18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

Impacts of spatial aggregation on national and European predictions of nitrogen and green house gas fluxes in response to changes in livestock, land cover and management

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Abstract:

In this study we compared three relatively simple process based models, developed for the national scale (INITIATOR2), European scale (MITERRA) and global scale (IMAGE), with respect to their predictions of N budgets in response to changes in livestock, land use and agricultural management based on the IPCC B2 baseline scenario for the period 2000–2030. Predictions focus on NH_3, N_2O and NO_x emissions to the atmosphere, N leaching to groundwater and N runoff to surface water. At the national and European scale, the comparison is quite good. For the year 2000, the results of INITIATOR2 and MITERRA at the national scale (the Netherlands) are within 10% for the N inputs (except for N fixation) and within 25% for most of the N outputs (crop uptake, NH_3 and N_2O emissions and N leaching). Larger differences, up to 60% occur for NO_x emissions and N runoff. Similarly, the results of IMAGE and MITERRA compare quite well at the European scale (all EU 27 countries). Total N inputs compare within 10%, although individual sources such as grazing and deposition deviate up to 30%, and most of the N outputs deviate by less than 30% (crop uptake, NH_3 and N_2O emission). Larger differences up to 100% occur for NO_x emissions and the sum of leaching and runoff. The comparability of predictions is different in 2030 as compared to 2000, due to differences in model assumptions. For example, an efficiency increase in N use in the period 2000-2030 is assumed in INITIATOR2 but not in MITERRA. Consequently, the N input by animal manure for the whole of the Netherlands is quite comparable in 2000, while it deviates by approximately 20% in 2030. Inversely, the estimated total NH_3, N_2O and NO_x emissions by INITIATOR2 are approximately 20-40% higher than the estimates by MITERRA in the year 2000, but emissions in the year 2030 are comparable for both models. As an efficiency increase in N use in the period 2000-2030 is also assumed in IMAGE, similar discrepancies occur at the European scale when comparing MITERRA with IMAGE.

Unlike the national and European scale predictions, results show that the area exceeding critical N loads and the average level of N exceedance is largely affected by spatial resolution of the input data. In this study, this holds specifically for effects on ground water quality (N leaching leading to NO_3 concentrations exceeding the limit of 50 mg NO_3/l), and to a lesser extent for impacts on terrestrial biodiversity (N deposition levels exceeding critical N loads). In summary, results imply that spatial aggregation has a limited effect on most national and continental scale N inputs and emission estimates but a moderate to large effect on the exceedance of critical N loads and critical NO_3 concentrations, respectively. Largest uncertainties occur in the emissions of NO_x and N leaching and runoff, both at the national and European scale. Differences in model results are mainly due to differences in the use of basic data, such as animal numbers and crop yields and in excretion, emission, uptake and leaching factors, and to a lesser extent related to differences in model structure.

Keywords: *nitrogen, green house gases, modeling, scaling, ammonia, methane, nitrous oxides, leaching, agriculture*

1. INTRODUCTION

Various models approaches have been developed for assessing emissions of different forms of reactive nitrogen such as NH_3, N_2O and NO_x emissions and N leaching and N runoff for various parts of Europe at various geographic resolutions and for various time periods. The modelling approaches vary from: (i) emission factor approaches at various spatial resolutions, such as UNFCC/IPCC, EDGAR, GAINS and EMEP to (ii) models combining more detailed emission factor approaches with simple process based and empirical models, such as IMAGE, MITERRA and INITIATOR and (iii) detailed ecosystem models, such as DNDC and the combination CAPRI-DNDC. In this study, three relatively simple process based models, developed for the national scale, i.e. INITIATOR2 (De Vries et al. 2005b), European scale, i.e. MITERRA (Velthof et al. 2009) and global scale, i.e. IMAGE (MNP 2006), were compared with respect to their predictions of N budgets in response to livestock, land use and management changes in agriculture, based on the IPCC B2 baseline scenario for the period 2000– 2030. Predictions focus on NH_3, N_2O and NO_x emissions to the atmosphere, N leaching to groundwater and N runoff to surface water. Changes in inputs, related to animal numbers and N fertilizer inputs are predicted by the IMAGE model. The predicted relative changes by IMAGE are used in INITIATOR2 and MITERRA while relating the animal categories and crop categories to those in IMAGE. We compared predictions for the years 2000 and 2030 for: (i) the Netherlands using INITIATOR2 and MITERRA and (ii) Europe (the current 27 EU countries) using MITERRA and IMAGE. The objective of the comparison was to get experience in linking the models across scales and to evaluate scale effects, in terms of aggregating input data, and modelling approach on the model outcomes.

2. METHODOLOGICAL APPROACHES

2.1. Models involved

IMAGE

The Integrated Model to Assess the Global Environment (IMAGE) is a dynamic integrated assessment modelling framework for global change (MNP 2006). IMAGE 2.4 simulations cover the 1970-2100 period (end year dependent of scenario choice). Data for 1970-2000 are used to calibrate the model. Simulations up to the year 2100 are made on the basis of scenario assumptions on, for example, demography, food and energy consumption and technology and trade. IMAGE 2.4 is global in application and makes standard predictions for 24 world regions (energy, trade and emissions). In Europe, a distinction is made in OECD Europe and Eastern Europe. However, IMAGE performs many of its calculations also on a high-resolution terrestrial 0.5 by 0.5 degree grid (land use and land cover) and for Europe it includes country based calculations of N fluxes (NH_3 and N_2O emissions and N leaching/runoff). In the IMAGE 2.4 framework general equilibrium economy is taken from different economic models.

MITERRA

MITERRA (often denoted as MITERRA-Europe) is a deterministic and static N cycling model which calculates N emissions on an annual basis, using N emission factors and N leaching fractions based on literature and expert knowledge (Velthof et al. 2009). The model can be used to assess the effects of measures and policies on the emissions of ammonia, nitrous oxide (N_2O), N oxides (NO_x), and methane (CH_4) to the atmosphere, leaching of N to groundwater and surface waters at EU-27 level, country level, and regional (NUTS-2) level. MITERRA focuses on agriculture only. MITERRA-Europe is based on the models RAINS/GAINS (Regional Air Pollution Information and Simulation; http://www.iiasa.ac.at/rains) and CAPRI (Common Agricultural Policy Regionalised Impact;www.capri-model.org), supplemented with an N cycle and N leaching module.

INITIATOR2

INITIATOR2 (Integrated Nutrient ImpacT Assessment Tool On a Regional scale) was developed to gain insight in all environmental impacts of excessive manure application in the Netherlands simultaneously (De Vries et al. 2005a; 2005b). It is an extension of the model INITIATOR that was developed to gain insight in the fate of all major nitrogen flows (De Vries et al. 2003) and also includes the emissions of carbon dioxide, methane, fine particles and odor and the accumulation, runoff and leaching of phosphate, base cations and heavy metals. A so-called CBS/GIAB database contains animal numbers and the location for each farm in the Netherlands. The NH_3, NO_x, N_2O, CH_4 and odor emissions from housing and manure storage systems are described by a multiplication with excretion factor and/or emission factor for different animal categories, depending on the type of emission (up to 65 categories in case of N excretion and NH_3 emission). Results of the N, P and metal excretion are input for a simple manure transport model predicting manure export from intensive animal husbandry areas and manure import in less intensive areas and related fertilizer use. NH_3 emissions due to N input by manure application and grazing are calculated in the soil model (the core) of INITIATOR2. Together with NH_3 emissions from housing systems, it forms the input of a transfer matrix, based on results of an atmospheric transport model.

2.2. Assessment of trends in livestock, land use and management

The predicted changes in the agricultural systems are changes in animal numbers, crop area, crop yield and N fertilizer inputs. These changes are calculated in response to the IPCC-SRES Regional Communities (B2) scenario, which was made more specific on agricultural policies. Trends in animal numbers and crop areas are based on the demand, trade and production of crops and animal products as provided by the GTAP model (Hertel 1997). The modules of the animal production systems in IMAGE are used to calculate the number of animals and their feed requirements from feed crop, grass, fodder etc. A detailed description of the animal production systems and future intensity increase is provided in Bouwman et al. (2005a). Changes in crop area are a result of changes in agricultural production, which is also calculated by the GTAP model, and changes in crop yield. Allocation of the production on a 30 min grid is done by the Land Cover Change Model (LCM) of IMAGE. The Terrestrial Vegetation sub Model (TVM) in IMAGE calculates crop yield on the basis of the potential crop productivity, which is multiplied by the fraction of actual yield to potential crop productivity (the so called "management factor" in IMAGE). This management factor is assumed to grow in time, based on (Bruinsma 2003). Additional to this external trend, yields also change because of the economically driven intensification as calculated by GTAP, through climate change and through change in agricultural area. In IMAGE fertilizer use depends on crop production expressed in dry matter. Hence, with changing crop production, the fertilizer requirement per hectare changes proportionally. However, at the same time the fertilizer use efficiency increases. This is expressed as the dry matter production in kg per kg of N fertilizer. For Western European countries this efficiency is assumed to increase by 20% in the period 2000-2030, whereas no change in fertilizer efficiency is assumed for Eastern European countries. More details on this approach are given in (Bouwman et al. 2005b).

2.3. Linkage of scenario results from IMAGE to MITERRA and INITIATOR2

The spatial resolution of input data used by the models IMAGE, MITERRA and INITIATOR2 varies, according to the geographic extent of the model. IMAGE uses input data at sub-continental level, but for Europe an IMAGE version exists that uses agricultural data at country level. MITERRA uses statistical data at the NUTS2 administrative level (NUTS 2; Nomenclature of Territorial Units for Statistics in the EU; ca 230 administrative areas of 160 – 440 km^2). INITIATOR2 uses data at the level of so-called STONE plots (4647 for agriculture in the Netherlands), that are plots consisting of a multiple of 250m $\times$ 250m grid cells with unique combinations of soil use, soil type and related soil properties and ground water table class. Regarding animal numbers, use is made of the so-called CBS/GIAB database containing agricultural statistics for each farm in the Netherlands. The principle of the linkage of the IMAGE results to MITERRA and INITIATOR2 is to superimpose the IMAGE predictions for the period 2000-2030 on animal numbers, crop area, crop yield and N fertilizer use land cover for the various IMAGE animal and crop categories on the more detailed data used by MITERRA and INITIATOR2 in the year 2000. To perform this action, tables are used that allocate the various animal and crop categories in IMAGE to those used by MITERRA and INITIATOR2, as described in detail in De Vries et al. (2009). An overview of the data sources used by IMAGE, MITERRA and INITIATOR2 for the year 2000 is also given in De Vries et al. (2009).

3. RESULTS ON NITROGEN BUDGETS AND NITROGEN FLUXES TO ATMOSPHERE AND WATER

3.1. Comparison at national scale

Aggregated national scale results

Estimated N budgets for agricultural land for the whole of the Netherlands for the years 2000 and 2030 are quite comparable for INITIATOR2 and MITERRA (Table 1). The largest differences occurs for the N input by manure application in 2030, which is higher in MITERRA compared to INITIATOR2 due to a much lower reduction in N excretion. Unlike MITERRA, an efficiency increase is assumed in INITIATOR2. Furthermore, the N balance by INITIATOR2 includes more sources, i.e. organic products and N mineralization of drained peat soils. The latter flux is considerable. Nevertheless, the net surplus, which determines the fate of N in terms of emissions to atmosphere and water, derived by both models is quite comparable due to an estimated higher N uptake by INITIATOR2 as compared to MITERRA.

Table **1**. N budgets for agricultural land for the Netherlands, estimated by INITIATOR2 and MITERRA for the years 2000 and 2030

N budget term	N flux (ktonN/yr)			
	2000		2030	
	INITIATOR	MITERRA	INITIATOR	MITERRA
Fertilizer	305	300	208	180
Manure application	314	308	235	272
Organic products	11	0	9.4	0
Grazing	108	122	87	97
Deposition	65	66	52	54
Fixation	16	7.8	15	7.0
Total input	820	803	606	610
N mineralization	69	0	63	0
Crop removal	425	337	385	343
Surplus	464	466	284	267
NH_3-N emissions	125	108	90	93
N_2O-N emissions	20.0	15.0	12.7	12.2
NO_x-N emissions	15.2	11.7	9.4	9.3
N leaching	88	108	53	53
N runoff	44	19.5	26	14.3

Results for the years 2000 show that the estimated total NH_3 emissions by INITIATOR2 are approximately 20% higher than the estimate by MITERRA, while the stimulates for both N_2O and NO_x are 40% higher (Table 1). The difference between the net surplus and the various N fluxes to atmosphere and water is an estimate for the N_2 emissions, which are quite comparable. The major differences affecting the INITIATOR2 and MITERRA output are (i) the agricultural area considered, (ii) the estimated N inputs by animal manure and mineral fertilizer and (iii) the emission factors for the various compounds considered (NH_3, N_2O, NO_x and CH_4) as further described in De Vries et al. (2009).

Results at a regional scale

With respect to the emission of green house gases, such as N_2O and CH_4, it is crucial to know whether the total emissions for the area considered (e.g. country or continent) are correct. Accurate information on the spatial distribution of the emissions is less relevant, because of strong atmospheric dispersion. The latter aspect is, however, crucial when assessing the risk of elevated NH_3 emissions, and related N deposition, and of N leaching and N runoff in view of eutrophication impacts on terrestrial and aquatic ecosystems. Here, aggregation of input data for large areas may cause (possibly accurate) average N deposition and N leaching levels that are below critical N deposition loads or critical N concentrations in ground water and surface water, while at regional scale such limits are exceeded. A comparison of the predicted total NH_3 emissions by INITIATOR2 and MITERRA per NUTS2 region for the year 2000 shows that results are in line with the national result. The deviations are generally less than 20%. However, while predicted total N leaching at the national scale by INITIATOR2 and MITERRA is comparable, the variation at NUTS2 level is considerable and can even be more than 100% (Figure 1).

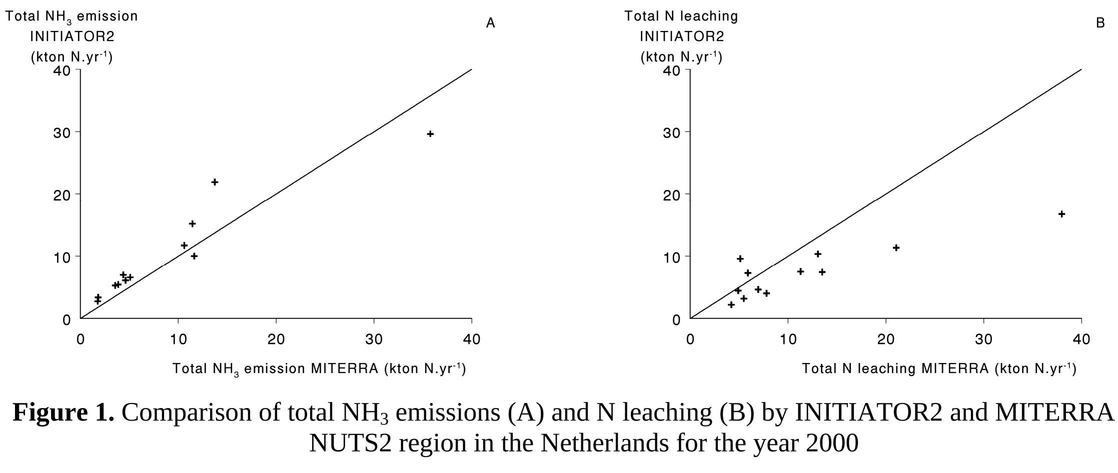

Figure 1. Comparison of total NH_3 emissions (A) and N leaching (B) by INITIATOR2 and MITERRA per NUTS2 region in the Netherlands for the year 2000

Even though the total NH_3 emissions at NUTS2 level are quite comparable, INITIATOR2 predicts a large spatial variation within theNUTS2 regions, that can deviate largely from the NUTS2 average emissions as shown in Figure 2. This variation affects the N deposition, mainly resulting from NH_3 emissions in agriculture and NOx emissions by traffic and industry. The N deposition was estimated by using the NH_3 emission results from both models while (i) using an emission-deposition transfer matrix in INITIATOR2 (see before), while adding available background NO_x deposition data and (ii) assuming that NH_3 deposition in each NUTS2 region is 55% of the NH_3 emission (average value for the Netherlands) and adding the same background deposition. The resulting present N loads were compared with available critical N loads for nature target types in the Netherlands (Van Dobben & van Hinsberg 2008). The exceedance of the critical N load thus derived is given in Table 2, in terms of (i) the area exceeding the critical N load, (ii) the accumulated N exceedance, being the product of area and exceedance for all areas where the N deposition in 2000 exceeds the critical N deposition and (iii) the average exceedance, being equal to the accumulated exceedance divided by the area where N exceedance occurs. The exceedance of the critical N leaching is also given in Table 2, where the criterion is the NO_3 concentration in the leachate of 50 mg NO_3/l. Results show that the area exceeding critical N loads and the average level of exceedance is largely affected by spatial aggregation of the input data, both for the effects on biodiversity (N deposition) and ground water quality (N leaching).

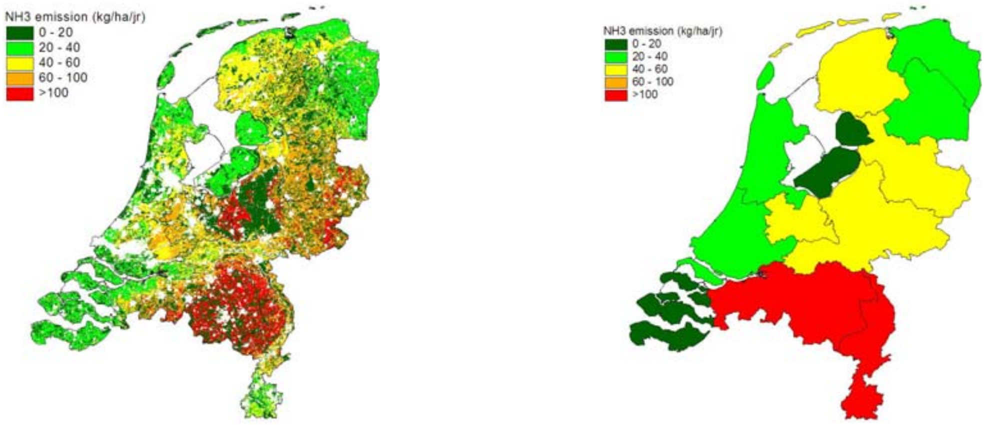

Figure 2. Geographic variation in total NH_3 emissions as derived by INITIATOR2 per STONE plot (left) and by MITERRA per NUTS2 region (right) in the Netherlands for the year 2000

Table **2**. Calculated exceedances of critical N loads in the Netherlands in view of impacts on biodiversity (N deposition) and ground water quality (N leaching) by INITIATOR and MITERRA in the year 2000

Type of exceedance	Model	Exceedance		
		Area (%)	Accumulated (ton/yr)	Average (kg/ha/yr)
Deposition	INITIATOR2	86	5174	8.5
	MITERRA	87	4294	6.4
Leaching	INITIATOR2	27	11	20
	MITERRA	70	51	37

3.2. Comparison at European scale

Aggregated European scale results

Estimated N budgets for agricultural land for Europe (limited to the 27 member states of the EU, EU27) for the years 2000 and 2030 are quite comparable for IMAGE and MITERRA (Table 3). Total N inputs compare within 10%, although individual sources such as grazing and deposition deviate up to 30%. The total N inputs are approximately 2750 kton N larger in IMAGE in the year 2000. The larger input in 2000 is compensated by a larger N uptake in IMAGE, leading to a comparable N surplus at the European scale. In 2030, the differences in total N inputs are almost negligible, due to an estimated increase in N fertilizer input by MITERRA in response to an increase in N crop uptake. The increase in N fertilizer input is because MITERRA did not assume an increase in N use efficiency in the period 2000-2030. Such an increase was however assumed in IMAGE and consequently, both the estimated N fertilizer input and N crop uptake decreases in 2030 as compared to 2000. In 2030, the lowering in N fertilizer input by IMAGE causes a slightly smaller predicted N surplus by this model as compared to MITERRA.

Results for the total emissions of NH_3 for EU27 are highly comparable for MITERRA and IMAGE, both in 2000 and 2030, whereas the calculated total emissions of N_2O and NO_x are 20-40% higher by IMAGE compared to MITERRA, both in 2000 and 2030. The estimated sum of N leaching and N runoff by IMAGE is even twice as high as the estimate by MITERRA (Table 3).

Table **3**. N budgets for agricultural land for EU 27 by IMAGE and MITERRA for the years 2000 and 2030

N budget term	N flux (kton/yr)			
	2000		2030	
	IMAGE	MITERRA	IMAGE	MITERRA
Fertilizer application	11223	11302	10312	11558
Manure application	4191	4785	3679	4162
Grazing	4609	3560	3141	2632
Deposition	2789	2015	1949	1812
Fixation	1385	832	1285	785
Total input	24179	22494	20366	20949
Crop removal	13500	10635	12270	11118
Surplus	10679	11860	9016	9832
NH_3-N emissions	2848	2873	2456	2584
N_2O-N emissions	434	318 (374)[1]	367	288 (343)[1]
NO_x-N emissions	219	93	184	85
N leaching and runoff	5945	2811	4443	2398

[1)] The value in brackets is the total N_2O emission calculated by MITERRA including also (indirect) N_2O emissions due to biological N fixation (10 kton/yr both in 2000 and 2030), N leaching (21 kton/yr in 2000 and 18 kton/yr 2030) and ammonia emission (30 kton/yr in 2000 and 27 kton/yr 2030).

Results at a national and regional scale

The predicted total NH_3 emissions by IMAGE and MITERRA are not only comparable at EU level but also at country level, as shown in Figure 3 for the year 2000. Results for NH_3 show a high very correlation. The correlation between the estimated N_2O emissions per country by IMAGE-N and MITERRA is also high but there is a systematic difference as mentioned before (Figure 3). This also holds for the sum of N leaching and runoff, while for NO_x emissions, there is a very limited correlation (see De Vries et al. 2009).

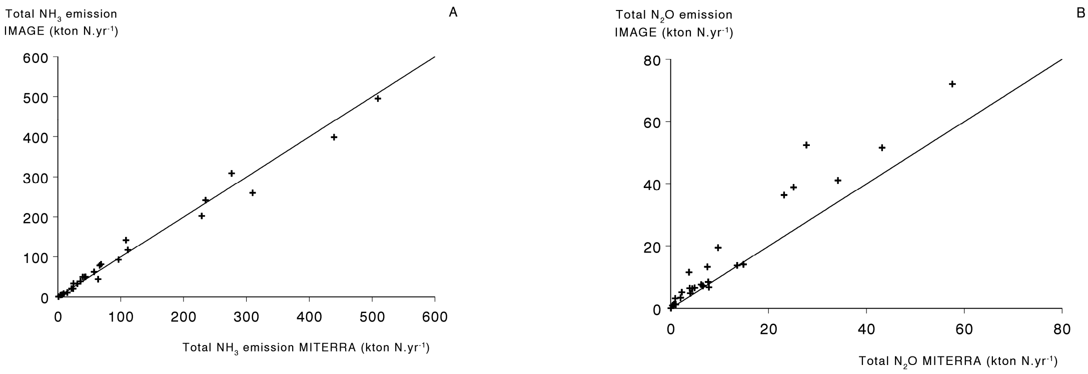

Figure 3. Comparison of total NH_3 emissions (A), N_2O emissions (B) NO_x emissions (C) and N leaching (D) by IMAGE-N and MITERRA per country for the year 2000

A map of e.g. NH_3 emissions at NUTS2 level gives again considerable variation, as compared to the country level variation by IMAGE (see De Vries et al. 2009), that will again affect the exceedance of critical loads at the European scale. For policy purposes reasons, however, the exceedance of national emission ceilings is most relevant, and here the results of IMAGE and MITERRA hardly differ (see De Vries et al. 2009), since predicted total NH_3 emissions by both modes are comparable at country level, as shown in Figure 3A.

4. DISCUSSION AND CONCLUSIONS

The results show that on a high spatial resolution (i.e. within a country when comparing INITIATOR2 and MITERRA and between countries when comparing MITERRA and IMAGE results) there are considerable variations between the model results. This implies that exceedances of critical loads for nitrogen in view of impacts on biodiversity and ground water quality differ considerably due to spatial aggregation of the data However, at the national or continental level the comparison of total estimates of N emissions and N leaching is much better. The comparison of predictions is, however, different for 2000 and 2030 related to differences in model assumptions. For example, an efficiency increase in N use in the period 2000-2030 is assumed in INITIATOR2 and IMAGE but not in MITERRA. Consequently, where the N input by animal manure for the whole of the Netherlands is quite comparable in 2000, it deviates by approximately 20% in 2030. Inversely, the estimated total NH_3, N_2O and NO_x emissions by INITIATOR2 are approximately 20-40% higher than the estimate by MITERRA in the year 2000, but emissions in the year 2030 are comparable for both models. Similarly, predicted total N input by IMAGE for EU 27 is higher in 2000 compared to MITERRA, whereas the N input is comparable in 2030.Apart from this difference in time caused by different model assumptions, the differences in model results are due to the use of basic data, such as animal numbers and crop yields, and in excretion, emission, uptake and leaching factors. In summary, results imply that spatial aggregation has a limited effect on national and continental scale emission estimates but a large effect on the exceedance of critical N loads and critical NO3 concentrations, respectively.

ACKNOWLEDGMENTS

This research has been funded by the Dutch BSIK programme Climate and Spatial Planning.

REFERENCES

Bouwman, A.F., van der Hoek, K.W., Eickhout, B., and Soenario, I. (2005a), Exploring changes in world ruminant production systems. *Agricultural Systems,* 84(2), 121-153.

Bouwman, A.F., Van Drecht, G., and Van der Hoek, K.W. (2005b), *Surface N balances and reactive N loss to the environment from intensive agricultural production systems for the period 1970-2030.* In Science in China Ser. C. Life Sciences, Vol. 48 Supp., pp. 1-13.

Bruinsma, J.A.M. (2003), *World agriculture: towards 2015/2030: An FAO perspective*. Earthscan Publications Ltd, London.

De Vries, W., Kros, J., and Oenema, O. (2001), Modeled impacts of farming practices and structural agricultural changes on nitrogen fluxes in the Netherlands. *The Scientific World*, 1(12-S2), 664-672.

De Vries, W., Kros, J., Oenema, O., and de Klein, J. (2003), Uncertainties in the fate of nitrogen II: A quantitative assessment of the uncertainties in major nitrogen fluxes in the Netherlands. *Nutrient Cycling in Agroecosystems*, 66(1), 71-102.

De Vries, W., Kros, J., Kuikman, P.J., Velthof, G.L., Voogd, J.C.H., Wieggers, H.J.J., Butterbach-Bahl, K., Denier Van Der Gon, H.A.C., and van Amstel, A.R. (2005a), Use of measurements and models to improve the national IPCC based assessments of soil emissions of nitrous oxide. *Environmental Sciences,* 2(2-3), 217-233.

De Vries, W., Kros, J., and Velthof, G. (2005b), Integrated evaluation of agricultural management on environmental quality with a decision support system. In: Zhu, Z., K. Minami and G. Xing (Eds.). *3rd International Nitrogen Conference, October 12-16, 2004*. Science Press, Nanjing. China, pp. 859-870.

De Vries, W., Kros, J., Voogd, J.C., Lesschen, J.P., Oudendag, D.A., Stehfest, E., and Bouwman, A.F. (2009), *Comparing predictions of nitrogen and green house gas fluxes in response to changes in live stock, land cover and land management using models at a national, European and global scale.* Alterra Wageningen UR, Wageningen, the Netherlands. Report 1867.

Hertel, T. (1997), *Global Trade Analysis: Modeling and Applications*. Cambridge University Press.

MNP (2006), *Integrated modelling of global environmental change. An overview of IMAGE 2.4*. Netherlands Environmental Assessment Agency (MNP), Bilthoven, The Netherlands.

Van Dobben, H.F., and van Hinsberg, A. (2008), *Overzicht van kritische depositiewaarden voor stikstof, toegepast op habitattypen en Natura 2000 gebieden.* Alterra, Wageningen. Alterra rapport 1654.

Velthof, G.L., Oudendag, D.A., Witzke, H.P., Asman, W.A.H., Klimont, Z., and Oenema, O. (2009), Integrated assessment of nitrogen emissions from agriculture in EU-27 using MITERRA-EUROPE. *Journal of Environmental Quality,* 38, 1-16.