is freely accessible on the Internet	Model shared on a case-by-case basis.	CAPRI (http://www.capri-model.org/dokuwiki/doku.php) The model is open/free for users.
Literature sources	Amann et al. (2011) Amann and Schoepp (2011), Heyes et al. (2011), Kiesewetter et al. (2014), Klimont and Winiwarter. (2011), Nguyen et al (2011), Winiwarter et al. (2010).	Pan et al., 2014,a,b, Tian et al., (2018), Tian et al., (2016), Tian et al., (2015a, b, c, d), Tian et al., (2014), Tian et al., (2010), Schimel et al., (2000), Zhang et al., (2017), Lu et al., (2017), Yang et al.,, 2014, 2015	Britz et al., 2006; Britz and Witzke, 2014; Leip et al., 2014; Weiss and Leip, 2012. Fellmann et al., 2017; Leip et al., 2015; Pérez Domínguez et al., 2016; van Doorslaer et al., 2015); Zimmermann and Latka, 2017)

1 MAgPIE: Global socio-economic agriculture and land-use model, cost-optimization model, recursive dynamic. REMIND: global intertemporal optimization model of the macro-economy and the energy sector. LPJmL: Dynamic Global Vegetation Model (DGVM)

References

IMAGE 3.0

Beusen A.H.W., van Beek L.P.H., Bouwman A.F., Mogollón J.M., Middelburg J.J. (2015) Coupling global models for hydrology and nutrient loading to simulate nitrogen and phosphorus retention in surface water – description of IMAGE–GNM and analysis of performance. Geosci. Model Dev. 8(12):4045-4067; doi:10.5194/gmd-8-4045-2015.

Beusen A.H.W., Bouwman A.F., Van Beek L.P.H., Mogollón J.M., Middelburg J.J. (2016). Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum, Biogeosciences, 13, 2441-2451, doi:10.5194/bg-13-2441-2016.

Bouwman, A. F., Beusen, A. H. W., Griffioen, J., Van Groenigen, J. W., Hefting, M. M., Oenema, O., Van Puijenbroek, P. J. T. M., Seitzinger, S., Slomp, C. P., and Stehfest, E.: Global trends and uncertainties in terrestrial denitrification and n2o emissions, Poster A11A-0031, American Geophysical Union Fall Meeting, San Francisco, December 2012, July 5, 2013, 2013a.

Bouwman, A. F., Beusen, A. H. W., Overbeek, C. C., Bureau, D. P., Pawlowski, M., and Glibert, P. M.: Hindcasts and future projections of global inland and coastal nitrogen and phosphorus loads due to finfish aquaculture, Reviews in Fisheries Science, 21, 112-156, 10.1080/10641262.2013.790340, 2013b.

Bouwman, A. F., Klein Goldewijk, K., Van der Hoek, K. W., Beusen, A. H. W., Van Vuuren, D. P., Willems, W. J., Rufino, M. C., and Stehfest, E.: Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900-2050 period, Proceedings of the National Academy of Sciences of the United States of America, 110, 20882-20887, doi/20810.21073/pnas.1012878108, 2013c.

Bouwman, L., Beusen, A., M. Glibert, P. M., Overbeek, C., Pawlowski, M., Herrera, J., Mulsow, S., Yu, R., and Zhou, M., 2013d. Mariculture: Significant and expanding cause of coastal nutrient enrichment, Environmental Research Letters, 8, 044026, doi:044010.041088/041748-049326/044028/044024/044026.

Bouwman, L., Goldewijk, K. K., Van Der Hoek, K. W., Beusen, A. H. W., Van Vuurena, D. P., Willems, J., Rufino, M. C., and Stehfest, E.: Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900-2050 period, Proceedings of the National Academy of Sciences of the United States of America, 110, 20882-20887, doi 10.1073/pnas.1012878108, 2013e.

Morée, A. L., Beusen, A. H. W., Bouwman, A. F., and Willems, W. J.: Exploring global nitrogen and phosphorus flows in urban wastes during the twentieth century, Global Biogeochemical Cycles, 27, 1–11, doi:10.1002/gbc.20072, 10.1002/gbc.20072, 2013.

Stehfest, E., Van Vuuren, D. P., Kram, T., and Bouwman, A. F.: Integrated assessment of global environmental change with image 3.0. Model description and policy applications, in, PBL Netherlands Environmental Assessment Agency (http://themasites.pbl.nl/models/image/index.php/Main_Page), The Hague, 2014.

MAGPIE

Bodirsky, Benjamin Leon, Alexander Popp, Hermann Lotze-Campen, Jan Philipp Dietrich, Susanne Rolinski, Isabelle Weindl, Christoph Schmitz, et al. 2014. “Reactive Nitrogen Requirements to Feed the World in 2050 and Potential to Mitigate Nitrogen Pollution.” Nature Communications 5 (May). doi:10.1038/ncomms4858.

Bodirsky, Benjamin Leon, Alexander Popp, Isabelle Weindl, Jan Philipp Dietrich, Susanne Rolinski, Lena Scheiffele, Christoph Schmitz, and Hermann Lotze-Campen, 2012. “N2O Emissions from the Global Agricultural Nitrogen Cycle – Current State and Future Scenarios.” Biogeosciences 9 (10): 4169–97. doi:10.5194/bg-9-4169-2012.

Popp, Alexander, Hermann Lotze-Campen, and Benjamin Bodirsky. 2010. “Food Consumption, Diet Shifts and Associated Non-CO2 Greenhouse Gases from Agricultural Production.” Global Environmental Change 20 (3): 451–62. doi:10.1016/j.gloenvcha.2010.02.001.

Lotze-Campen, Hermann, Christoph Müller, A. Bondeau, S. Rost, Alexander Popp, and W. Lucht. 2008. "Global Food Demand, Productivity Growth, and the Scarcity of Land and Water Resources: A Spatially Explicit Mathematical Programming Approach." Agricultural Economics 39 (3): 325–38.

Klein, David, Gunnar Luderer, Elmar Kriegler, Jessica Strefler, Nico Bauer, Marian Leimbach, Alexander Popp, et al. 2013. "The Value of Bioenergy in Low Stabilization Scenarios: An Assessment Using REMIND-MAgPIE." Climatic Change, 1–14. Accessed October 9. doi:10.1007/s10584-013-0940-z.

Strefler, Jessica, Gunnar Luderer, Elmar Kriegler, and Malte Meinshausen. 2014. "Can Air Pollutant Controls Change Global Warming?" Environmental Science & Policy 41 (August): 33–43. doi:10.1016/j.envsci.2014.04.009.

Bodirsky, Benjamin Leon. 2015. "Scenarios of Future Agricultural Phosphorus Stocks and Flows." presented at the ESPCS2, Berlin.

Humpenöder, Florian, Alexander Popp, Miodrag Stevanovic, Christoph Müller, Benjamin Leon Bodirsky, Markus Bonsch, Jan Philipp Dietrich, et al. 2015. "Land-Use and Carbon Cycle Responses to Moderate Climate Change: Implications for Land-Based Mitigation?" Environmental Science & Technology, May, 150504131040007. doi:10.1021/es506201r.

GLOBIOM

Havlík, P., H. Valin, M. Herrero, M. Obersteiner, E. Schmid, M. C. Rufino, A. Mosnier, P. K. Thornton, H. Böttcher, R. T. Conant, S. Frank, S. Fritz, S. Fuss, F. Kraxner and A. Notenbaert (2014). "Climate change mitigation through livestock system transitions." Proceedings of the National Academy of Sciences 111(10): 3709-3714.

GAINS

Amann M, Imrich Bertok, Jens Borken-Kleefeld, Janusz Cofala, Chris Heyes, Lena Höglund-Isaksson, Zbigniew Klimont, Binh Nguyen, Maximilian Posch, Peter Rafaj, Robert Sandler, Wolfgang Schöpp, Fabian Wagner, Wilfried Winiwarter, Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications, Environmental Modelling & Software, Volume 26, Issue 12, December 2011, Pages 1489-1501, ISSN 1364-8152, http://dx.doi.org/10.1016/j.envsoft.2011.07.012

Amann M, Schoepp W (2011) Calculation of Cause-specific Mortality Impacts of Fine Particulate Matter in GAINS. CIAM-Report 2/2011, Draft Version 1. IIASA, Laxenburg, Austria

Heyes C, Klimont Z, Wagner F. Markus Amann (2011). Extension of the GAINS model to include short-lived climate forcers. Final Report. IIASA, Laxenburg, January 2011

Kiesewetter, G., Borken-Kleefeld, J., Schöpp, W., Heyes, C., Thunis, P., Bessagnet, B., Terrenoire, E., Gsella, A., and Amann, M., 2014. Modelling NO_2 concentrations at the street level in the GAINS integrated assessment model: projections under current legislation, Atmos. Chem. Phys., 14, 813-829, doi:10.5194/acp-14-813-2014.

Klimont, Z., and W. Winiwarter, 2011. Integrated ammonia abatement – Modelling of emission control potentials and costs in GAINS. IIASA Interim Report IR-11-027. IIASA, Laxenburg, September 2011.

Nguyen B, Wagner F, Schoepp W (2011) GAINS - An interactive tool for assessing international GHG mitigation regimes. Information and Communication on Technology for the Fight against Global Warming. Lecture Notes in Computer Science Volume 6868, 2011, pp 124-135

Winiwarter, W., L. Höglund-Isaksson, W. Schöpp, A. Tohka, F. Wagner & M. Amann. Emission mitigation potentials and costs for non-CO2 greenhouse gases in Annex-I countries according to the GAINS model. Journal of Integrative Environmental Sciences 7 (S1), 235-243 (2010).

DLEM

Lu C. and Tian H. 2017. Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century, shifted hot spots and nutrient imbalance. Earth Syst. Sci. Data, 9, 181.

Lu, C. and H. Tian. 2013. Net greenhouse gas balance in response to nitrogen enrichment: Perspectives from a coupled biogeochemical model. Global Change Biology, 19: 571–588. doi: 10.1111/gcb.12049.

Liu, M., H. Tian, Q. Yang, J. Yang, X. Song, S.E. Lohrenz, W. Cai. 2013. Long-term trends in evapotranspiration and runoff over the drainage basins of the gulf of Mexico during 1901-2008. Water Resources Research 49, 1988–2012

Ren, W., H. Tian, B. Tao, Y. Huang, and S. Pan. (2012) China's crop productivity and soil carbon storage as influenced by multifactor global change. Goble Change Biology doi: 10.1111/j.1365-2486.2012.02741.x

Yang Q C, Tian H, Friedrichs M, Hopkinson C, Lu C, Najjar R. 2015. Increased nitrogen export from eastern North America to the Atlantic Ocean due to climatic and anthropogenic changes during 1901-2008. Journal of Geophysical Research 120, 1046-1068.

Tian H Q, Yang J, Lu C Q, Xu R T, Canadell J G, Jackson R, Arneth A, Chang J F, Chen G S, Ciais P, Gerber S, Ito A, Huang Y Y, Joos F, Lienert S, Messina P, Olin S, Pan S F, Peng C H, Saikawa E, Thompson R L, Vuichard N, Winiwarter W, Zaehle S, Zhang B W, Zhang K, Zhu Q A. 2018. The global N_2O Model Intercomparison Project (NMIP), *Bull. Amer. Meteor. Soc.*, 0, https://doi.org/10.1175/BAMS-D-17-0212.1

Tian, H., C. Lu, P. Ciais, A.M. Michalak, J.G. Canadell, E. Saikawa, D.N. Huntzinger, K. Gurney, S. Sitch, B. Zhang, J. Yang, P. Bousquet, L. Bruhwiler, G. Chen, E. Dlugokencky, P. Friedlingstein, J. Melillo, S. Pan, B. Poulter, R. Prinn, M. Saunois, C.R. Schwalm, S.C. Wofsy (2016) The terrestrial biosphere as a net source of greenhouse gases to the atmosphere, Nature 531, 225-228.

Tian, H., W. Ren, J. Yang, B. Tao, W. Cai, S. E. Lohrenz, C.S. Hopkinson, M. Liu, Q. Yang, C. Lu, B. Zhang, K. Banger, S. Pan, R. He and Z. Xue (2015) Climate extremes dominating seasonal and interannual variations in carbon export from the Mississippi River Basin. Global Biogeochem. Cycles, 29, 1333–1347.

Tian, H., G. Chen· C. Lu· X. Xu· D. J. Hayes· W. Ren· S. Pan· D.N. Huntzinger· S.C. Wofsy (2014) North American terrestrial CO2 uptake largely offset by CH4 and N2O emissions: Toward a full accounting of the greenhouse gas budget. Climatic Change 129:423-426.

Tian, H, X. Xu, M. Liu, W. Ren, C. Zhang, G. Chen, and C. Lu. 2010. Spatial and temporal patterns of CH_4 and N_2O fluxes in terrestrial ecosystems of North America during 1979–2008, Biogeosciences 7, 2673-2694.

Tian, H., Yang, R. G. Najjar, W. Ren, M. A. M. Friedrichs, C. S. Hopkinson, and S. Pan (2015) Anthropogenic and climatic influences on carbon fluxes from eastern North America to the Atlantic Ocean: A process-based modeling study. Journal of Geophysical Research 120, 757-772.

Tian, H., C. Lu, J. Yang, K. Banger, D. N. Huntzinger, C. R. Schwalm, A. M. Michalak, R. Cook, P. Ciais, D. Hayes, et al. (2015), Global patterns and controls of soil organic carbon dynamics as simulated by multiple terrestrial biosphere models: Current status and future directions, Global Biogeochem. Cycles, 29, 775–792.

Tian, H., C. Lu, J. Melillo, W. Ren, Y. Huang, X. Xu, M. Liu, C. Zhang, G. Chen, S. Pan, J. Liu and J. Reilly. 2012. Food benefit and climate warming potential of nitrogen fertilizer use in China. Environ. Res. Lett. 7 (2012) 044020 (8pp) doi:10.1088/1748-9326/7/4/044020

Tian, HQ, X. Xu, C. Lu, M. Liu, W. Ren, G. Chen, J. Melillo and J. Liu. 2011. Net exchanges of CO2, CH4, and N2O between China's terrestrial ecosystems and the atmosphere and their contributions to global climate warming. Journal of Geophysical Research doi:10.1029/2010JG001393.

Xu, R. T., Pan, S. F., Chen, J., Chen, G. S., Yang, J., Dangal, S. R. S.,S. Shepard, Tian, H.Q. (2018). Half-century ammonia emissions from agricultural systems in southern Asia: Magnitude, spatiotemporal patterns and implications for human health. GeoHealth, 2, 40-53.

Zhang B W, Tian H, Lu C, Dangal S R, Pan S. 2017. Global manure nitrogen production and application in cropland during 1860–2014: a 5 arc-min gridded global dataset for Earth system modeling. Earth Syst. Sci. Data, 9, 667-678.

Zhang, J., H. Tian, J. Yang and S. Pan (2018) Improving Representation of Crop Growth and Yield in the Dynamic Land Ecosystem Model and its Application to China, Journal of Advances in Modeling Earth Systems, https://doi.org/10.1029/2017MS001253

CAPRI

Britz, W., Witzke, P., 2014. CAPRI model documentation. Bonn, Germany.

Fellmann, T., Witzke, P., Weiss, F., Van Doorslaer, B., Drabik, D., Huck, I., Salputra, G., Jansson, T., Leip, A., 2017. Major challenges of integrating agriculture into climate change mitigation policy frameworks. Mitig. Adapt. Strateg. Glob. Chang. doi: http://dx.doi.org/10.1007/s11027-017-9743-2

Leip, A., Bielza, M., Bulgheroni, C., Ciaian, P., Lamboni, M., Paracchini, M., Terres, J., Weiss, F., Witzke, H., 2015. Spatially Explicit Evaluation of the Agri - environmental Impact of CAP, in: International Conference of Agricultural Economists; ICAE2015.

Leip, A., Weiss, F., Lesschen, J.P., Westhoek, H., 2014. The nitrogen footprint of food products in the European Union. J. Agric. Sci. 152, 20–33. doi: http://dx.doi.org/10.1017/S0021859613000786

Pérez Domínguez, I., Fellmann, T., Weiss, F., Witzke, H.-P., Barreiro-Hurle, J., Himics, M., Jansson, T., Salputra, G., Leip, A., 2016. An economic assessment of GHG mitigation policy options for EU agriculture (EcAMPA 2), JRC Science for Policy Report. Available at: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC101396/jrc101396_ecampa2_final_report.pdf.

Weiss, F., Leip, A., 2012. Greenhouse gas emissions from the EU livestock sector: A life cycle assessment carried out with the CAPRI model. Agric. Ecosyst. Environ. 149, 124–134. doi: http://dx.doi.org/10.1016/j.agee.2011.12.015

Zimmermann, A., Latka, C., 2017. The drivers of crop production at regional level in the EU: an econometric analysis. Deliverable 4.5 of the SUSFANS project H2020 / SFS-19-2014: Sustainable food and nutrition security through evidence based EU agro-food policy, GA no. 633692.

Annex 2 Meta-description of Pressure-State (emission, air, soil and water quality) models.

Emission models

Model type/ name	Overall emission model EDGAR	Agricultural emission model MITERRA Global	Air Quality models TM5-FASST	Air Quality models EMEP4Earth
Contact person	Greet Maenhout greet.maenhout@ec.europa.eu	Jan Peter Lesschen Janpeter.lesschen@wur.nl	Rrita.van-dingenen @ec.europa.eu	Massimo Vieno mvi@ceh.ac.uk
Model aim/ Functionality	GHG and air pollutant emissions for all world countries in a consistent way bottom-up calculated, following IPCC (2006) guidelines	MITERRA-Global is an environmental assessment model, which calculates greenhouse gases and nitrogen emissions from agriculture on a deterministic and annual basis. The model is based on relatively simple and transparent calculations using emission factors and statistical data at sub-national level. The model is used for scenario analysis and assessment of policy options and measures and results can be presented both as total and LCA based emissions.	TM5-FASST is a reduced-form model based on a full set of global SR receptor calculations with the TM5 CTM for 57 world regions, shipping and aircraft. It is extensively used to provide a fast screening of air pollution emission scenarios with regard to health, crop and climate impacts.	EMEP4Earth model is designed to calculate air concentrations and deposition fields for major acidifying and eutrophying pollutants, photo-oxidants and particulate matter. The model is driven by real time meteorology calculated by the WRF model. The EMEP4Earth is model is derived from the EMEP/MSC-W model.
Inputs/ Drivers of change	Activity data from IEA, FAO, US Geological Survey, World Steel association, International Fertiliser association, UNDP population statistics, etc. Emission factors from IPCC (2006) GL and literature	Input data from economic models is required, which results in changes in crop areas, crop yield, livestock numbers, fertilizer inputs etc.	Emission scenarios (e.g. NH_3, NO_x, SO_2, PM components, CO, VOC, CH_4 emissions.	Emission scenarios (e.g. NH_3, NO_x, SO_2, $PM_{2.5}$, PM_{10}, PM_{coarse}, CO, VOC) Land use scenarios
Outputs	Emission time series 1970-2012 per country and sector (and for CO_2 till t-1 for most important countries); sector-specific grid maps per year and month for each substance (GHG and air pollutant)	Nitrogen emissions (NH_3, N_2O, NO_x), N leaching and runoff, GHG emissions (N_2O, CH_4, CO_2), changes in soil organic carbon, nutrient balances. All outputs can be provided at the sub-national (e.g. province) and national level. In addition results can be expressed as LCA based per product emissions.	Global fields of hourly-monthly 3D concentrations changes, deposition fluxes, and the associated metrics (e.g. SOMO35, AOT40 for ozone, RF for climate)	Global fields of hourly 3D atmospheric concentrations, deposition fluxes, and the associated metrics (e.g. SOMO35, AOT40 for ozone)
Biophysical representation	Regular updates (CO_2 report annual)	MITERRA Global distinguishes 40 crop types and 12 livestock categories. Calculations are done at sub-national level (n = 2400) using average biophysical data from detailed GIS data sets (e.g. climate, soil and land cover)	Dynamic based on the meteorological year 2001.	Dynamic for BVOC emissions and soil NO_x,
Steady state / dynamic	Dynamic	Dynamic	IMAGE-GNC is a dynamic model, as it keeps track of soil N and	Dynamic

			P reserves and N transport in groundwater	
Data needs	Statistics from IEA, FAO, USGS, WSA, IFA, …	Main inputs are livestock numbers and production, crop areas, crop yield, fertilizer consumption and spatial data on land cover, soil and climate	Emission scenarios	Emissions and land use scenarios
Validation status	Via inverse modelling	Not validated, but use of accepted emission factors such as IPCC etc.	Mostly compared to the full TM5 model, which was validated in various intercomparisons.	Mostly validated across Europe and the UK in particular. However, the official EMEP MSC-W team (www.met.no) have applied the model globally and in China.
Spatial resolution	0.1deg x 0.1deg	Sub-national level (i.e. provinces or states), n = 2400, at which statistical input data is available. GIS data is derived from more detailed maps.	In the emission regions 1x1 degree, with sub-grid parameterisation for population exposure.	Globally 1.0x1.0 degrees with the possibility to include nested regions (i.e. Africa 0.1x0.1 degrees, UK 0.05x0.05 degrees)
Temporal resolution	monthly	1 year	Underlying: hourly. Most output aggregated to monthly. Impacts on annual scale.	Hourly, daily, monthly and annual
Linkage to scenarios and mitigation / measures	CIRCE scenarios calculated from 1990-2050	MITERRA-Global has been used to assess the total and LCA per product GHG from livestock production in Europe, Africa and Latin America. The European version of MITERRA has been used in several scenario studies and parameterized mitigation options are available for ammonia and GHG emissions, soil carbon sequestration and N leaching and runoff. Mitigation costs have not been included yet in MITERRA-Global, but for Europe several studies are available.	Flexible; used for UNEP, HTAP, OECD, CCAC, etc. scenarios.	Use of the INMS scenarios for the available emitted species and using a simple rescale of the HTAPv2 for the remaining emitted species.
Operationality		Fully operational		
Accessibility	http://edgar.jrc.ec.europa.eu/	Model is not publically available, but can be adapted easily by developers to fit to stakeholder requirements	http://tm5-fasst.jrc.ec.europa.eu/	https://github.com/metno/emep-ctm
Primary literature source	IEA fuel combustion book statistics: part III (2016), Janssens-Maenhout et al., 2013; 2015, Crippa et al, 2016	Zhu et al. (submitted); Lesschen et al. (2014): Based on MITERRA-Europe: Velthof et al. (2009), Lesschen et al. (2011) and Leip et al. (2014)	Huijnen et al (2010); Van Dingenen et al (2017) and reference therein.	Vieno et. al 2016 and Simpson et al. 2012

Water quantity (hydrological) and water quality models

Model type/ name	Hydrological models WBM/VIC	Hydrological models PCR-GLOBWB	Water quality models IMAGE GNM	Water quality models GLOBAL NEWS
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Model aim/ Functionality	The Variable Infiltration Capacity (VIC) model (Liang et al., 1994) is a grid-based macro-scale hydrological model that hat solves both the surface energy balance and water balance equations.	PCR-GLOBWB models the water fluxes from precipitation, evaporation and evapotranspiration, soil moisture, aquifers to streams and rivers, accounts for water temperature. PCR-GLOBWB focuses on floodplains, wetlands, lakes and keeps track of the construction and filling of reservoirs. PCR-GLOBWB not only simulates water availability, but can also simulate flooding in river basins. It has a spatial resolution of 5 by 5 minutes and a temporal (output) resolution of 1 day	IMAGE Global Nutrient Model (GNM) is part of the integrated assessment model IMAGE and keeps track of soil nutrient reserves, and computes the fate of nutrients from wastewater discharge to surface water, nutrient release from aquaculture, agricultural and natural runoff, leaching to groundwater and groundwater transport and denitrification, processes in riparian zones, and instream retention in the world's rivers, lakes, wetlands, reservoirs, and river export to the coastal seas; marine aquaculture release of nutrients	Global *NEWS*-2 quantifies river export of different nutrients (N, P, C, Si) in different forms (dissolved inorganic, dissolved organic, particulate) for past (1970, 2000) and future (2030, 2050) years for more than 6000 river basins. The model quantifies the indicator for coastal eutrophication potential (ICEP).
Inputs/ Drivers of change	Climate parameters, land surface	Climate parameters, water usage, land surface, land use, reservoir construction, location of lakes, wetlands, reservoirs.	Drivers are land use and nutrient budgets, population and wastewater discharge, climate, hydrology, dam construction and reservoir development determining the travel time of the water and retention	Main drivers are population, economic development (income), land use, livestock and crop production. Main inputs are land use, use of synthetic and organic fertilizers, atmospheric N deposition, biological N2 fixation, total population, population with sewage connection, nutrient removal during treatment, water discharges, runoff, dams. Inputs for land use, population, diffuse and point sources of nutrients are from IMAGE; inputs for hydrology are from WBM. Inputs for future years were derived from IMAGE and WBM as well.
Outputs	Surface runoff and base flow are routed along the stream network to the basin outlet with an offline routing model	Water balance, water fluxes, water temperature, discharge, runoff, water storage, water availability. Flooding areas, water depth and area. Routing along the stream network including lakes, wetlands, reservoirs.	Soil N and P contents and changes therein; nutrient delivery to surface water from surface runoff, groundwater, aquaculture, sewage water and open sewers, wastewater treatment plants, weathering; IMAGE-GNC computes concentrations in all grid cells and routes the water and nutrients through the river bed, floodplains, lakes, wetlands, reservoirs to the mouth of all world rivers	Main outputs are N, P, C and Si export by rivers to coastal waters (river mouth) and ICEP for 1970, 2000, 2030 and 2050.
Steady state / dynamic	Dynamic	Dynamic	IMAGE-GNC is a dynamic model, as it keeps track of soil N and P reserves and N transport in groundwater	Steady state
Biophysical representation	The model represents sub-grid variability in	The land surface in PCR-GLOBWB is represented	IMAGE-GNC includes the hydrological model PCR-	River export of dissolved nutrients is quantified

	vegetation and elevation, partitioning each grid cell into multiple land cover (vegetation) and elevation classes. The soil column is commonly divided into three soil layers. Evapotranspiration is calculated based on Penman-Monteith equation. Surface runoff in the upper soil layer is calculated based on the variable infiltration curve, and release of baseflow from the lowest soil layer is simulated according to the non-linear Arno recession curve.	by a topsoil (0.3 m thick or less) and a subsoil (1.2 m thick or less). Precipitation falls as rain if air temperature exceeds 0°C, and as snow otherwise. Snow accumulates on the surface, and melt is temperature controlled. Potential evapotranspiration is broken down into canopy transpiration and bare-soil evaporation, which are reduced to an actual evapotranspiration rate based on soil moisture content. Vertical transport in the soil column arises from percolation or capillary rise, depending on the vertical hydraulic gradient present between these layers.	GLOBWB for computing runoff . IMAGE uses climate data for the past and predicts future climate to account for changes in the hydrology relevant to the cycling of N and instream processes; uses soil and geological information.	based on a mass-balance approach. River export of particulate nutrients is quantified using the regression analysis with total suspended solids.
Data needs	Climate data, land cover	Climate parameters, land surface, land use, reservoir construction, location of lakes, wetlands, reservoirs.	Apart from the biophysical data, IMAGE uses FAOSTAT country data on food, feed and fodder crop production, livestock production, land use, inputs; equivalent subnational data for USA, China, India; IEA data on energy use; emission factors from EDGAR. Fertilizer use by crop from IFA.	All inputs are from IMAGE and WBM
Validation status	The model has been validated using hydrological datasets	The model has been validated using hydrological datasets	IMAGE is calibrated to historical carbon cycle and CO_2 concentration. River nutrient concentrations and nutrient export has been validated with measurement data for different stations inside river basins for Europe, USA and large world rivers; all comparisons are satisfactory for a non-calibrated global model	Global *NEWS*-2 was validated and calibrated for large world rivers by comparing modelled river export of nutrients with measured values for 2000.
Spatial resolution	0.5 x 0.5 degree	5 by 5 minutes	0.5 by 0.5 degree	Basin. Basin inputs were aggregated from inputs (from IMAGE and WBM) of 0.5 by 0.5 degree
Temporal resolution	Hourly, daily, monthly, annual	Output resolution is 1 day	1 year	Annual
Linkage to scenarios and mitigation / measures	VIC has been widely used for change impact and scenario studies at global, European or large-river basin levels, as well as for seasonal forecasting work.	Through its linkage with IMAGE, PCR-GLOBWB can be used to simulate future scenarios; recent work also includes projections of hydropower and reservoir construction on the basis of the most suitable location in landscapes (energy, storage). PCR-GLOBWB has been used to implement the Shared Socioeconomic Pathways	IMAGE is especially designed for scenario analysis. The wastewater model includes several options to improve sewage connection and wastewater treatment. The nutrient model can deal with several measures such as incorporation of manure, reduce emissions from animal houses, substitution of fertilizer by manure, integration of	Millennium Ecosystem Assessment scenarios are used.

		to elaborate nutrient futures.	livestock and crop systems, increased efficiency in livestock and crop systems, as well as recycling of human excreta to substitute fertilizers. IMAGE allows for analysing in which parts of river basins measures are most effective to reduce nutrient concentrations and river export to the coastal seas	
Operationality	Fully operational	Fully operational	Fully operational	
Accessibility	VIC model development is led by the Computational Hydrology group in the Department of Civil and Environmental Engineering at the University of Washington. In collaboration with this group at University of Washington, the WSG-group of Wageningen University contributes to the development of VIC5.1.	PCR-GLOBWB model development is in the Department of Physical Geography, Physical Landscape functioning, geo-computation and hydrology - Geographical Hydrology group of Utrecht University, and is now shared with the Department of Earth Sciences, Geochemistry, Faculty of Geosciences, Utrecht University for the biogeochemistry applications.	PC version of IMAGE and executable of IMAGE-GNC is available for public; input data and output will be made publicly available	Website with public information on Global *NEWS*-2
Primary literature source	Liang et al (1994) http://www.wur.nl/en/Expertise-Services/Chair-groups/Environmental-Sciences/Water-Systems-and-Global-Change-Group/research/Water-pollution-assessments-1/VIC.htm	Van Beek et al., 2012;Van Beek et al., 2011;Wada et al., 2011;Winsemius et al., 2013 http://pcraster.geo.uu.nl/projects/applications/pcrglobwb/	Stehfest et al. (2014b); Bouwman et al. (2013e); Bouwman et al. (2013b); Bouwman et al. (2013f); Beusen (2014)	Mayorga et al. (2010) for model description; Seitzinger et al. (2010) for scenario description; Bouwman et al. (2009) for diffuse sources of nutrients; Van Drecht et al. (2009) for point sources of nutrients; Fekete et al. (2010b) for hydrology

References

EDGAR

Crippa, M., G. Janssens-Maenhout, F. Dentener, D. Guizzardi, K. Sindelarova, M. Muntean, R. Van Dingenen and C. Granier, 2016. Forty years of improvements in European air quality: regional policy-industry interactions with global impacts. Atmos. Chem. Phys., 16, 3825–3841.

Janssens-Maenhout, G., Pagliari, V., Guizzardi, D., and Muntean, M., 2013. Global emission inventories in the Emission Database for Global Atmospheric Research (EDGAR) – Manual (I): Gridding: EDGAR emissions distribution on global gridmaps, JRC Report, EUR 25785 EN, ISBN 978-92-79-28283-6, doi:10.2788/8145.

Janssens-Maenhout, G., M. Crippa, D. Guizzardi, F. Dentener, M. Muntean, G. Pouliot, T. Keating, Q. Zhang, J. Kurokawa, R. Wankmüller, H. Denier van der Gon, J. J. P. Kuenen, Z. Klimont, G. Frost, S. Darras, B. Koffi, and M. Li4, 2015. HTAP_v2.2: a mosaic of regional and global emission grid maps for 2008 and 2010 to study hemispheric transport of air pollution. Atmos. Chem. Phys., 15, 11411–11432.

MITERRA-Global

Lesschen JP, Staritsky I, Oenema O (2014). Improvements in MITERRA framework/tool and the extension to Africa and Latin America. Report AnimalChange (Deliverable 3.5). http://www.animalchange.eu, 37 pp.

Lesschen J, Van den Berg M, Westhoek H, Witzke H, Oenema O (2011). Greenhouse gas emission profiles of European livestock sectors. Animal Feed Science and Technology 166, 16-28.

Leip, A., Weiss, F., Lesschen, J.P., Westhoek, H. 2014. The nitrogen footprint of food products in the European Union. Journal of Agricultural Science, 152: S20–S33.

Velthof G, Oudendag D, Witzke H, Asman W, Klimont Z, Oenema O (2009). Integrated assessment of nitrogen losses from agriculture in EU-27 using MITERRA-EUROPE. Journal of Environmental Quality 38, 402-417.

Zhu, B., Kros, H., Lesschen, J.P. and Staritsky, I. Sumbitted. Assessment of uncertainties in greenhouse gas emission profiles of livestock sectors in Europe, Latin America and Africa. Regional Environmental Change.

TM5-FASST

Huijnen, V., J. Williams, M. van Weele, T. van Noije, M. Krol, F. Dentener, A. Segers, S. Houweling, W. Peters, J. de Laat, F. Boersma, P. Bergamaschi, P. van Velthoven, P. Le Sager, H. Eskes, F. Alkemade,R. Scheele, P. Nedelec and H.-W. Patz, 2010. The global chemistry transport model TM5: description and evaluation of the tropospheric chemistry version 3.0. Geosci. Model Dev., 3, 445–473.

Van Dingenen, R., F. Dentener and S. Rao, 2017. TM5-FASST: a global atmospheric source-receptor model for rapid impact analysis of emission changes on air quality and short-lived climate pollutants. (manuscript in preparation for the special HTAP issue in Atmos. Chem. Physics)

EMEP/EMEP4Earth

Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L. D., Fagerli, H., Flechard, C. R., Hayman, G. D., Gauss, M., Jonson, J. E., Jenkin, M. E., Nyiri, A., Richter, C., Semeena, V. S., Tsyro, S., Tuovinen, J.-P., Valdebenito, Á. & Wind, P. The EMEP MSC-W chemical transport model -- technical description Atmos. Chem. Physics, 2012, 12, 7825-7865

Simpson, D., Nyiri, A., Tsyro, S., Valdebenito, Á. & Wind, P. Updates to the EMEP/MSC-W model, 2015--2016 Transboundary particulate matter, photo-oxidants, acidifying and eutrophying components. EMEP Status Report 1/2015, The Norwegian Meteorological Institute, Oslo, Norway, 2016, 133-139

Ots, R., Vieno, M., Allan, J. D., Reis, S., Nemitz, E., Young, D. E., Coe, H., Di Marco, C., Detournay, A., Mackenzie, I. A., Green, D. C., and Heal, M. R.: Model simulations of cooking organic aerosol (COA) over the UK using estimates of emissions based on measurements at two sites in London, Atmos. Chem. Phys., 16, 13773-13789, 10.5194/acp-16-13773-2016, 2016.

Ots, R., Heal, M. R., Young, D. E., Williams, L. R., Allan, J. D., Nemitz, E., Di Marco, C., Detournay, A., Xu, L., Ng, N. L., Coe, H., Herndon, S. C., Mackenzie, I. A., Green, D. C., Kuenen, J. J. P., Reis, S., and Vieno, M.: Modelling carbonaceous aerosol from residential solid fuel burning with different assumptions for emissions, Atmos. Chem. Phys., 18, 4497-4518, 10.5194/acp-18-4497-2018, 2018.

Vieno, M., Dore, A. J., Stevenson, D. S., Doherty, R., Heal, M. R., Reis, S., Hallsworth, S., Tarrason, L., Wind, P., Fowler, D., Simpson, D., and Sutton, M. A.: Modelling surface ozone during the 2003 heat-wave in the UK, Atmospheric Chemistry and Physics, 10, 7963-7978, DOI 10.5194/acp-10-7963-2010, 2010.

Vieno, M., Heal, M. R., Hallsworth, S., Famulari, D., Doherty, R. M., Dore, A. J., Tang, Y. S., Braban, C. F., Leaver, D., Sutton, M. A., and Reis, S.: The role of long-range transport and domestic emissions in determining atmospheric secondary inorganic particle concentrations across the UK, Atmos. Chem. Phys., 14, 8435-8447, 10.5194/acp-14-8435-2014, 2014.

Vieno, M., Heal, M. R., Twigg, M. M., MacKenzie, I. A., Braban, C. F., Lingard, J. J. N., Ritchie, S., Beck, R. C., Móring, A., Ots, R., Marco, C. F. D., Nemitz, E., Sutton, M. A., and Reis, S.: The UK particulate matter air pollution episode of March–April 2014: more than Saharan dust, Environmental Research Letters, 11, 044004, 2016a.

Vieno, M., Heal, M. R., Williams, M. L., Carnell, E. J., Nemitz, E., Stedman, J. R., and Reis, S.: The sensitivities of emissions reductions for the mitigation of UK PM2.5, Atmos. Chem. Phys., 16, 265-276, 10.5194/acp-16-265-2016, 2016b.

VIC

Liang X, Lettenmaier DP, Wood EF, Burges SJ. A Simple Hydrologically Based Model of Land-Surface Water and Energy Fluxes for General-Circulation Models. Journal of Geophysical Research-Atmospheres. 1994;99:14415-28.

PCR-GLOBWB

Van Beek, L. P. H., Eikelboom, T., Van Vliet, M. T. H., and Bierkens, M. F. P.: A physically based model of global freshwater surface temperature, Water Resources Research, 48, 2012.

Van Beek, L. P. H., Wada, Y., and Bierkens, M. F. P.: Global monthly water stress: 1. Water balance and water availability, Water Resour. Res., 47, W07517, 10.1029/2010wr009791, 2011.

Wada, Y., van Beek, L. P. H., Viviroli, D., Dürr, H. H., Weingartner, R., and Bierkens, M. F. P.: Global monthly water stress: 2. Water demand and severity of water stress, Water Resour. Res., 47, W07518, 10.1029/2010wr009792, 2011.

Winsemius, H. C., Van Beek, L. P. H., Jongman, B., Ward, P. J., and Bouwman, A.: A framework for global river flood risk assessments, Hydrology and Earth System Sciences, 17, 1871-1892, 2013.

Global NEWS

Kroeze, C., Bouwman, A.F., Seitzinger, S. (2012) Modeling global nutrient export from watersheds. Current Opinion in Environmental Sustainability 4, 195-202.

Mayorga, E. , Seitzinger, S.P. , Harrison, J.A. , Dumont, E.L. , Beusen, A.H.W. , Bouwman, A.F. , Fekete, B.M. , Kroeze, C. , Drecht, G. van (2010) Environmental Modelling & Software 25 (2010)7. - ISSN 1364-8152 - p. 837 - 853.

Seitzinger, S.P. , Mayorga, E. , Bouwman, A.F. , Kroeze, C. , Beusen, A.H.W. , Billen, G. , Drecht, G. van , Dumont, E.L. , Fekete, B.M. , Garnier, J. , Harrison, J. (2010) Global Biogeochemical Cycles 24 (2010). - ISSN 0886-6236 - p. GB0A08 - GB0A08.

Strokal, M., Kroeze, C., Wang, M., Bai, Z., Ma, L. (2016) The MARINA model (Model to Assess River Inputs of Nutrients to seAs): Model description and results for China. Science of The Total Environment 562, 869-888.

van Wijnen, J., Ivens, W.P.M.F., Kroeze, C., Löhr, A.J. (2015) Coastal eutrophication in Europe caused by production of energy crops. Science of The Total Environment 511, 101-111.

IMAGE GNM

Beusen, A. H. W.: Transport of nutrients from land to sea. Global modeling approaches and uncertainty analyses, PhD, Department of Earth Sciences - Geochemistry, Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands, 191 pp., 2014.

Bouwman, A. F., Beusen, A. H. W., and Billen, G.: Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050, Global Biogeochemical Cycles, 23, GB0A04, 2009.

Bouwman, A. F., Beusen, A. H. W., Griffioen, J., Van Groenigen, J. W., Hefting, M. M., Oenema, O., Van Puijenbroek, P. J. T. M., Seitzinger, S., Slomp, C. P., and Stehfest, E.: Global trends and uncertainties in terrestrial denitrification and N2O emissions, Philosophical Transactions of the Royal Society B: Biological Sciences, 368, 2013a.

Bouwman, A. F., Klein Goldewijk, K., Van der Hoek, K. W., Beusen, A. H. W., Van Vuuren, D. P., Willems, W. J., Rufino, M. C., and Stehfest, E.: Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900-2050 period, Proceedings of the National Academy of Sciences of the United States of America, 110, 20882-20887, doi/20810.21073/pnas.1012878108, 2013b.

Bouwman, L., Beusen, A., M. Glibert, P. M., Overbeek, C., Pawlowski, M., Herrera, J., Mulsow, S., Yu, R., and Zhou, M.: Mariculture: significant and expanding cause of coastal nutrient enrichment, Environmental Research Letters, 8, 044026, doi:044010.041088/041748-049326/044028/044024/044026, 2013c.

Fekete, B. M., Wisser, D., Kroeze, C., Mayorga, E., Bouwman, L., Wollheim, W. M., and Vörösmarty, C.: Millennium ecosystem assessment scenario drivers (1970–2050): climate and hydrological alterations, Global Biogeochemical Cycles, 24, GB0A12, 2010.

Stehfest, E., Van Vuuren, D. P., Kram, T., and Bouwman, A. F. (Eds.): Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications, PBL Netherlands Environmental Assessment Agency (http://themasites.pbl.nl/models/image/index.php/Main_Page), The Hague, 2014.

Van Drecht, G., Bouwman, A. F., Harrison, J., and Knoop, J. M.: Global nitrogen and phosphate in urban wastewater for the period 1970 to 2050, Global Biogeochemical Cycles, 23, GB0A03, 2009.

Annex 3 Meta-description of impact models.

Crop growth and productivity models

Model type/ name	Crop growth/Terrestrial productivity; LPJml	Crop growth Terrestrial productivity; EPIC	Terrestrial biodiversity GLOBIO	Aquatic biodiversity IMAGE-GLOBIO Aquatic	Marine Ecosystem ERSEM-NEMO
Contact person	Christoph Muller Christoph.Mueller@ pik-potsdam.de	Juraj Balkovič, Erwin Schmid or Petr Havlík balkovic@iiasa.ac.at	Aafke Schipper, Jelle Hilbers Aafke.Schipper @pbl.nl	Jan Janse Jan.Janse@pbl.nl	Icarus Allan or Jason Holt jia@pml.ac.uk jholt@noc.ac.uk
Model aim Functiona-lity	Dynamic global vegetation model of natural and managed land, including a hydrology and a nitrogen module. The model can be used to quantify water, carbon and nitrogen dynamics under changes in climate, land use and management at the global scale or selected regions of interest. Provides consistent information on biogeochemical pools and fluxes, natural vegetation dynamics, crop yields and managed grassland dynamics.	Dynamic crop growth model. It contains routines for simulating crop growth, yield and competition, hydrological, nutrient and carbon cycle, weather simulation, soil temperature and moisture, soil erosion and a wide range of crop management options, including tillage, fertilization, irrigation, liming and pesticides. EPIC operates on a daily time step and can be used for long-term assessments spanning decades to centuries.	GLOBIO is a spatially explicit model to simulate the impacts of various anthropogenic pressures, such as climate change, land-use change and pollution, on terrestrial biodiversity intactness (quantified based on the mean species abundance (MSA) metric). The model is part of the IMAGE framework.	GLOBIO-Aquatic is a spatially explicit model to simulate the composite effect of pressure factors on biodiversity for catchments. In addition to biodiversity indicators, the model calculates the occurrence of harmful algal blooms in lakes	ERSEM is a marine generic lower trophic level/ biogeochemical cycling model. It describes pelagic and benthic ecosystems in terms of phytoplankton, bacteria, zooplankton, zoobenthos, and the cycling of C, N, O, P and Si. NEMO is a 3D hydrodynamic model that provides temporally and spatially resolved currents and mixing transports to ERSEM. Together ERSEM-NEMO simulate past and future ecosystem states, and assess anthropogenic impacts.
Inputs/ Drivers of change	Temperature, Precipitation, Radiation, CO_2, soil, land use, organic and inorganic fertilizers.	Daily min and max temperature, solar radiation, precipitation; CO_2, soil and terrain, crop-specific sowing and harvest dates, cultivar specification, inorganic and organic fertilizers, irrigation, residue management.	The direct drivers of biodiversity loss considered in the current version (GLOBIO 4) are land-cover change, land-use intensity, habitat fragmentation, climate change, atmospheric nitrogen deposition, infrastructure (roads) and hunting (in tropical regions).	The drivers of aquatic biodiversity used are land use and land cover, nitrogen and phosphorus discharge to surface water (see IMAGE-Global Nutrient Model) river discharge, water temperature and hydrological disturbance by dams	Spatiotemporally resolved climatic inputs: air temperature, wind, precipitation etc. Riverine and diffuse inputs of freshwater, nutrients, sediments, DOM, DIC Alkalinity etc Atmospheric nitrogen deposition. Off shore infrastructure Fishing/aquaculture
Outputs	Global gridded (0.5° or more disaggregated, depending on input resolution) NPP, soil respiration, NEE, carbon and nitrogen pools, crop yields, nitrification, denitrification, leaching, runoff, volatilisation, nutrient stress, composition of biomass,…	Global gridded (from 5 arc-min to 0.5 arc-deg) crop yield, aboveground biomass, root biomass, soil carbon and nitrogen pools and fluxes, incl. volatilization, leaching, denitrification…, soil hydrology (runoff, percolate, subsurface flow, ET), erosion.	Spatially explicit (gridded) layers of mean species abundance (MSA), reflecting the degree to which the ecosystem is intact.	Mean species abundance (MSA), reflecting the degree to which the ecosystem is intact. The model also calculates the amount of harmful algal blooms in lakes.	Gridded 4D marine ecosystem and biogeochemical state and flux variables, e.g. biomass, primary production, O_2, pH etc. Aggregated and derived metrics. Typically daily-monthly.

Steady state /dynamic	Dynamic	Dynamic	Static	Static	Dynamic
Biophysical representa-tion	Process-based	Process-based	GLOBIO uses empirical relationships between drivers and outputs	GLOBIO aquatic uses empirical relationships between drivers and outputs	Fully coupled 4D hydrodynamics and mass conserving C, N, P, Si cycles through pelagic and benthic systems
Data needs	See inputs/drivers	See inputs/drivers	GLOBIO 4 requires spatially explicit input data on land use, climate change (global mean temperature increase), atmospheric nitrogen deposition, the global road network, and rural settlements in tropical biomes.	Apart from the biophysical data, GLOBIO-Aquatic has no specific data needs.	See inputs and drivers *In-situ* and earth observation data for validation and process assessment
Validation status	Validated in various peer-reviewed publications participated in AgMIP, ISIMIP, GGCMI	Validated in various peer-reviewed publications participated in AgMIP, ISIMIP, GGCMI	The pressure-impact relationships in GLOBIO are built on extensive global datasets that compare local species composition under influence of a particular pressure to species composition in an undisturbed reference situation. These datasets as well as the model itself have been published in peer-reviewed articles.	The empirical relationships between aquatic biodiversity and land use, nutrient budgets and hydrological changes, were derived from an extensive compilation of case studies on rivers, lakes and wetlands. There is a geographical bias towards well studied regions, and regions where both disturbed systems and comparable reference systems still exist, such as in North America, Australia and New Zealand, and to a lesser extent Europe. Use of the model for other regions requires some caution, but is considered appropriate for large-scale assessments.	NEMO is widely used in operational forecasting scales from climate (CMIP), seasonal to short-term. It is widely validated in this context. ERSEM is extensively validated in regional simulations, e.g. NW European shelf seas where NEMO-ERSEM provides the operational oceanographic system for Copernicus. It has also been validated in the basinscale and global context as part of research projects.
Spatial resolution	Any resolution for which climate, soil and management data is available. Usually 0.5°	5′′ to 0.5° Any resolution for which management data is available	10 arc-seconds	0.5 by 0.5 degree	1° global 1/4 ° global planned in 2-3yrs 1/12 ° regional, NW European and SE Asia
Temporal resolution/ extent	Daily, monthly/yearly	Daily, monthly, yearly	Yearly, decadal	1 year	Daily/Monthly Last 50yrs to next 100 years
Linkage to scenarios mitigation/ measures	(RCP) climate scenarios, land use scenarios, management scenarios	Climate scenarios, crop management scenarios	Climate scenarios, land-use scenarios, management scenarios (RCPs, SSPs)	Policy options analysed with GLOBIO-Aquatic and relevant for the nitrogen cycle include reduction of agricultural area (e.g. by means of consumption changes and/or reduction of food waste, and improved efficiency	Climate scenarios, terrestrial/atmospheric input, management scenarios. Coastal and sea scenarios e.g. fishing.

				of nutrient use in agriculture, reduction of urban emissions, and designation/restoration of natural areas like wetlands and riparian buffer zones.	
Operatio-nality	Basic version fully operational; nitrogen module is short before submission	Fully operational for 16 crops	Fully operational	Fully operational	Fully operational
Accessibility	Upon request, open source release after some quarantine time	Upon request	The source code of the model is available upon request. A stand-alone version with documentation is currently being developed.	Accessible; however, the operation of the model may require assistance from PBL-Netherlands Environmental Assessment Agency	Model codes open-source. Some configurations available on request. Requires High Performance Computing resource
Primary literature sources	Bondeau et al (2007), Rost et al (2008), Schaphoff et al (2013), Waha et al (2012), Muller et al (2016)	(Balkovič et al., 2014, 2013, Izaurralde et al., 2012, 2006; Müller et al., 2016; Williams, 1995)	Schipper et al. 2019 (for earlier model versions: Schipper et al. 2016; Alkemade et al. 2009)	Janse et al. (2015)	Allen et al (2007); Barange et al. (2014); Bruggeman et al (2014); Blackford et al (2004); Butenschön et al. (2016); Edwards et al. (2012); Glibert et al. (2014); Holt et al. (2014); Wakelin et al. (2015).

References

LPJ-ml

Bondeau A, Smith PC, Zaehle S, Schaphoff S, Lucht W, Cramer W, Gerten D, Lotze-Campen H, Müller C, Reichstein M, Smith B. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Glob. Change Biol. 2007; 13: 679-706.

Biemans, H., Hutjes, R., Kabat, P., Strengers, B., Gerten, D., Rost, S. 2009. Impacts of precipitation uncertainty on discharge calculations for main river basins, J. Hydrometeor. 10, 1011–1025.

Müller C, Elliott J, Chryssanthacopoulos J, Arneth A, Balkovic J, Ciais P, Deryng D, Folberth C, Glotter M, Hoek S, Iizumi T, Izaurralde RC, Jones C, Khabarov N, Lawrence P, Liu W, Olin S, Pugh TAM, Ray D, Reddy A, Rosenzweig C, Ruane AC, Sakurai G, Schmid E, Skalsky R, Song CX, Wang X, de Wit A, and Yang H. 2016, Global Gridded Crop Model evaluation: benchmarking, skills, deficiencies and implications, Geosci. Model Dev. Discuss., 2016, 1-39, doi: 10.5194/gmd-2016-207.

Rost, S., Gerten, D., Bondeau, A. et al. 2008: Agricultural green and blue water consumption and its influence on the global water system. Water Resour. Res. 44, W09405.)

Schaphoff, S., Heyder, U., Ostberg, S., Gerten, D., Heinke, J., Lucht, W. 2013. Contribution of permafrost soils to the global carbon budget. Environ. Res. Lett. 8, 014026.

Waha K, van Bussel LGJ, Müller C, Bondeau A (2012): Climate-driven simulation of global crop sowing dates. Global Ecology and Biogeography, 21,2, pp. 247-259, doi: 10.1111/j.1466-8238.2011.00678.x

EPIC

Balkovič, J., van der Velde, M., Schmid, E., Skalský, R., Khabarov, N., Obersteiner, M., Stürmer, B., Xiong, W., 2013. Pan-European crop modelling with EPIC: Implementation, up-scaling and regional crop yield validation. Agric. Syst. 120, 61–75. doi:10.1016/j.agsy.2013.05.008

Balkovič, J., van der Velde, M., Skalský, R., Xiong, W., Folberth, C., Khabarov, N., Smirnov, A., Mueller, N.D., Obersteiner, M., 2014. Global wheat production potentials and management flexibility under the representative concentration pathways. Glob. Planet. Change 122, 107–121. doi:10.1016/j.gloplacha.2014.08.010

Izaurralde, R.C., McGill, W.B., Williams, J.R., 2012. Development and Application of the EPIC Model for Carbon Cycle, Greenhouse Gas Mitigation, and Biofuel Studies, in: Managing Agricultural Greenhouse Gases. Elsevier, pp. 293–308.

Izaurralde, R.C., Williams, J.R., McGill, W.B., Rosenberg, N.J., Jakas, M.C.Q., 2006. Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecol. Model. 192, 362–384. doi:10.1016/j.ecolmodel.2005.07.010

Müller, C., Elliott, J., Chryssanthacopoulos, J., Arneth, A., Balkovic, J., Ciais, P., Deryng, D., Folberth, C., Glotter, M., Hoek, S., Iizumi, T., Izaurralde, R.C., Jones, C., Khabarov, N., Lawrence, P., Liu, W., Olin, S., Pugh, T.A.M., Ray, D., Reddy, A., Rosenzweig, C., Ruane, A.C., Sakurai, G., Schmid, E., Skalsky, R., Song, C.X., Wang, X., de Wit, A., Yang, H., 2016. Global Gridded Crop Model evaluation: benchmarking, skills, deficiencies and implications. Geosci. Model Dev. Discuss. 1–39. doi:10.5194/gmd-2016-207

Williams, J.R., 1995. The EPIC model, in: Singh, V.P. (Ed.), Computer models of watershed hydrology. Water resources publisher, Colorado, pp. 909–1000.

GLOBIO and GLOBIO-Aquatic

Alkemade, R. M. Van Oorschot, L. Miles, C. Nellemann, M. Bakkenes, B. Ten Brink (2009). GLOBIO3: A framework to investigate options for reducing global terrestrial biodiversity loss. Ecosystems, 12(3), pp.374-390.

Janse, J.H., J.J. Kuiper, M.J. Weijters, E.P. Westerbeek, M.H.J.L. Jeuken, M. Bakkenes, R. Alkemade, W.M. Mooij, J.T.A. Verhoeven, GLOBIO-Aquatic, a global model of human impact on the biodiversity of inland aquatic ecosystems, Environmental Science & Policy, Volume 48, April 2015, Pages 99-114, ISSN 1462-9011, https://doi.org/10.1016/j.envsci.2014.12.007.

Schipper, A.M., Hilbers, J.P., Meijer, J.R., Antão, L.H., Benítez-López, A., De Jonge, M.J.M., Leemans, L.H., Scheper, E, Alkemade, R., Doelman, J.C., Mylius, S., Stehfest, E., Van Vuuren, D.P., Van Zeist, W-J, Huijbregts, M.A.J. (2019) Projecting terrestrial biodiversity intactness with GLOBIO 4. Global Change Biology, in press. https://doi.org/10.1111/gcb.14848

Schipper, A.M, Bakkenes, M., Meijer, J., Alkemade, R., & Huijbregts, M.A.J. (2016). The GLOBIO Model. A technical description of version 3.5. PBL publication 2369, PBL Netherlands Environmental Assessment Agency, The Hague. https://www.pbl.nl/en/publications/globio-35-technical-model-description.

Stehfest, E., Van Vuuren, D. P., Kram, T., and Bouwman, A. F.: Integrated assessment of global environmental change with image 3.0. Model description and policy applications, in, PBL Netherlands Environmental Assessment Agency (http://themasites.pbl.nl/models/image/index.php/Main_Page), The Hague, 2014.

ERSEM-NEMO

Allen, JI; Somerfield, PJ; Gilbert, FJH. 2007 Quantifying uncertainty in high-resolution coupled hydrodynamic-ecosystem models. Journal of Marine Systems, 64. Mar-14. 10.1016/j.jmarsys.2006.02.010

Barange, M; Merino, G; Blanchard, JL; Scholtens, J; Harle, J; Allison, EH; Allen, JI; Holt, JT; Jennings, S. 2014 Impacts of climate change on marine ecosystem production in societies dependent on fisheries. Nature Climate Change. 6, pp. 10.1038/NCLIMATE2119

Baretta, J.W., W. Ebenhoh and P. Ruardij, 1995. The European Regional Seas Ecosystem Model, A Complex Marine Ecosystem Model Netherlands Journal of Sea Research 33(3):233-246.

Bruggeman, J; Bolding, K. 2014 A general framework for aquatic biogeochemical models. Environmental Modelling & Software, 61. 249-265. 10.1016/j.envsoft.2014.04.002

Blackford, JC; Allen, JI; Gilbert, FJH. 2004 Ecosystem dynamics at six contrasting sites: a generic modelling study. Journal of Marine Systems, 52 (1 - 4). 191 - 215. 10.1016/j.jmarsys.2004.02.004

Butenschön, M., Clark, J., Aldridge, J.N., Allen, J.I., Artioli, Y., Blackford, J., Bruggeman, J., Cazenave, P., Ciavatta, S., Kay, S., Lessin, G., van Leeuwen, S., van der Molen, J., de Mora, L., Polimene, L., Sailley, S., Stephens, N., Torres, R., 2016. ERSEM 15.06: a generic model for marine biogeochemistry and the ecosystem dynamics of the lower trophic levels. Geosci. Model Dev., 9, 1293-1339.

Edwards, K.P., Barciela, R., Butenschon, M., 2012. Validation of the NEMO-ERSEM operational ecosystem model for the North West European Continental Shelf. Ocean Sci., 8, 983-1000.
Glibert, PM; Allen, JI; Artioli, Y; Beusen, A; Bouwman, L; Harle, J; Holmes, R; Holt, JT. 2014 Vulnerability of coastal ecosystems to changes in harmful algal bloom distribution in response to climate change: projections based on model analysis. Global Change Biology. n/a-n/a. 10.1111/gcb.12662
Holt, J., Allen, J.I., Anderson, T.R., Brewin, R., Butenschon, M., Harle, J., Huse, G., Lehodey, P., Lindemann, C., Memery, L., Salihoglu, B., Senina, I., Yool, A., 2014. Challenges in integrative approaches to modelling the marine ecosystems of the North Atlantic: Physics to Fish and Coasts to Ocean. Progress in Oceanography, doi:10.1016/j.pocean.2014.04.024, 285-313.
Wakelin SL, Artioli Y, Butenschon M, Allen JI, Holt JT. 2015. Modelling the combined impacts of climate change and direct anthropogenic drivers on the ecosystem of the northwest European continental shelf. Journal of Marine Systems, 152. 51-63. 10.1016/j.jmarsys.2015.07.006

Global-scale modelling of flows and impacts of nitrogen use:

Modelling approaches, Linkages and Scenarios

In this report document, we discuss the approach to a global integrated nitrogen assessment model chain allowing to evaluate the consequences of different socio-economic drivers (scenarios) and N mitigation management in terms of: (i) benefits, including food, feed, fibre (wood) and energy production and (ii) threats, including pollutant and greenhouse gas emissions, affecting the quality of air, soil and water and related climate, human health and biodiversity impacts and (iii) cost- effectiveness. This is done by addressing:

- The overall modelling approach, including (i) the type of models that are needed to simulate nitrogen benefits and threats and (ii) the model linkages needed to enable a consistent multi-model approach in response to a consistent set of scenarios of drivers (population development, income etc.) and N mitigation measures.

- The modelling practice including (i) the modelling approaches, distinguishing between empirical and process-based models, and (ii) the available models that would serve an integrated global scale nitrogen assessment, considering the variety of impacts and scales.

- A modelling protocol of the involved models including information on: (i) the models involved, (ii) basic agreements on base year (2010), spatial extent and resolution, temporal extent and resolution, (iii) scenarios, (iv) model outputs and (v) model linkages.

- A database platform for the INMS model inputs and outputs.

Keywords: modelling, nitrogen flows, nitrogen impacts: modelling approaches, scenarios, global scale