Biogeosciences Discuss., 9, 6051–6094, 2012
www.biogeosciences-discuss.net/9/6051/2012/
doi:10.5194/bgd-9-6051-2012

Biogeosciences
Discussions

Uncertainties in model predictions of nitrogen fluxes from agro-ecosystems in Europe

J. Kros[1], G. B. M. Heuvelink[2], G. J. Reinds[1], J. P. Lesschen[1], V. Ioannidi[1], and W. de Vries[1,3]

[1]Alterra, part of Wageningen UR, P.O. Box 47, 6700 AA Wageningen, The Netherlands
[2]Land Dynamics Group, Wageningen University, P.O. Box 47, 6700 AA Wageningen, The Netherlands
[3]Environmental Systems Analysis Group, Wageningen University, P.O. Box 47, 6700 AA Wageningen, The Netherlands

Received: 26 April 2012 – Accepted: 27 April 2012 – Published: 29 May 2012

Correspondence to: J. Kros (hans.kros@wur.nl)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

To assess the responses of nitrogen and greenhouse gas emissions to pan-European changes in land cover, land management and climate, an integrated dynamic model, INTEGRATOR, has been developed. This model includes both simple process-based descriptions and empirical relationships, and uses detailed GIS-based environmental and farming data in combination with various downscaling methods. This paper analyses the propagation of uncertainties in model inputs and model parameters to outputs of INTEGRATOR, using a Monte Carlo analysis. Uncertain model inputs and parameters were represented by probability distributions, while spatial correlation in these uncertainties was taken into account by assigning correlation coefficients at various spatial scales. The uncertainty propagation was analysed for the emissions of NH_3, N_2O and NO_x and N leaching to groundwater and N surface runoff to surface water for the entire EU27 and for individual countries. Results show large uncertainties for N leaching and N runoff (relative errors of ~ 19 % for Europe as a whole), and smaller uncertainties for emission of N_2O, NH_3 and NO_x (relative errors of ~ 12 %). Uncertainties for Europe as a whole were much smaller compared to uncertainties at Country level, because errors partly cancelled out due to spatial aggregation.

1 Introduction

The nitrogen cycle is of fundamental importance in ecosystem functioning, global change and human health issues. Nitrogen provides a key control of the global carbon cycle through effects on primary production and decomposition. It is a major determinant of terrestrial and aquatic biodiversity (Dise et al., 2011). It influences particle formation and other chemical production processes in the atmosphere. It has major impacts on greenhouse gas (GHG) fluxes via nitrous oxide (N_2O) and indirectly carbon dioxide (CO_2) and methane (CH_4) (Butterbach-Bahl et al., 2011; De Vries et al., 2011a).

Several estimates have been made of European-wide land nitrogen (N) budgets, including emissions of ammonia (NH_3), nitrogen oxides (NO_x) nitrous oxide (N_2O) and di-nitrogen (N_2), and the leaching and runoff of N (mainly nitrate, NO) to ground- and surface waters (Stohl et al., 1996; Bouwman et al., 1997; Mosier et al., 1998; Freibauer, 2003; Van Drecht et al., 2003). These estimates were based on coarse or generic data, because much of the information required for a detailed assessment of N and GHG emissions from agriculture is not included in current European databases (Leip, 2004). De Vries et al. (2011b) disclosed these detailed data, which are used in the model INTEGRATOR for European-wide N and CH_4 emissions estimates. The model was developed within the framework of the European Integrated Project NitroEurope (Sutton et al., 2007). NitroEurope provided a foundation for integrated nitrogen assessment that can inform future mitigation strategies. Hence, the INTEGRATOR model is especially developed to model the response of Nr and GHG emissions due to land-use changes (De Vries et al., 2011b) and the effect of mitigation measures (Kros et al., 2011).

Until now, a systematic uncertainty assessment of all N fluxes from terrestrial systems at large regional scales is lacking almost completely. One of the few examples is from De Vries et al. (2003), who performed an uncertainty analysis of all major N flows in the Netherlands, using the INITIATOR model. This research, however, neglected the uncertainty due to spatial model inputs such as soil type and land use, which also influence the uncertainty in GHG predictions (Mosier et al., 1998; Pihlatie et al., 2004), and spatial correlations between these uncertain model inputs. Most research has been focussed on uncertainties in N_2O emissions, which have been quantified at field scale (e.g., Lehuger et al., 2009), at landscape scale (e.g., Nol et al., 2010) and at national scale (e.g., Del Grosso et al., 2010). Nol et al. (2010) performed an uncertainty propagation analysis for a Dutch fen meadow landscape using the INITIATOR model, while including uncertain spatial model inputs. They used a Monte Carlo (MC) analysis combined with a novel method for estimating and simulating continuous-numerical and categorical input variables, handling spatial and cross-correlations. Del Grosso et al. (2010) performed a nation-wide uncertainty analysis using the DAYCENT model combined with an empirically based approach to quantify uncertainties in soil N_2O emissions from croplands in the USA. Uncertainty assessments have also been done for total atmospheric emissions of NH_3, N_2O and NO_x for various countries, such as the Netherlands (Van Gijlswijk et al., 2004).

Apart from uncertainty assessments that focus on the propagation of model input uncertainty to model outputs, insight in the uncertainty of N fluxes can also be derived from model inter-comparisons. The results of INTEGRATOR have for example been thoroughly compared with the results of other European-wide N budget models, including NH_3, N_2O and NO_x emissions and the sum of N leaching and N runoff to ground- and surface water (De Vries et al., 2011c). Furthermore, Leip et al. (2011b) provided an overview of European-wide N_2O estimates based on different empirical and process-based model applications.

Until now a systematic European-wide uncertainty assessment of nitrogen fluxes has not been carried out and uncertainties mentioned in the literature vary widely. The aim of this paper is to analyse how uncertainties in model inputs and parameters propagate to model outputs, using an MC analysis while focusing on uncertainties in continuous model inputs (e.g. fertilizer use) and model parameters (e.g. excretion factors and emission fractions). We present a MC propagation analysis with INTEGRATOR at the European scale. The considered outputs are N_2O, NO_x and NH_3 emission, and N leaching to ground- and surface water for the year 2000. Uncertainties in climate and land cover, soil type and drainage status were not included. The study aimed at (i) the quantification of uncertainty of N fluxes for the entire EU27 and for individual member states (uncertainty quantification, UQ), (ii) the identification of the main sources of uncertainty for all N output variables (uncertainty analysis, UA), and (iii) the quantification of the robustness of the uncertainty assessment (robustness analysis, RA).

Title Page
Abstract Introduction
Conclusions References
Tables Figures
|◀ ▶|
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

2 Modelling N fluxes in agriculture at the European scale

INTEGRATOR has specifically been developed to assess N and GHG (N_2O, CH_4 and CO_2) emissions from all major terrestrial ecosystems in response to changes in land use, land management and climate at a high spatial resolution for the EU27. INTEGRATOR uses (i) relatively simple and transparent model calculations based on the use and adaptation of available simple model approaches, (ii) empirical relationships between model outputs and environmental variables and (iii) high-resolution spatially explicit input data.

INTEGRATOR includes various sub-models for the prediction of N (NH_3, NO_x, N_2O and N_2) emissions and N leaching from (i) housing and manure storage systems and agricultural soils, i.e. an adapted version of the MITERRA-Europe model (Velthof et al., 2009; Lesschen et al., 2011), and (ii) non-agricultural terrestrial systems, and (iii) an emission-deposition matrix for NH_3 and NO_x, based on the EMEP model (Simpson et al., 2006) to assess interactions between agricultural and non-agricultural land. This study is limited to the calculation of major N fluxes from the entire EU27 agricultural sector for the year 2000, making use of the adapted MITERRA-Europe model. An overview of the N transfer processes represented in this model is given in Fig. 1, and a summary of the used approach is presented below.

The agricultural module of INTEGRATOR calculates the total manure production at FSSNUTS level, i.e. Farm Structure Survey (FSS) regions which are either at NUTS (Nomenclature of Territorial Units for Statistics) 2 or 3 level (Leip et al., 2008), from the animal numbers and the N excretion per animal category. A division is made between excretion of animals in housing systems and grazing animals in pastures, based on data at Country level. It is assumed that all manure produced in housing and manure storage systems within a FSSNUTS region, corrected for nutrient losses (gaseous and leaching) in these storage systems, is applied within that region (no manure transport between regions). The distribution of animal manure over grassland, fodder maize and arable land, is country dependent.

Fertilizer N application is based on national fertilizer consumption rates. For each country, the mineral fertilizer is distributed over crops using weighing factors. The weighing factors are calculated from the N uptake of the crop (sum of N in harvested products and N in crop residues) and the total area of the crop. The gaseous N compounds (NH_3, N_2O, NO and N_2) escape from feces and urine during storage in manure storage systems, by grazing of free ranging animals, after application of manure and fertilizers to agricultural land, due to atmospheric deposition, nitrogen fixation and crop residue input. As in MITERRA-Europe (Velthof et al., 2009), the NH_3, N_2O and NO_x emission from housing and manure storage is derived by multiplying the number of animals and excretion rates per animal category with country-specific emission factors based on the GAINS model (Klimont and Brink, 2004). Contrary to MITERRA, which uses generic N_2O emission factors for fertilizer and animal manure application, the adapted version used in INTEGRATOR uses soil emission factors that vary with the N source (three fertilizer types, seven manure types, three crop residue types, mineralized soil organic N, biological N fixation and atmospheric deposition), manure application technique, soil type, land use and precipitation (see Lesschen and Velthof, 2009; Lesschen et al., 2011).

Losses of N from agricultural systems to ground- and surface waters accounted for in the model include: (i) leaching from stored manure to groundwater, (ii) surface runoff to surface waters, (iii) subsurface runoff to surface waters, and (iv) downward leaching to groundwater (Fig. 1). Leaching from stored manure to groundwater is calculated by multiplying the N stored by leaching fractions that depend on the storage system (liquid or solid manure), the presence of concrete floors and manure storage. Data on the distribution of the storage systems and the percentage of covered manure storage in countries are derived from RAINS. Surface runoff is calculated as a fraction of the various N inputs, using runoff fractions that depend on slope, precipitation, land cover, soil type and soil depth. The sum of N leaching and subsurface runoff from soils is derived by multiplying the N surplus with leaching fractions. The remaining fraction is assumed to be denitrification to N_2. The N surplus in soils is calculated from the total

N input, corrected for gaseous N losses and surface runoff losses directly following application, and the N removal via harvested crops. The division of total N leaching over downward leaching and subsurface runoff is derived by multiplying the total N leaching by a subsurface runoff fraction that depends on soil texture, slope and landuse, based on Keuskamp et al. (2012). Indirect emissions due to deposition of emitted NH_3 on non-agricultural soils and re-emission of N_2O from N leached to ground- and surface waters are calculated using the generic IPCC emission fraction for indirect emissions.

Three types of grasslands (intensively managed grasslands, extensively managed grasslands, and rough grazing), 30 crop types and 8 animal categories (dairy cows, other cows, pigs, laying hens, other poultry, horses, sheep and goats and fur animals) are distinguished. Data on current crop yields are based on FAOSTAT. Animal categories and numbers per NUTS2 were equal to those in the GAINS model (Klaassen et al., 2004), which in turn were equal to those in MITERRA-Europe. The animal numbers at NUTS2 were (area weighted) downscaled to the FSSNUTS regions. Data on housing systems and grazing periods are derived from GAINS. The mean country-specific N excretion per animal head is also derived from GAINS. Eventually the emissions are calculated for spatial units that consist of clusters of 1 km^2 grid cells (NCU, NitroEurope Computational Units), characterized by similar environmental and/or agronomic conditions. For the EU27 (excluding Malta and Cyprus) 35,101 NCUs were distinguished and 744 FSSNUTS regions. To avoid confusion with the EU25 in 2004, i.e. EU27 without Bulgaria and Romania, we used “EU27” to depict the analysed member states in this study.

3 Uncertainty quantification and uncertainty analysis

3.1 Overall approach

Model output uncertainty is determined by three categories of uncertainty sources: (1) model input uncertainty, (2) model structure uncertainty, and (3) model solution uncertainty. In this paper we solely focus on model input uncertainty. It was assumed that model solution uncertainty, which refers to errors caused by rounding, numerical evaluation of integrals, suboptimal optimization solutions etc. has a marginal contribution to the output uncertainty and can therefore be ignored. The uncertainties due to model structure are not easy to quantify. A possibility is by comparing results of INTEGRATOR with results from other models, which has been done by De Vries et al. (2011d).

In this study we performed both an uncertainty quantification (UQ) and uncertainty analysis (UA), focusing on the air emissions of N_2O, NO_x and NH_3, N leaching to groundwater and N runoff to surface waters from agricultural systems, using a Monte Carlo (MC) simulation approach (see e.g. Rypdal and Winiwarter, 2001). Attractive properties of the MC method are the easy implementation, the general applicability and the resulting entire probability distribution of the model output (Heuvelink, 1998). The UQ analyses how uncertainties in model inputs and model parameters propagate to the model output, while UA quantifies the contribution of individual sources of uncertainty to the output uncertainty. The application of UQ and UA involved the following steps:

1. Selection of model input parameters to be included in the uncertainty propagation analysis.
2. Parameterize the probability distribution of the uncertain inputs.
3. Generate realizations of the uncertain inputs by random drawing from their probability distributions.
4. Submit realizations to INTEGRATOR and perform MC runs.
5. Calculate summary measures of the outputs of the MC runs (e.g. mean, standard deviation, confidence limits).

For UQ we considered all selected model parameters as uncertain. For UA we selected groups of model parameters for which we estimated the uncertainty contribution.

INTEGRATOR was applied for the EU27 (excluding Malta and Cyprus). Using the NCU as the spatial support for the application of UQ/UA implies that spatial variability within an NCU was not taken into account. The size of the NCUs was highly variable with a mean area of 163 km^2 and standard deviation of 557 km^2. This was because in flat areas with uniform soil type the NCUs are larger but in mountainous areas with variable soils they are much smaller.

3.2 Assessment of the uncertainty of the INTEGRATOR model inputs

The UQ focuses on model input uncertainty, where "inputs", are defined as all information needed to run a model that is not incorporated in the model itself, including: (1) initial values (i.e. values of state variables at the start of the simulation), (2) model parameters and (3) environmental constants and variables. In the sequel these three groups are referred to as "model inputs".

Uncertainties in categorical data such as land use maps and soil maps are not included in the analysis. The modelling of uncertainty in spatially distributed categorical variables is as yet a challenging task (Heuvelink et al., 2007), which was beyond the scope of this work. In arable land, however, the uncertainty in crop rotation sequences, affecting the N input, was included. The uncertainty in model input data was limited to (i) model inputs affecting N inputs to the system, i.e. N fixation, N deposition, N manure input and N fertilizer and (ii) model inputs affecting N fluxes in and from the ecosystems. The uncertainty about N manure input was derived from uncertainties in N excretion rates and other INTEGRATOR inputs affecting the N input, including the uncertainties in animal numbers.

For each model input we defined the following statistical properties:

1. Uncertainty in terms of coefficient of variation (CV) or standard deviation (SD), distribution type (normal or lognormal), minimum (min) and maximum (max) at NCU level.

2. Spatial correlation coefficients between plots in different:

- NCUs within the same FSSNUTS region (ρ_{NCU}).
- FSSNUTS regions within the same Country (ρ_{NUTS}).
- Countries within Europe (ρ_{COUNTRY}).

3. Cross correlation for certain pairs of model inputs i and j ($\rho_{\text{cc}}(i,j)$).

In assessing the uncertainty of model inputs and their spatial correlation, we distinguished four scale levels: (i) 35,101 NCUs characterized by similar environmental and/or agronomic conditions, (ii) 744 FSSNUTS regions, (iii) 25 countries, and (iv) EU27 as a whole. An example for these spatial levels is presented for the Netherlands and surroundings in Fig. 2.

For model inputs with assumed lognormal distributions, the spatial and cross-correlations of these variables were defined at the log-transformed scale. The selected model inputs (51 in total) and their statistical properties and spatial levels are given in Table 5. Details of each aspect are further described below.

3.2.1 Values used for coefficient of variation and standard deviation

To characterize the uncertainty in model inputs, we used the CV rather than the SD, assuming that the SD is proportional to the average value of a model input. For lognormal model inputs we used the conventional approach to defined the uncertainty by the CV at the log-transformed scale (Limpert et al., 2001).

Because we have little quantitative information on the uncertainty of the used model inputs we decided to use only three levels of CVs, i.e. low (CV = 0.10), moderate (CV = 0.25) and high (CV = 0.50), with the following assignments:

- Low: used for model inputs based on accurate quality statistics for agronomic data: animal numbers, national N fertilizer inputs, N input data and crop N uptake fractions.

- High: used for guestimated model inputs, such as N_2O emission fractions from solid manure systems and N fixation for arable land and grassland.

- Moderate: used for all other model inputs.

As distribution type, we used the normal distribution as a standard, except for: (i) all N_2O and NO emission fractions, and (ii) the ratio between NO_x and N_2O emission fractions. These model inputs, with a strongly positive skew distribution, were considered lognormally distributed.

Since the information on the assigned CVs or SDs is largely based on expert judgement, we applied a robustness analysis by using three uncertainty scenarios (optimistic (O), reference (R) and pessimistic (P)). For the CVs and SDs, explicit values were assigned for each scenario (see Table 1).

In order to prevent unrealistic, i.e. physically unrealistic values, we set (i) a minimum of 0 and a maximum of 1 in case of fractions, and (ii) in other cases a physical minimum (generally 0, sometimes minus infinity) a physical maximum (generally infinity).

3.2.2 Cross-correlations

Some model inputs are correlated with other model inputs; therefore cross-correlations need to be considered. The considered cross-correlations are given in Table 2. The selected pairs of correlated inputs and assigned correlations were fully determined by expert judgement. It is clear that the *N excretion rate of cattle* (fNexf_ca) is positively correlated with the *N content of grass intensive* (ctNplmx_gi). The negative correlation between *crop yield* (Yieldopt) and the *maximum N content in the harvested crops* (ctNplmx) prevents the occurrence of unrealistic values of crop removal (in terms of N), which is calculated by the product of Yieldopt and ctNplmx. Although processes related to N_2O emission and NH_3 emission are different, we also included a correlation between the NH_3 *emission fraction from housing systems* (fNemhs_NH3) and *those for* N_2O (fNemhs_N2O) since "open" stables or non-covered manure storages leading to a high fNemhs_NH3, also result in a higher N_2O emission. Since NO and N_2O emission from housing systems are highly related processes, we assigned a high correlation between the emission fractions for these N forms.

3.2.3 Spatial correlations

A crucial aspect is to include spatial correlation. If it is not included, the uncertainty assigned independently to each NCU will vanish completely at the European scale (see e.g. Heuvelink and Pebesma, 1999). The common geostatistical procedure to include spatial correlations in uncertain inputs is to define variograms and determine for each model input the sill, nugget, range and shape of the variogram. On top of that, it is also needed to include cross-variograms for inputs that are cross-correlated. Since hardly any data are available to derive these variograms and cross-variograms, we included spatial correlation by taking a more pragmatic approach as suggested by Lesschen et al. (2007). They incorporated the degree of spatial correlation as an effect on the variance of the aggregated results.

This methodology is also attractive because (i) it can easily be applied in a situation with variable support, whereas the geostatistical procedure assumes a constant support, and (ii) it can take explicit differences between countries into account, e.g. due to legislation and/or country-specific management, whereas the geostatistical procedure cannot cope easily with administrative boundaries.

The degree of spatial correlation was defined as the correlation between inputs in (i) different NCUs within the same FSSNUTS region (ρ_{NCU}), (ii) different FSSNUTS regions within the same Country (ρ_{NUTS}), and (iii) different countries within the EU27 (ρ_{COUNTRY}). The uncertainty of inputs at NCU level was assumed to be constant and independent of the size of the NCU. The uncertainty of most inputs, however, was only available at either FSSNUTS level, e.g. animal numbers, or at national level, e.g. fertilizer amounts and model inputs on N excretion, distribution and emission. For model inputs whose uncertainty was defined at FSSNUTS or Country level, the value of ρ_{NCU}, was set to 1 (perfect correlation). Recall from Sect. 3.1 that we also assumed that there was no spatial variability within NCUs, thus correlations within an NCU were always 1.

To complete the definition of uncertainties in spatial inputs with probability distributions the next step is to specify the spatial cross-correlation coefficients between a model input at some location with another model input at another location. These were taken as:

$$\rho_{\mathrm{NCU}}(i,j) = \rho_{\mathrm{cc}}(i,j) \cdot \sqrt{\rho_{\mathrm{NCU}}(i) \cdot \rho_{\mathrm{NCU}}(j)} \quad (1)$$

$$\rho_{\mathrm{NUTS}}(i,j) = \rho_{\mathrm{cc}}(i,j) \cdot \sqrt{\rho_{\mathrm{NUTS}}(i) \cdot \rho_{\mathrm{NUTS}}(j)} \quad (2)$$

$$\rho_{\mathrm{COUNTRY}}(i,j) = \rho_{\mathrm{cc}}(i,j) \cdot \sqrt{\rho_{\mathrm{COUNTRY}}(i) \cdot \rho_{\mathrm{COUNTRY}}(j)} \quad (3)$$

where i and j refer to model inputs i and j and where $\rho_{\mathrm{cc}}(i,j)$ is the correlation coefficient between model inputs i and j for the same plot.

We limited the number of values for the spatial correlation coefficients ρ to five classes:

- Perfect: for model inputs that are not linked to the NCU but to a higher aggregation level (see above).
- High: in case of a strong spatial correlation.
- Moderate: in case of a moderate spatial correlation.
- Low: in case of a weak spatial correlation.
- None: when there is no spatial correlation.

Furthermore, as with CV and SD, we used three scenarios (optimistic (O), reference (R) and pessimistic (P)) to investigate the robustness of the assigned correlations. The values of the spatial correlation coefficients in all these cases are given in Table 3.

3.2.4 Generation of multiple model inputs

The uncertain model inputs were divided into four groups according to the four spatial scale levels of INTEGRATOR in order of increasing size: NCU, FSSNUTS, Country and EU27. Although the spatial support of INTEGRATOR model was the NCU, as mentioned earlier, not all model inputs were available for each NCU within EU27. Some model inputs were linked to the NUTS level (e.g. animal numbers), some to the Country level (e.g. N excretion rates), and some were linked to the European level (e.g. N fertilizer distribution). The generation of MC simulations was implemented in R (http://www.r-project.org/), by linking each model input to the NCU, NUTS, Country, or Generic level while taking into account the (spatial) correlations.

We generated sets of multiple model inputs randomly drawn from the input distribution functions, using the rmultnorm function from the MSBVAR library. Spatial correlation coefficient matrices were built by linking all model inputs to each of the 35,101 NCUs, while incorporating the ρ_{NCU}, ρ_{NUTS} and ρ_{COUNTRY} coefficients. At the same time the cross-correlations were taken into account.

Based on preliminary testing, we decided to perform 1000 MC runs. At this relatively high number of MC runs, the predefined distributions and their correlation structure were adequately represented. The analysis was done for the three robustness scenarios, so in total three sets of 1000 MC runs were generated.

3.3 Quantification of the uncertainty contribution

The INTEGRATOR model includes a large number of model inputs. Consequently, we quantified the contribution of model inputs to the uncertainty in model outputs for groups of model inputs affecting certain model outputs, such as N excretion, N emission, N uptake, etc. We grouped the INTEGRATOR inputs into seven groups for which we analysed the uncertainty separately (Table 4). The uncertainty contribution of each individual model input group to the total output uncertainty was estimated. This was accomplished by a MC simulation considering only the model input group uncertain for which the contribution was to be estimated. The other six groups were considered certain by using their default values as stored in the INTEGRATOR database. Therefore the model was run again in seven separate rounds, and each time only one of the seven groups was made uncertain. The uncertainty contribution was based on a comparison of the resulting output variances. The selected parameters (56) and their statistical properties and spatial levels are given in Table 5.

4 Results

4.1 Uncertainty in model outputs

4.1.1 Uncertainty at EU27 and Country level

Results at EU27 level show relatively large uncertainties for N leaching to groundwater and N runoff to surface water (relative errors of ~ 19 %), and smaller uncertainties for the emission of N_2O, NO_x and NH_3 (relative errors of ~ 12 %) (Fig. 3 and Table 6).

The larger uncertainties in N runoff to surface water and N leaching to groundwater are caused by the larger number of uncertain model inputs from which a relatively large number have a high uncertainty (CV = 0.50), whereas the uncertainties in N_2O, NO_x and NH_3 are affected by fewer uncertain model inputs with usually a lower uncertainty (CV = 0.25) (see Table 4).

The uncertainties can vary considerably among countries (Table 7). Some countries have large uncertainties for all outputs, e.g. Austria, whereas other countries have relatively high uncertainties for only one output, e.g. Denmark for $N_{\mathrm{le\ gw}}$. As shown in Table 6, the uncertainties in the average emissions and leaching fluxes at European level are clearly smaller than those at Country level. The average relative uncertainty for N_2O at Country level is 16 % (Table 7), whereas at EU27 level it decreases to 12 % (Table 6).

4.1.2 Spatial distribution of uncertainty at NCU level

Figures 4 and 5 depict the spatial variability for the EU27 at NCU level. The figures show the mean values and the relative uncertainty expressed as a CV. The results show that N fluxes are highly correlated with agricultural intensity. High fluxes occur in areas with a high agricultural intensity regarding animals, manure and fertilizer application, such as the Po Valley, Northern Germany, the Netherlands and Bretagne, and hilly regions such as the Alps in Southern Germany and Northern Spain (see e.g. Leip et al., 2011a). Compared to other outputs, NH_3 emissions show a smaller spatial variability. NH_3 emissions are caused by livestock manure production and manure application, which are provided at FSSNUTS level, whereas N_2O and NO_x fluxes and N leaching and runoff fluxes also are largely influenced by environmental conditions such as soil type and hydrological conditions, which are available at NCU level.

The variation in the uncertainty of the N_2O and NO_x emission among the NCUs is relatively small, and varies mostly between 20 and 40 %. This is larger than the uncertainty at Country level, which is generally below 20 % for both N_2O and NO (Table 7).

The spatial variation of the uncertainty of NH_3 emission at NCU level is somewhat larger and more or less distributed in two classes, either less than 20 % or between 20 and 40 %. (It seems that areas with a higher uncertainty are areas where most of the NH_3 emission is caused by grazing and manure application, such as in Spain and Ireland.)

Contrary to the gaseous emissions (Fig. 4), N runoff to surface water and especially N leaching to groundwater show a relatively large spatial variation (Fig. 5). In large parts of Central and Northern Europe, but also in parts of the UK, Ireland, France, Spain and Italy the uncertainty at NCU level of N leaching to groundwater is even larger than 100 %. For N runoff to surface water there are fewer areas with an uncertainty of more than 100 %. Large uncertainties in N leaching to groundwater are generally related to countries with a relatively large area of sandy soils, for which the uncertainty is larger compared to clay and peat soils (not shown). Moreover, the large variation in the uncertainty for leaching and runoff is mostly due to the leaching fraction and runoff fractions, which are related to soil type, texture and organic matter.

As discussed before, uncertainties increase when going from EU27 level to Country level and to NCU level, as shown in Table 8. This table shows that the uncertainty (expressed as CV) for the outputs at NCU level are ~ 3 times greater and at Country level ~ 1.35 times greater than the uncertainties at EU27 level. Results confirm that uncertainties and spatial variation in model outputs are partly cancelled out due to spatial aggregation.

4.2 Uncertainty contribution of various inputs

Uncertainty in the N_2O emission is mainly caused by uncertainty in N inputs, and crop uptake parameters (each group contribute > 20 %) and to a lesser extend to the uncertainty in housing emission (19 %), excretion (10 %) and soil emission parameters (2 %) (Fig. 6). The same is more or less true for the NO emission, but the uncertainty contribution of the soil emission parameters (5 %) is somewhat larger and the contribution of housing emission parameters is smaller (4 %). For NH_3 emissions the largest uncertainties originated from the excretion parameters (51 %), followed by the uncertainty in N inputs (20 %). As with the N_2O and NO emissions, the uncertainty contributions of the housing emission (14 %) and soil emission parameters (2 %) are rather small. The uncertainty in N leaching and N runoff is mainly caused by uncertainty in N inputs (48 % and 57 %, respectively), N leaching parameters (26 % and 17 %, respectively) and crop uptake (13 % and 16 %, respectively).

4.3 Robustness analysis

The results of the robustness analysis are presented in Table 9. Results show that the uncertainty for the EU27 expressed as CV varies from 4 to 6 % for the optimistic scenario, from 12 to 19 % for the reference scenario and from 19 to 30 % for the pessimistic scenario. The maximum values of the optimistic and pessimistic scenario vary from 12 to 55 %. The uncertainty due to the three robustness scenarios is about 50 % (CV_{rob}, Table 9).

In addition, the robustness analysis shows that the mean also depends on the scenario. The mean values increase when shifting from the optimistic to the pessimistic scenario. This is due to non-linearities and the lognormal distribution of some of the uncertain model inputs, which causes a shift towards higher values.

5 Discussion and Conclusions

This study shows large variation in uncertainties and uncertainty contributions of the different input sources across the various model outputs. Furthermore, the uncertainty in nitrogen and greenhouse gas fluxes differs per country.

The most prominent result of this study is that the uncertainty at the EU27 level is smaller than 30 % for all considered model outputs, which is rather low. The results indicate that the uncertainty in all N fluxes at EU27 level is most likely in the range of 5–30 %, including all three scenarios of the robustness analysis, and increases in the direction: $NH_{3\ em} < NO_{x\ em} < N_2O_{em} < N_{ro\ gw}$, $N_{le\ sw}$. Using the reference scenario, the uncertainty in N fluxes varies from 11 to 19 %. The relative uncertainty in model outputs is about 1.3–2 larger for the pessimistic scenario and ranges from 16 to 30 %, while the uncertainty is about 2–3.3 smaller for the optimistic scenario and ranges from 4 to 6 % only. The spatial variation in the uncertainty in the N fluxes can be large, in particular for the leaching fluxes to groundwater ($N_{le\ gw}$).

The uncertainty in INTEGRATOR outputs is also scale dependent and decreases when outputs are aggregated to a higher spatial level. Note that this result is obtained while taken spatial correlations between spatial variables into account in the regional uncertainty assessments. The neglect can either result in an overestimation of the uncertainty at EU27 level, when the correlation is assumed to be perfect or the uncertainty will vanish completely, when assuming no spatial correlation. Presumably most regional uncertainty assessment studies that do not include spatial correlation, choose for a perfect correlation thus overestimating the uncertainty.

5.1 Plausibility of the uncertainty quantification

The leaching fluxes to groundwater and runoff fluxes to surface water have the largest relative (CV) and absolute (SD) uncertainties. The NH_3 emission has the smallest relative uncertainty (CV), but the largest absolute uncertainty (SD). In general the results show that the further in the calculation chain, and the more uncertain processes are involved, the larger the uncertainty in the outputs.

Regarding N_2O emissions, earlier studies show comparable uncertainties. Nol et al. (2010) estimated an average N_2O emission at landscape scale of $20.5\,\mathrm{kg\,N_2O{-}N\,ha^{-1}\,yr^{-1}}$ and a standard deviation of $10.7\,\mathrm{kg\,N_2O{-}N\,ha^{-1}\,yr^{-1}}$, implying a relative uncertainty of 52 %. This is clearly larger than the uncertainty at the EU27 level from this study (12 %), but also larger than uncertainties from this study at NCU level (26–44 %). The reason for the larger uncertainty might be that Nol et al. (2010) also included uncertainty on detailed management information, which is lacking in our study. Due to the different nature and character of the agricultural sources, among regions and countries, as well as by the limited number and uneven spread of the measurements concerning related emission parameters, the uncertainty in local scale estimates of N_2O emissions can be rather large (Oenema et al., 2003).

At the national scale De Vries et al. (2003) estimated the uncertainty of modelled N fluxes from agriculture for the Netherlands. At national level they quantified a relative uncertainty of 24 % for N_2O, 16 % for NO and 16 % for the NH_3 emissions and 47 % for the leaching and runoff to ground- and surface water. Except for NH_3 these uncertainties are 20 to 50 % larger than found in our study for the Netherlands (see Table 7). Since De Vries et al. (2003) ignore spatial correlation, by assuming a perfect correlation between the uncertainties of their spatial units, it is likely that De Vries et al. (2003) overestimated the uncertainty in the national N fluxes.

In addition, Van Gijlswijk et al. (2004) performed an uncertainty assessment for the total atmospheric emissions of NH_3 using a Tier 1 approach applied at the national scale, thus upscaling and spatial correlation are not relevant. They found an uncertainty of 17 % in the national total NH_3 emission based on a national scale MC analysis, which is almost equal to the 16 % from this study and also to the 16 % from De Vries et al. (2003).

Another national scale study was performed for the USA by Del Grosso et al. (2010), who estimated soil N_2O emission from major commodity crops at 201 Gg N in 2007, with a 95 % confidence interval of 133–304 Gg N. This implies an uncertainty range of about −35 % to +50 % or a relative uncertainty of 42 % at the national level. The relative uncertainty tended to be larger at the regional level, particularly in regions with low emissions. The national level uncertainty for the USA is clearly larger than the 17 % from this study for the EU27 level. This might again be due to the neglect of spatial correlation, which was not considered by Del Grosso et al. (2010). However, the study from Del Grosso et al. (2010) also included model structure uncertainty which contributed 83 % to the total uncertainty. The remaining 17 % was due to uncertainty in model input data, implying a relative uncertainty of 7 % (0.17 × 42 %). This is substantially smaller than the 12 % from this study. The difference might be caused by the fact that the Del Grosso study is confined to soil emission, whereas this study also included housing emissions. Moreover, the model structure uncertainty of Del Grosso et al. (2010) also included parameter uncertainty, which was considered part of the model input uncertainty in this study.

For the EU-25, Schulze et al. (2009) estimated an uncertainty in the total N_2O emission from agriculture of 50 %, which was based on the IPCC guidelines 2006 (IPCC, 2006) while assuming a perfect spatial correlation. Based on the results of this study and other studies discussed here, it is likely that Schulze et al. (2009) overestimated the uncertainty in the N_2O emission.

The plausibility of the INTEGRATOR results was examined by De Vries et al. (2011c) by comparing the computed mean values against estimates by three other models with different complexity and data requirements. They found that the estimated overall variation at EU27 level is small for the emissions of ammonia and nitrous oxide, but large for N leaching and runoff. At smaller spatial level, however, large differences in N output fluxes were found.

The analysis presented in this work was limited to input uncertainty and ignored uncertainty due to model structure. However, model structural uncertainties can be large because these include the many assumptions and simplifications that any modelling exercise makes (see e.g. Del Grosso et al., 2010; Refsgaard et al., 2006; van der Sluijs, 2007). Possibilities for getting more insight in model structure uncertainty is to put more effort on the inter-comparison of results from independently developed models (Leip et al., 2011b) and of course by using a validation with independent observations.

5.2 Contribution of different sources to the uncertainty

The uncertainty of most of the considered outputs is mainly influenced by the uncertainty in model inputs that influence the N soil input such as the allocation of animal manure and fertilizer use. Notable is the relatively large contribution due to N uptake. Moreover, both the emission factors (for housing and soil) for N_2O and NH_3 contribute, but their contribution is not large (less than 20 %). Apparently, their contribution is overruled by other uncertainties in the N cycle. This implies that more emphasis on reliable N uptake data can seriously help reduce the uncertainty in the considered N fluxes for EU27, rather than putting more effort on improving emission factors. However, this low contribution of the emission factors is partly due to the choices made on the spatial correlation (cf. Table 5), which might be disputed. A robustness analysis for the spatial correlation factors could be recommended as well.

For N leaching, the uncertainty contribution of soil parameters is larger compared to the gaseous N emissions. Improving N leaching and runoff fractions should therefore receive more attention.

The uncertainty contribution was based on a comparison of the resulting output variances, which has some disadvantages, as the addressed uncertainty is only based on the inputs that are considered uncertain. The other inputs have fixed reference values that are not necessarily true values. In addition, the correlations between the uncertain and the fixed inputs are ignored. Although these disadvantages cannot be completely avoided, there are techniques developed to tackle the problem more thoroughly (see e.g. Jansen et al., 2000; Saltelli et al., 2004), but these techniques are computational more intensive.

5.3 Concluding remarks

The prominent result of this study is that the uncertainty in N fluxes at the EU27 level is most likely in the range of 5–30 %, which is rather low. Although an objective comparison is not straightforward, the uncertainties in N fluxes at EU27 level are generally smaller compared to results from other studies. The uncertainties and spatial variation in model outputs are partly cancelled out at higher scale levels due to spatial aggregation. Indeed, uncertainties in N fluxes at EU27 level were smaller at larger spatial aggregation levels than at smaller scales.

In this study activity data, such as N fertilizer, N manure and N uptake, were the main sources of uncertainty. It is therefore advised that more effort is put on obtaining reliable information about those model inputs, rather than putting more effort on improving the accuracy of emission factors.

As far as we know, this research is the first attempt to quantify the uncertainty in N fluxes at the EU27 level, while including a correlation between spatially variable model inputs, which is crucial in regional scale assessment. Neglecting this either causes an overestimation of the uncertainty or the uncertainty vanishes completely at the European scale, as discussed before. Unfortunately, for many of the spatially variable inputs very little information on their uncertainties was available. Therefore, the uncertainty of most of the model inputs was based on guestimates rather than real data. It is imperative that further effort is put on the gathering of spatial variable input data and quantification of associated uncertainties.

Acknowledgements. The authors gratefully acknowledge funding by the European Commission DG Research, 6th Framework Programme under the NitroEurope Integrated Project (017841). The research is co-funded by the Dutch Ministry of Agriculture, Nature and Food Quality as part of the strategic research programmes "Sustainable spatial development of ecosystems, landscapes, seas and regions" and "Climate change", carried out by Wageningen University and Research Centre. We thank Tom Hoogland and Dennis Walvoort for implementation of algorithms.

References

Bouwman, A. F., Lee, D. S., Asman, W. A. H., Dentener, F. J., van der Hoek, K. W., and Olivier, J. G. J.: A global high-resolution emission inventory for ammonia, Global Biogeochem. Cy., 11, 561–587, 1997.

Butterbach-Bahl, K., Billen, G., Boeckx, P., Garnier, J., Goddard, R., Kreuzer, M., Magnani, F., Oenema, O., Reis, S., Simpson, D., de Vries, W., and Zaehle, S.: Nitrogen as a threat to the European greenhouse balance in: The European Nitrogen Assessment, edited by: Sutton, M. A., Howard, C. M., Erisman, J. W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., and Grizzetti, B., Cambridge University Press, Chapter 19, Cambridge, UK, 434–462, 2011.

De Vries, W., Kros, J., Oenema, O., and de Klein, J.: Uncertainties in the fate of nitrogen II: a quantitative assessment of the uncertainties in major nitrogen fluxes in the Netherlands, Nutr. Cycl. Agroecosyst., 66, 71–102, doi:10.1023/A:1023354109910, 2003.

De Vries, W., Kros, J., Reinds, G. J., and Butterbach-Bahl, K.: Quantifying impacts of nitrogen use in European agriculture on global warming potential, Curr. Opin. Environ. Sustain., 3, 291–302, 2011a.

De Vries, W., Leip, A., Reinds, G. J., Kros, J., Lesschen, J. P., and Bouwman, A. F.: Comparison of land nitrogen budgets for European agriculture by various modeling approaches, Environ. Pollut., 159, 3254–3268, doi:10.1016/j.envpol.2011.03.038, 2011b.

De Vries, W., Leip, A., Reinds, G. J., Kros, J., Lesschen, J. P., Bouwman, A. F., Grizzetti, B., Bouraoui, F., Butterbach Bahl, K., Bergamaschi, P., and Winiwarter, W.: Geographic variation in nitrogen budgets in agricultural and other terrestrial ecosystems over Europe, in: The European Nitrogen Assessment, edited by: Sutton, M. A., Howard, C. M., Erisman, J. W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., and Grizzetti, B., Cambridge University Press, Chapter 15, Cambridge, UK, 317–344, 2011c.

Del Grosso, S. J., Ogle, S. M., Parton, W. J., and Breidt, F. J.: Estimating uncertainty in N_2O emissions from US cropland soils, Global Biogeochem. Cy., 24, GB1009, doi:10.1029/2009gb003544, 2010.

Dise, N. B., Ashmore, M., Belyazid, S., Bleeker, A., Bobbink, R., de Vries, W., Erisman, J. W., van den Berg, L., Spranger, T., and Stevens, C.: Nitrogen as a threat to European terrestrial biodiversity, in: The European Nitrogen Assessment, edited by: Sutton, M. A., Howard, C. M., Erisman, J. W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., and Grizzetti, B., Cambridge University Press, Chapter 20, Cambridge, UK, 463–494, 2011.

Freibauer, A.: Regionalised inventory of biogenic greenhouse gas emissions from European agriculture, Eur. J. Agron., 19, 135–160, 2003.

Heuvelink, G. B. M.: Error Propagation in Environmental Modelling with GIS, Taylor & Francis, London, 127 pp., 1998.

Heuvelink, G. B. M. and Pebesma, E. J.: Spatial aggregation and soil process modelling, Geoderma, 89, 47–65, 1999.

Heuvelink, G. B. M., Brown, J. D., and van Loon, E. E.: A probabilistic framework for representing and simulating uncertain environmental variables, Int. J. Geogr. Inf. Sci., 21, 497–513, doi:10.1080/13658810601063951, 2007.

IPCC: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, edited by: Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K., IGES, Kamiyamaguchi, Japan, 2006.

Jansen, M. J. W., Schouwenberg, E. P. A. G., Mol-Dijkstra, J. P., Kros, J., and Houweling, H.: Variance-based regression-free uncertainty analysis for groups of inputs applied to a model chain in nature conservation, in: Foresight and Precaution, edited by: Cottam, M. P., Harvey, D. W., Pape, R. P., and Tait, J., Balkema, Rotterdam, 1127–1131, 2000.

Keuskamp, J., van Drecht, G., and Bouwman, A. F.: European scale modelling of groundwater denitrification and associated N_2O production, Environ. Pollut., 165, 67–76, doi:10.1016/j.envpol.2012.02.008, 2012.

Klaassen, G., Amann, M., Berglund, C., Cofala, J., Höglund-Isaksson, L., Heyes, C., Mechler, R., Tohka, A., Schöpp, W., and Winiwarter, W.: The extension of the RAINS model to greenhouse gases, International Institute for Applied Systems AnalysisInterim Report IR-04-015, Laxenburg, Austria, 136, 2004.

Klimont, Z. and Brink, C.: Modelling of emissions of air pollutants and greenhouse gases from agricultural sources in Europe, International Institute for Applied Systems AnalysisInterim Report IR-04-048, Laxenburg, Austria, 75, 2004.

Kros, J., Frumau, K. F. A., Hensen, A., and De Vries, W.: Integrated analysis of the effects of agricultural management on nitrogen fluxes at landscape scale, Environ. Pollut., 2011.

Lehuger, S., Gabrielle, B., van Oijen, M., Makowski, D., Germon, J.-C., Morvan, T., and Hénault, C.: Bayesian calibration of the nitrous oxide emission module of an agro-ecosystem model, Agr. Ecosyst. Environ., 133, 208–222, doi:10.1016/j.agee.2009.04.022, 2009.

Leip, A.: Gap analysis of the Activity Data for the calculation of European Greenhouse Gas Emissions from Agriculture, Internal paper addressed to services of the European Commission, JRC, Ispra, Italy, 2004.

Leip, A., Marchi, G., Koeble, R., Kempen, M., Britz, W., and Li, C.: Linking an economic model for European agriculture with a mechanistic model to estimate nitrogen and carbon losses from arable soils in Europe, Biogeosciences, 5, 73–94, doi:10.5194/bg-5-73-2008, 2008.

Leip, A., Achermann, B., G, B., Bleeker, A., Bouwman, A. F., de Vries, W., Dragosits, U., Döring, U., Fernall, D., Geupel, M., Johnes, P., Le Gall, A. C., Monni, S., Nevečeřal, R., Orlandini, L., Prud'homme, M., Reuter, H. I., Simpson, D., Seufert, G., Spranger, T., Sutton, M. A., van Aardenne, J., Voß, M., and Winiwarter, W.: Integrating nitrogen fluxes at the European scale, in: The European Nitrogen Assessment, edited by: Sutton, M. A., Howard, C. M., Erisman, J. W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., and Grizzetti, B., Cambridge University Press, Chapter 16, Cambridge, UK, 345–376, 2011a.

Leip, A., Busto, M., Corazza, M., Bergamaschi, P., Koeble, R., Dechow, R., Monni, S., and de Vries, W.: Estimation of N_2O fluxes at the regional scale: data, models, challenges, Curr. Opin. Environ. Sustain., 3, 328–338, 2011b.

Lesschen, J. P., Stoorvogel, J. J., Smaling, E. M. A., Heuvelink, G. B. M., and Veldkamp, A.: A spatially explicit methodology to quantify soil nutrient balances and their uncertainties at the national level, Nutr. Cycl. Agroecosyst., 78, 111–131, doi:10.1007/s10705-006-9078-y, 2007.

Lesschen, J. P. and Velthof, G. L.: Estimation of N_2O emission factors for soils depending on environmental conditions and crop management, 5th International Symposium on Non-CO_2

Greenhouse Gases: Science, Control, Policy and Implementation, 30 June–3 July 2009, Wageningen, the Netherlands, 2009.

Lesschen, J. P., Velthof, G. L., Kros, J., and de Vries, W.: Estimation of N_2O emission factors for soils depending on environmental conditions and crop management, Environ. Pollut., 159, 3215–3222, doi:10.1016/j.envpol.2011.04.001, 2011.

Limpert, E., Stahel, W. A., and Abbt, M.: Log-normal distributions across the sciences: keys and clues, Bioscience, 51, 341–352, 2001.

Mosier, A., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S., and van Cleemput, O.: Closing the global N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle, OECD/IPCC/IEA phase II development of IPCC guidelines for national greenhouse gas inventory methodology, Nutr. Cycl. Agroecosyst., 52, 225–248, 1998.

Nol, L., Heuvelink, G. B. M., Veldkamp, A., de Vries, W., and Kros, J.: Uncertainty propagation analysis of an N_2O emission model at the plot and landscape scale, Geoderma, 159, 9–23, doi:10.1016/j.geoderma.2010.06.009, 2010.

Oenema, O., Kros, H., and de Vries, W.: Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies, Eur. J. Agron., 20, 3–16, 2003.

Pihlatie, M., Syvasalo, E., Simojoki, A., Esala, M., and Regina, K.: Contribution of nitrification and denitrification to N_2O production in peat, clay and loamy sand soils under different soil moisture conditions, Nutr. Cycl. Agroecosyst., 70, 135–141, 2004.

Refsgaard, J. C., van der Sluijs, J. P., Brown, J., and van der Keur, P.: A framework for dealing with uncertainty due to model structure error, Adv. Water Resour., 29, 1586–1597, doi:10.1016/j.advwatres.2005.11.013, 2006.

Rypdal, K. and Winiwarter, W.: Uncertainties in greenhouse gas emission inventories – evaluation, comparability and implications, Env. Sci. Pol., 4, 107–116, 2001.

Saltelli, A., S. Tarantola, F. Campolongo, and Ratto, M.: Sensitivity Analysis in Practice, A Guide to Assessing Scientific Models, Wiley, New York, 2004.

Schulze, E. D., Luyssaert, S., Ciais, P., Freibauer, A., Janssens, I. A., Soussana, J. F., Smith, P., Grace, J., Levin, I., Thiruchittampalam, B., Heimann, M., Dolman, A. J., Valentini, R., Bousquet, P., Peylin, P., Peters, W., Rödenbeck, C., Etiope, G., Vuichard, N., Wattenbach, M., Nabuurs, G. J., Poussi, Z., Nieschulze, J., and Gash, J. H.: Importance of methane and nitrous oxide for Europe's terrestrial greenhouse-gas balance, Nat. Geosci., 2, 842–850, doi:10.1038/ngeo686, 2009.

Simpson, D., Butterbach-Bahl, K., Fagerli, H., Kesik, M., Skiba, U., and Tang, S.: Deposition and emissions of reactive nitrogen over European forests: A modelling study, Atmos. Environ., 40, 5712–5726, doi:10.1016/j.atmosenv.2006.04.063, 2006.

Stehfest, E. and Bouwman, L.: N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions, Nutr. Cycl. Agroecosyst., 74, 207–228, 2006.

Stohl, A., Williams, E., Wotawa, G., and Kromp-Kolb, H.: A European inventory of soil nitric oxide emissions and the effect of these emissions on the photochemical formation of ozone, Atmos. Environ., 30, 3741–3755, doi:10.1016/1352-2310(96)00104-5, 1996.

Sutton, M. A., Nemitz, E., Erisman, J. W., Beier, C., Butterbach-Bahl, K., Cellier, P., de Vries, W., Cotrufo, F., Skiba, U., Di Marco, C., Jones, S., Laville, P., Soussana, J. F., Loubet, B., Twigg, M., Famulari, D., Whitehead, J., Gallagher, M. W., Neftel, A., Flechard, C. R., Herrmann, B., Calanca, P. L., Schjoerring, J. K., Daemmgen, U., Horvath, L., Tang, Y. S., Emmett, B. A., Tietema, A., Peñuelas, J., Kesik, M., Brueggemann, N., Pilegaard, K., Vesala, T., Campbell, C. L., Olesen, J. E., Dragosits, U., Theobald, M. R., Levy, P., Mobbs, D. C., Milne, R., Viovy, N., Vuichard, N., Smith, J. U., Smith, P., Bergamaschi, P., Fowler, D., and Reis, S.: Challenges in quantifying biosphere-atmosphere exchange of nitrogen species, Environ. Pollut., 150, 125–139, doi:10.1016/j.envpol.2007.04.014, 2007.

van der Sluijs, J. P.: Uncertainty and precaution in environmental management: insights from the UPEM conference, Environ. Modell. Softw., 22, 590–598, 2007.

Van Drecht, G., Bouwman, A. F., Knoop, J. M., Beusen, A. H. W., and Meinardi, C. R.: Global modeling of the fate of nitrogen from point and nonpoint sources in soils, groundwater, and surface water, Global Biogeochem. Cy., 17, 1115, doi:10.1029/2003GB002060, 2003.

Van Gijlswijk, R., Coenen, P., Pulles, T., and van der Sluijs, J.: Uncertainty assessment of NO_x, SO_2 and NH_3 emission in the Netherlands, TNO Environ. Energy Proc. Innov., ApeldoornR 2004/100, 102, 2004.

Velthof, G. L., Oudendag, D. A., Witzke, H. P., Asman, W. A. H., Klimont, Z., and Oenema, O.: Integrated assessment of nitrogen emission losses from agriculture in EU-27 using MITERRA-EUROPE, J. Environ. Qual., 38, 1–16, doi:10.2134/jeq2008.0108, 2009.

Table 1. Values used for CVs and SDs in three scenarios, to assess the robustness of the uncertainty analysis.

Class of CV or SD	Opt (O)	Ref (R)	Pes (P)
Low CV (L)	0.05	0.10	0.15
Moderate CV (M)	0.10	0.25	0.30
High CV (H)	0.40	0.50	0.60
SD[1]	0.5× SD	SD	1.5× SD

[1] This was only the case for the Ratio between NO_x and N_2O emission fractions.

Table 2. Model inputs for which cross-correlations are included.

Model input 1	Model input 2	ρ_{cc}
fNexf_ca	ctNplmx_gi	0.5
N excretion rate of cattle	N content of grass intensive	
Yieldopt	ctNplmx	−0.8
crop yield	maximum N content in the harvested crops	
fNemhs_NH3	fNemhs_N2O	0.5
NH_3 emission fraction from housing systems	N_2O emission fraction from housing systems	
fNemhs_N2O	fNemhs_NO	0.8
N_2O emission fraction from housing systems	NO emission fraction from housing systems	

Table 3. Values of spatial correlation coefficients for three robustness scenarios.

Class of correlation	Opt (O)	Ref (R)	Pes (P)
Perfect (P)	1.0	1.0	1.0
High (H)	0.8	0.85	0.9
Moderate (M)	0.3	0.5	0.7
Low (L)	0.1	0.2	0.3
None (N)	0.0	0.0	0.0

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 4. Model input groups for which the uncertainty contribution was quantified.

Group	Description
ANI	Animal numbers
LEX	Livestock excretion data
LEM	Livestock emission data
NIN	Nitrogen input data
NUP	Nitrogen uptake/immobilization data
SEM	Soil emission data
SLE	Leaching, runoff and climatic data

Table 5. Statistical properties and spatial levels of uncertain model inputs.

Model input	Spatial[1] Level	Group[2]	Distrib.[3]	CV[4]	SD[4]	ρ_{NCU}[5]	ρ_{NUTS}[5]	$\rho_{COUNTRY}$
Livestock excretion data								
Animal numbers, dairy cattle (Head)	NAT	ANI	N	L		P	P	M
Animal numbers, other cattle (Head)	NAT	ANI	N	L		P	P	M
Animal numbers, pigs and poultry (Head)	NAT	ANI	N	L		P	P	M
Animal numbers, other animals (Head)	NAT	ANI	N	L		P	P	M
N excretion rates, dairy cattle ($kg\,N\,head^{-1}$)	NUT	LEX	N	M		P	H	M
N excretion rates, other cattle ($kg\,N\,head^{-1}$)	NUT	LEX	N	M		P	H	M
N excretion rates, pigs and poultry ($kg\,N\,head^{-1}$)	NUT	LEX	N	M		P	H	M
N excretion rates other animals (horses, sheep and goats and other animals) ($kg\,N\,head^{-1}$)	NUT	LEX	N	M		P	L	L
Housing fractions, dairy cattle (–)	NUT	NIN	N	M		P	M	L
Housing fractions, other cattle (–)	NUT	LEX	N	M		P	M	L
Fraction of excreted amount stored as liquid manure in the housing system, cattle (–)	NUT	LEX	N	M		P	H	M
Fraction of excreted amount stored as liquid manure in the housing system, pigs and poultry (–)	NUT	LEX	N	M		P	H	M
Housing emission data								
NH_3 emission fraction from housing systems (–)	NUT	LEM	N	M		P	H	M
NH_3 emission fraction from manure storage systems ()	NUT	LEM	N	M		P	H	M
N_2O emission fraction from housing systems (liquid) (–)	NUT	LEM	L		M	P	H	M
N_2O emission fraction from manure storage systems(liquid) (–)	NUT	LEM	L		M	P	H	M
NO emission fraction from housing systems (liquid) ()	NUT	LEM	L		M	P	H	M
NO emission fraction from manure storage systems(liquid) (–)	NUT	LEM	L		M	P	H	M
N_2O emission fraction from housing systems (solid) (–)	NUT	LEM	L		H	P	H	M
N_2O emission fraction from manure storage systems(solid) (–)	NUT	LEM	L		H	P	H	M
NO emission fraction from housing systems (solid) (–)	NUT	LEM	L		H	P	H	M
NO emission fraction from manure storage systems(solid) (–)	NUT	LEM	L		H	P	H	M

Table 5. Continued.

Model input	Spatial[1] Level	Group[2]	Distrib.[3]	CV[4]	SD[4]	ρ_{NCU}[5]	ρ_{NUTS}[5]	$\rho_{COUNTRY}$
Nitrogen input data								
Allocation fraction for arable and grassland in the manure and N input assessment procedure (–)	NUT	NIN	N	M		P	M	L
Weighing factor for grassland and fodder in the manure and N input assessment procedure (–)	NUT	NIN	N	M		P	M	L
Areas of intensively and extensively managed grassland (Area_ext = Area_grass- Area_int) (–)	NUT	NIN	N	M		P	M	L
National fertilizer N inputs (t N country^{-1})	NAT	NIN	N	L		P	P	M
N deposition data (kg N ha^{-1})	NCU	NIN	N	M		M	L	L
N fixation, arable (arable + fodder) (kg N ha^{-1})	NCU	NIN	N	H		M	L	L
N fixation, grass (int +ext) (kg N ha^{-1})	NCU	NIN	N	H		M	L	L
N fixation, legume (kg N ha^{-1})	NCU	NIN	N	M		M	L	L
Availability fraction of N deposition compared to N fertilizer (–)	GEN	LEX	N	M		P	P	P
Availability fraction of organic N in animal manure (either applied or excreted by grazing) in crop residues and from soil mineralized N compared to N fertilizer (–) for arable land and grassland (–)	GEN	NIN	N	M		P	P	P
Nitrogen uptake /immobilization data								
Yields, arable (t FW ha^{-1})	NCU	NUP	N	M		H	M	L
Yields, fodder (t FW ha^{-1})	NCU	NUP	N	M		H	M	L
Yields, grass intensive (t FW ha^{-1})	NCU	NUP	N	M		H	H	M
Yields, grass extensive (t FW ha^{-1})	NCU	NUP	N	M		H	M	M
Maximum N content in the harvested crops, arable (g N (kg FW)$^{-1}$)	NCU	NUP	N	M		M	L	L
Maximum N content in the harvested crops, fodder (g N (kg FW)$^{-1}$)	NCU	NUP	N	M		M	M	L
Maximum N content in the harvested crops, grass intensive (g N (kg FW)$^{-1}$)	NCU	NUP	N	M		M	M	L
Maximum N content in the harvested crops, grass extensive (g N (kg FW)$^{-1}$)	NCU	NUP	N	M		H	H	M
N index (–)	NCU	NUP	N	M		M	L	L
Uptake fraction (–)	NCU	NUP	N	L		M	M	L
Ratio between minimum and maximum N uptake (–)	NCU	NUP	N	M		M	M	L
Soil C/N ratio (kg C (kg N)$^{-1}$)	NCU	NUP	N	M		M	M	L

Table 5. Continued.

Model input	Spatial[1] Level	Group[2]	Distrib.[3]	CV[4]	SD[4]	ρ_{NCU}[5]	ρ_{NUTS}[5]	ρ_{COUNTRY}
Soil emission data				M				
NH_3 emission factors from soil inputs for all manure types (–)	NCU	SEM	N	M		M	M	L
N_2O emission fractions from soil inputs[6] (–)	NCU	SEM	N	M		L	L	L
Ratio between NO_x and N_2O emission fractions[7] (–)	NCU	SEM	L		0.75	M	L	L
Leaching and runoff data								
N leaching fractions from the soil (–)	NCU	SLE	N	M		M	M	L
N leaching fractions from stored manure (–)	NUT	NIN	N	H		P	H	M
Surface runoff fractions (–)	NCU	SLE	N	M		M	M	L
Sub-surface runoff fractions (–)	NCU	SLE	N	M		M	M	L

[1] NCU: NCU level, NUT: FSSNUTS level, NAT: country level and GEN: EU27 level.

[2] See Table 4.

[3] N: Normal, L: Log-normal. The given statistical moments are given as log-transformed values. In case of lognormal distributions, values refer to the log transformed (e-log) value. For normal distributions we used the CV, whereas for lognormal we used the SD.

[4] See Table 1.

[5] See Table 3.

[6] We assigned the uncertainty to each applicable emission factor, related to the different N sources, i.e., deposition, fixation, animal manure, fertilizer, mineralisation and crop residues.

[7] In INTEGRATOR, NO_x soil emissions were derived as a fraction of the N_2O soil emissions. The SD of this fraction was based on Stehfest and Bouwman dataset (Stehfest and Bouwman, 2006).

Table 6. Overall uncertainty for the EU27 due to input uncertainty in the European average N_2O emission (N_2O_{em}), NO_x emission ($NO_{x\ em}$), NH_3 emission ($NH_{3\ em}$), N leaching to groundwater ($N_{le\ gw}$) and N runoff to surface water ($N_{ro\ sw}$) for the year 2000.

Model output	MEAN	SD	P05	P50	P95	CV (SD/Mean)
		kg N ha^{-1} yr^{-1}				
N_2O_{em}	1.9	0.2	1.6	1.9	2.3	0.12
$NO_{x\ em}$	1.0	0.1	0.9	1.0	1.2	0.11
$NH_{3\ em}$	15.1	1.6	12.5	15.0	17.7	0.11
$N_{le\ gw}$	6.9	1.3	5.0	6.7	9.3	0.19
$N_{ro\ sw}$	10.4	1.9	7.9	10.2	13.7	0.18

Table 7. Overall uncertainty (expressed as CV) and mean (in $\mathrm{kt\,N\,yr^{-1}}$) in the area-weighted average N_2O emission (N_2O_{em}), NO_x emission ($NO_{x\ em}$), NH_3 emission ($NH_{3\ em}$), N leaching to groundwater ($N_{le\ gw}$) and N runoff to surface water ($N_{ro\ sw}$) per country for the year 2000.

Country	N_2O		NO_x		NH_3		$N_{le\ gw}$		$N_{ro\ sw}$	
	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean
Austria	0.3	7	0.31	3	0.34	50	0.74	27	0.68	27
Belgium	0.18	9	0.16	4	0.17	72	0.32	20	0.23	39
Bulgaria	0.17	4	0.15	2	0.13	27	0.21	18	0.24	9
Czech Republic	0.15	8	0.14	4	0.15	51	0.29	41	0.27	51
Denmark	0.19	6	0.16	3	0.18	63	0.41	20	0.25	70
Estonia	0.2	1	0.22	1	0.17	5	0.27	4	0.24	6
Finland	0.19	3	0.19	1	0.14	10	0.34	13	0.32	22
France	0.14	80	0.13	43	0.13	516	0.19	203	0.19	279
Germany	0.16	48	0.14	26	0.14	529	0.28	210	0.25	376
Greece	0.21	5	0.2	3	0.16	30	0.29	38	0.28	35
Hungary	0.15	8	0.16	5	0.18	57	0.22	40	0.23	30
Ireland	0.17	25	0.16	14	0.19	86	0.26	22	0.22	38
Italy	0.14	27	0.13	17	0.14	323	0.22	159	0.19	258
Latvia	0.14	2	0.14	1	0.15	9	0.28	6	0.2	11
Lithuania	0.15	5	0.14	2	0.23	34	0.35	24	0.26	52
Luxembourg	0.26	1	0.26	0	0.18	3	0.38	2	0.36	1
Netherlands	0.19	12	0.17	7	0.16	131	0.41	31	0.26	95
Poland	0.21	24	0.16	10	0.2	244	0.35	114	0.3	247
Portugal	0.2	5	0.2	3	0.15	47	0.22	43	0.2	45
Romania	0.15	11	0.11	5	0.14	100	0.17	52	0.17	39
Slovakia	0.15	2	0.14	1	0.15	23	0.2	14	0.2	15
Slovenia	0.2	2	0.19	1	0.14	14	0.22	5	0.21	4
Spain	0.16	16	0.15	12	0.15	206	0.24	119	0.24	128
Sweden	0.19	4	0.17	1	0.16	26	0.29	16	0.25	24
UK	0.14	54	0.13	27	0.15	237	0.21	98	0.2	133
EU27[1]	0.16	199	0.15	40	0.16	2941	0.26	1341	0.23	2039

[1] Refers to the area weighted average of the CV and Mean at country level.

Table 8. Uncertainty (expressed as CV) for outputs at EU27 level, at Country and NCU levels. Shown are the area-weighted average CV of N_2O emission (N_2O_{em}), NO_x emission ($NO_{x\ em}$), NH_3 emission ($NH_{3\ em}$), N leaching to groundwater ($N_{le\ gw}$) and N runoff to surface water ($N_{ro\ sw}$) for the EU27 for the year 2000.

Level	N_2O	NO_x	NH_3	$N_{le\ gw}$	$N_{ro\ sw}$
			(CV = SD/Mean)		
EU27	0.12	0.11	0.11	0.19	0.18
Country	0.16	0.15	0.16	0.26	0.23
(0.14–0.30) [1]	(0.11–0.31)	(0.13–0.34)	(0.17–0.74)	(0.17–0.68)	
NCU	0.35	0.37	0.26	0.58	0.49
(0.26–0.44) [2]	(0.37–0.45)	(0.18–0.39)	(0.38–0.88)	(0.36–0.58)	

[1] The minimum and maximum value of the CV per country are bracketed.

[2] The minimum and maximum value of the averaged NCU value per country are bracketed.

Table 9. Effect of optimistic and pessimistic scenarios on the overall mean and CV in the EU27-average N_2O emission, NO_x emission, NH_3 emission, N_{le} groundwater and N_{ro} surface water for the year 2000.

Model output	Mean			CV			CV_{rob} [1]
	Opt	Ref	Pes	Opt	Ref	Pes	
N_2O_{emis}	1.8	1.9	2.0	0.04	0.12	0.19	0.53
$NO_{x\ emis}$	1.0	1.0	1.1	0.04	0.11	0.18	0.52
$NH_{3\ emis}$	15.0	15.1	15.4	0.04	0.11	0.16	0.48
$N_{le\ gw}$	6.2	6.9	7.5	0.06	0.19	0.30	0.54
$N_{ro\ sw}$	9.6	10.4	11.4	0.06	0.18	0.28	0.52

[1] Calculated as the CV of CVs for the three scenarios.

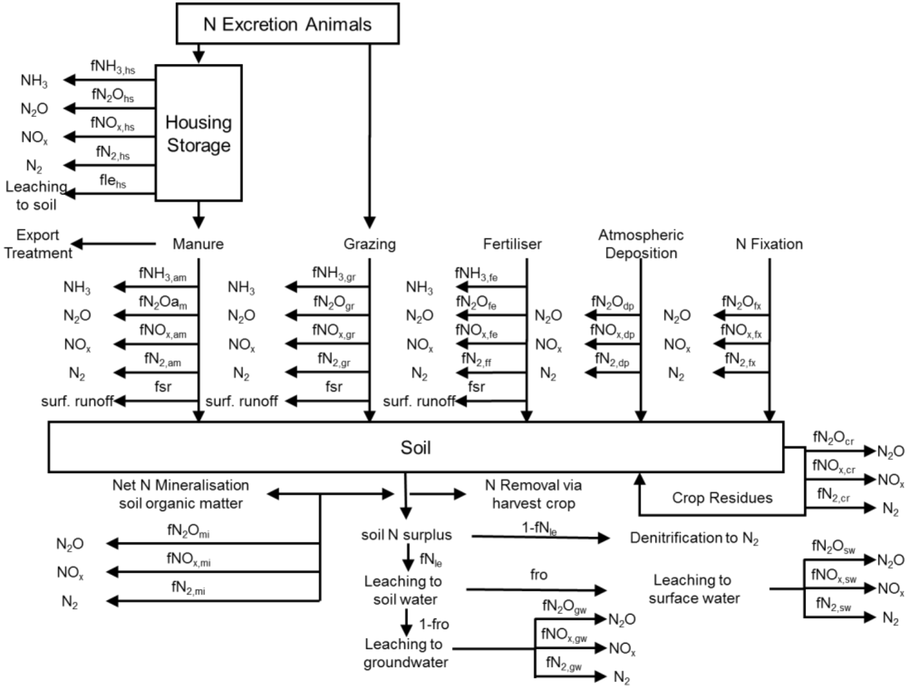

Fig. 1. N transfer processes included in the agricultural module of INTEGRATOR (the adapted MITERRA-Europe model).

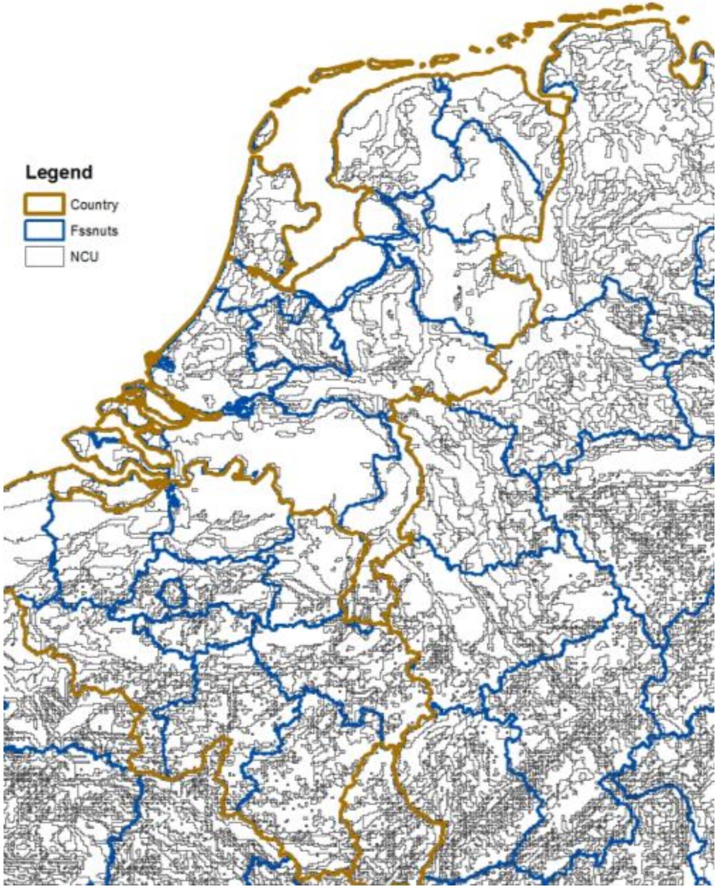

Fig. 2. Map of the Netherlands depicting the NCU, FSSNUTS, and Country spatial aggregation levels.

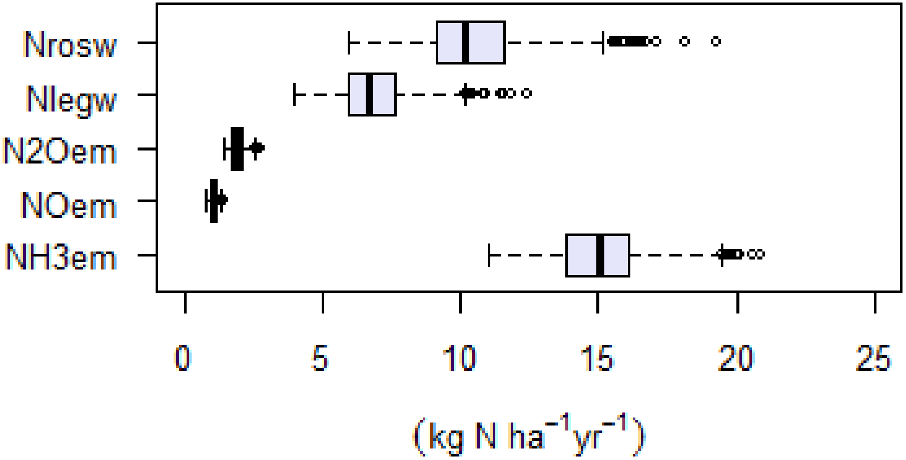

Fig. 3. Boxplots with 95 % prediction interval and outliers of the area-weighted average (per NCU) N_2O emission (N_2O_{em}), NO_x emission ($NO_{x\ em}$), NH_3 emission ($NH_{3\ em}$), N leaching to groundwater ($N_{le\ gw}$) and N runoff to surface water ($N_{ro\ sw}$) for the EU27 for the year 2000.

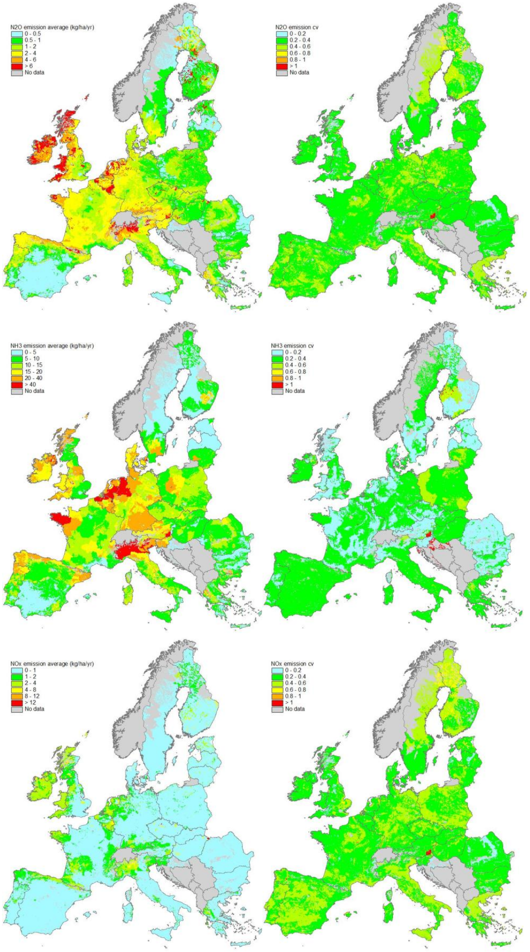

Fig. 4. The mean (left) and CV (right) of the area-weighted average N_2O, NH_3 and NO_x, emission per NCU for the year 2000.

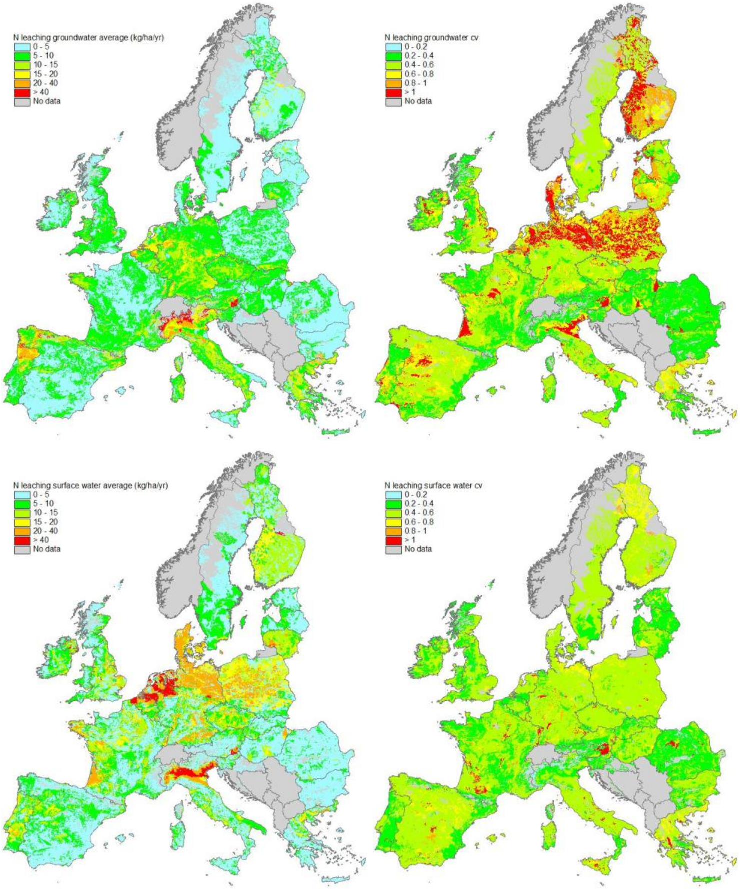

Fig. 5. The mean (left) and CV (right) of the area-weighted average N_{le} groundwater (top) and N_{ro} surface water (bottom) per NCU for the year 2000.

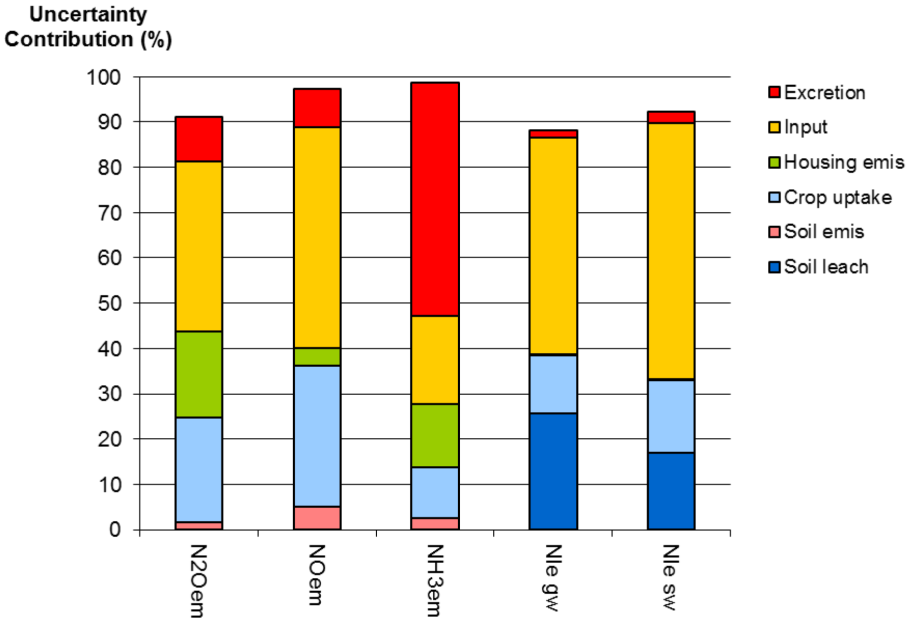

Fig. 6. Relative uncertainty contributions of individual model input groups (CV in %) to N_2O emission, NH_3 emission, N leaching to groundwater and N runoff to surface water for the EU27 for the year 2000.