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Global-scale scenarios and modelling as tools for managing large-scale nitrogen pollution

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Abstract

UNEP's GEO Yearbook 2003 (UNEP, 2004) characterizes problems related to reactive nitrogen (nitrogen overloads in some areas and nitrogen deficiencies in other areas of the globe) as an emerging global environmental issue. Global modelling and scenario analysis may help to investigate linkages and feedbacks between global change and water pollution, and to identify appropriate management options.

To get an overview of the present-day global situation of nitrogen input and fate and to derive scenarios of the future that simulate the impact of global change (climate, population, agriculture, waste water treatment, etc.), the global model WaterGAP-N is being developed. WaterGAP-N will simulate the input and fate of terrestrial nitrogen, including the input from diffuse (industrial fertilizer and manure, biological fixation, and atmospheric deposition) and point sources, and the transport of dissolved N and its loss by denitrification in soil and groundwater as well as in surface waters (rivers, lakes, wetlands). With a spatial resolution of 0.5°, the model computes the N loads in each cell as well as the input to the oceans. Here we present first results of WaterGAP-N and show how the model will be used to derive management options for large-scale nitrogen pollution on the background of the SRES scenarios of the Intergovernmental Panel on Climate Change (IPCC).

1. Introduction

Scenarios can help to understand the consequences of today's decisions in a quite distant and uncertain future. They describe a range of consistent and plausible images of alternative futures in an integrated manner, considering the most important driving forces of the socio-environmental system of interest. State-of-the-art environmental scenarios combine qualitative with quantitative elements, i.e. storylines with model calculations. The development of qualitative-quantitative scenarios may consist of the following steps (Döll, 2004):

- Identification of the problem field and the participants of the scenario process
- System definition including driving forces as well as temporal and spatial resolution and extent
- Definition of indicators of the system state
- Development of qualitative reference scenarios in the form of storylines
- Development of quantitative reference scenarios using mathematical models
- Assessment of the impact of management decisions against the background of the reference scenarios
- Evaluation of the scenarios.

Environmental scenarios are always interdisciplinary and have to consider linkages within the social-environmental system. Spatial linkages (transport processes) or temporal linkages (buffer and transformation processes) generally produce an even higher degree of complexity.

Nitrogen pollution has been recognized as a large-scale problem that does no longer affect only developed countries (UNEP, 2002). Due to the future increase of population and wealth, and the related extension and intensification of agriculture, even larger areas of the globe will potentially be subject to high nitrate levels in the groundwater and the eutrophication of surface waters (terrestrial and marine). Global modelling and scenario analysis may help to investigate linkages and feedbacks between global change and water pollution and to identify appropriate management options. In particular, global modelling helps to explore linkages between food consumption in one region and environmental effects in another one.

In order to assess management options for large-scale soil and water pollution, it would be ideal to derive integrated quantitative scenarios of various pollutants (nitrogen, phosphorus, pesticides, salt etc.). These scenarios would be based on mathematical models, which relate driving forces (population, food consumption patterns, climate etc.) and specific management options with the level of pollution. For efficiency and consistency reasons they should rely on existing global change scenarios (SRES report by the Intergovernmental Panel on Climate Change (IPCC), Nakicenovic, 2000). The SRES scenarios describe the future world development in four scenario groups along a matrix of the attributes *global* versus *regional* and *economic* versus *environmental* and provide consistent scenario assumptions with regard to major driving forces like demographic change, social and economic development and rate and direction of technological change, which are also relevant driving forces of water and soil pollution. However, it is necessary to complement the SRES scenarios by assumptions specific to pollutions of soil and water.

As a first step towards integrated global scenarios of water and soil pollution we are developing WaterGAP-N, a global model of terrestrial N-input and fate. This model is specifically designed for use in scenario development.

2. Development and first results of the WaterGAP-N model

WaterGAP-N simulates the amount of nitrogen transported by rivers into the world’s oceans by first computing diffuse and point sources of reactive nitrogen and then its transport through soil, groundwater and surface waters (rivers, lakes and wetlands) to the ocean, taking into account denitrification losses. The model uses monthly time steps and covers the whole land area of the globe (except Antarctica), with a spatial resolution of 0.5° longitude by 0.5° latitude (approximately 67,000 cells). WaterGAP-N processes information on global land cover, crop distribution and crop productivity as well as information on livestock numbers and productivity as provided by the IMAGE 2.2 implementation of the SRES scenarios (IMAGE Team, 2001), hydrological information as provided by the WaterGAP model (Alcamo et al., 2003) and information from several other sources (Fig. 1).

Since N pollution of ground and surface waters is closely linked to land use and management, it is necessary to consider scenarios of land use to derive estimates of future N pollution. IMAGE 2.2 is the only existing global model that simulates land use as well as productivity of crops and livestock up to the year 2100 consistent with the SRES scenarios. Therefore land use and productivity in WaterGAP-N is based on modified simulation results of the IMAGE 2.2 model although for present day conditions other land use maps, which are based on remote sensing and actual sub-national statistics, would be more appropriate (e.g. Leff et al., 2004).

The part of WaterGAP-N that computes diffuse inputs of reactive nitrogen into ground water is already functioning while the other parts of the model exist as concepts and have still to be developed. First results of the soil nitrogen balance as simulated by WaterGAP-N show that the largest turnover of reactive nitrogen occurs in regions with high plant productivity (Fig. 2a and 2b). In areas covered by natural vegetation or forests most of the N-inputs go into plant uptake, and the highest values of N leaching from the soil are found in intensively used agricultural areas (eastern part of the United States, Western Europe, India and the eastern part of China). Nitrogen leaching has increased between the early sixties and the early nineties in particular in Asia (Fig. 2c and 2d).

A comparison to results of other global studies indicates that the simulation results of WaterGAP-N are in the range of other existing global models and that even in the global summery the uncertainty of the simulation results is high (Tab. 1). It is very difficult to assess the uncertainty of the results systematically because measurements of N-leaching on such a scale are not possible. Systematic measurements are only available for the nitrogen concentration in the rivers, which is however at the end of the chain of nitrogen transformation and transport processes.

Because the SRES scenarios and the IMAGE 2.2 model were developed with focus on greenhouse gas emissions and climate change, specific assumptions related to water pollution are missing in the existing scenarios. In case of nitrogen pollution these are in particular:

- Assumptions on the amount and efficiency of waste water treatment,
- Assumptions related to the management of biofuel crops,
- Extent of and specific management in organic agriculture,
- Fertilizer management in agriculture (e.g. type of fertilizer spreading, storage of manure).

To simulate future nitrogen pollution it is necessary to complement the existing scenarios by those and some other assumptions. The range of meaningful assumptions is determined up to a given degree by the specific scenario but active pollution management can also influence it. Therefore options for large-scale pollution management may be those which make sense in the given scenario and also lead to low soil and water pollution.

3. Conclusions

In order to use the WaterGAP-N model to derive options for managing large-scale nitrogen pollution it is necessary to finish model development (including model validation), and to modify and complement assumptions of the SRES scenarios. Then, it will be possible to assess the impacts of e.g. increased population and wealth on nitrogen pollution and to compute, for example, the effect of improved waste water treatment or fertilizer management. However, many management options appear to be related to changing global food consumption and agricultural production and trade patterns. In order to assess such options it would be necessary to first develop an improved global land use model which would then be coupled to WaterGAP-N to obtain scenarios of land use that does not result in excessive N pollution.

References

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T., Siebert, S. (2003) Development and testing of the WaterGAP 2 global model of water use and availability, *Hydrological Sciences Journal 48*, 3, 317-338.

Döll, P. (2004) Qualitative-quantitative scenarios as a means to support sustainability-oriented regional planning, in: Marquina, A. (ed.) Environmental Challenges in the Mediterranean 2000-2050, Proceedings of the NATO Advanced Research Workshop, held in Madrid, Spain, 2-5 October 2002. NATO Science Series IV: Earth and Environmental Sciences, Vol. 37, Kluwer, 47-60.

Van Drecht, G., Bouwman, A.F., Knoop, J.M., Beusen, A.H.W., Meinardi, C.R. (2003) Global modeling of the fate of nitrogen from point and nonpoint sources in soils, groundwater and surface water, *Global Biogeochemical Cycles 17 (4)*, 1115, DOI 10.1029/2003GB002060.

IMAGE Team (2001) The IMAGE 2.2 implementation of the SRES scenarios. A comprehensive analysis of emissions, climate change and impacts in the 21st century, *CD-ROM publication 481508018*, National Institute for Public Health and the Environment, Bilthoven, Netherlands.

Leff, B., Ramankutty, N., and Foley, J.A. (2004) Geographic distribution of major crops across the world, *Global Biogeochemical Cycles 18 (1)*, 1009, DOI 10.1029/2003GB002108.

Mosier, A., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S., van Cleemput, O. (1998) Closing the global N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle, *Nutrient Cycling in Agroecosystems 52*, 225-248.

Nakicenovic, N. (ed.) (2000) Emissions Scenarios. IPCC Special Report on Emissions Scenarios, Cambridge University Press.

Nevison, C.D., Esser, G., Holland, E.A. (1996) A global model of changing N_2O emissions from natural and perturbed soils, *Climatic Change 32*, 327-378.

Sheldrick, W.F., Syers, J.K., Lingard, J. (2002) A conceptual model for conducting nutrient audits at national, regional and global scales, *Nutrient Cycling in Agroecosystems 62*, 61-72.

United Nations Environment Programme (UNEP) (2004) GEO Yearbook 2003, Earthscan. (http://www.unep.org/geo/yearbook/)

UNEP (2002) Global Environment Outlook 3, Earthscan.

Table 1 – Compartments of the nitrogen soil balance as modelled by WaterGAP-N compared to other global studies, values in Tg N yr^{-1}

Source	Sheldrick et al. (2002)	Nevison et al. (1996)	Mosier et al. (1998)	Van Drecht et al. (2003)		WaterGAP-N model	
Base year(s)	1996	1990	1989	1995		average 1991-1995	
Extent	arable cropland	global land area	agricult. area	agricult. area	global land area	agricult. area	global land area
Synthetic fertilizer use	78.2	78.0	79.0	76.5	76.5	73.0	73.0
Manure use*	33.3	102.0	124.2	105.3	105.3	107.7	107.7
Biological N-Fixation	7.7	n.a.	9.7	40.8	159.7	34.8	160.7
Deposition	21.6	n.a.	n.a.	40.8	65.5	n.c.	58.3
Mineralization	n.c.	828.0	n.a.	n.c.	n.c.	n.c.	1147.0
Soil mining	18.3	n.c.	n.c.	n.c.	n.c.	n.c.	17.4
Plant uptake**	101.2	835.0	n.a.	*91.0*	n.a.	108.9	1101.1
Leaching	n.a.	172.0	n.a.	55.0	n.a.	n.c.	80.2
Denitrification	n.a.	128.0	n.a.	79.0	n.a.	n.c.	158.0
NH_3-volatilization	n.a.	n.a.	n.a.	30.0	n.a.	40.3	40.3

n.c. : not considered
n.a. : not available
* : N content before NH_3-volatilization
** : values in italic refer to N-export by the harvested parts of biomass

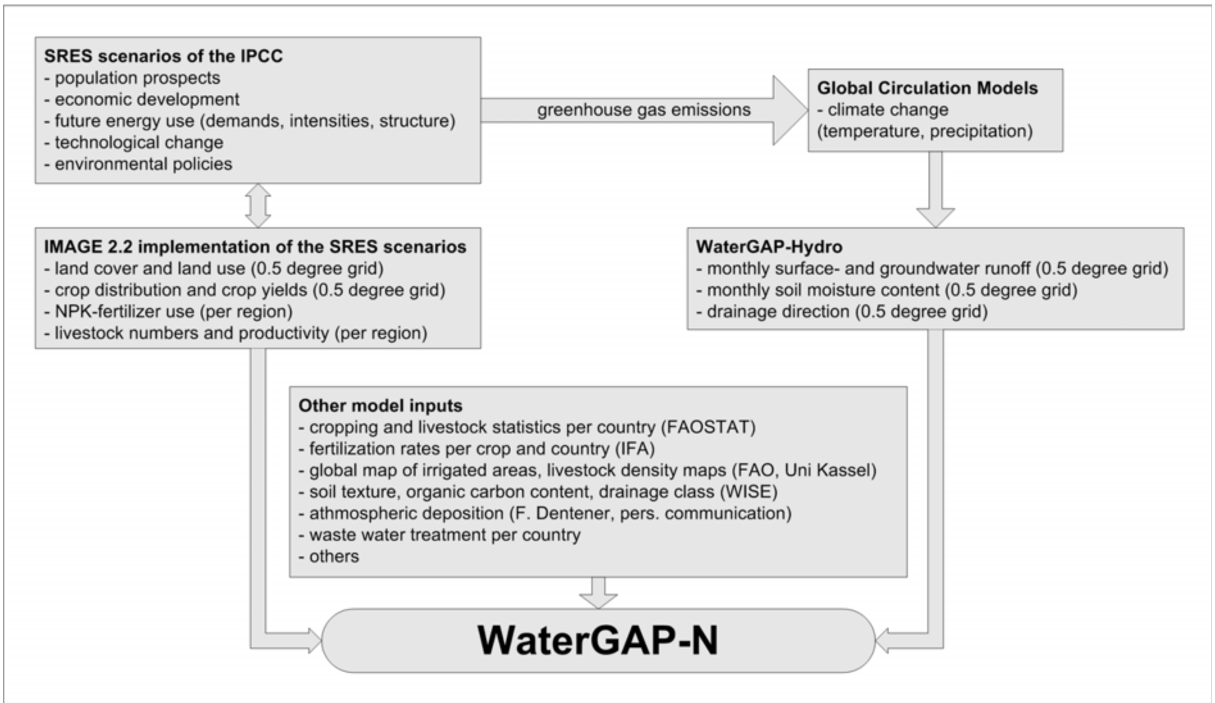

Figure 1: Input data for the WaterGAP-N model.

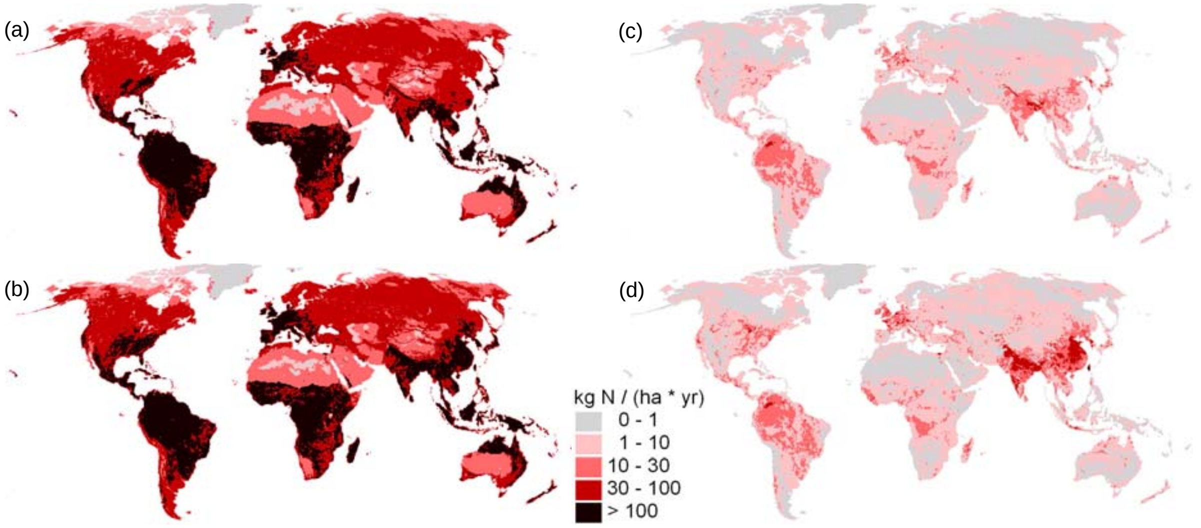

Figure 2: Total diffuse inorganic nitrogen load of the soil (sum of mineralization of organic matter, synthetic fertilizers, deposition, symbiotic N-fixation of crops) and leaching of nitrogen below the root zone as computed by WaterGAP-N (kg N ha^{-1} yr^{-1}), a) average annual nitrogen loads 1961-1965, b) average annual nitrogen loads 1991-1995, c) average annual nitrogen leaching 1961-1965, d) average annual nitrogen leaching 1991-1995.