4th International Workshop on Uncertainty in Atmospheric Emissions

7-9 October 2015, Krakow, Poland

PROCEEDINGS

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About the Workshop

The assessment of greenhouse gases and air pollutants (indirect GHGs) emitted to and removed from the atmosphere is high on the political and scientific agendas. Building on the UN climate process, the international community strives to address the long-term challenge of climate change collectively and comprehensively, and to take concrete and timely action that proves sustainable and robust in the future. Under the umbrella of the UN Framework Convention on Climate Change, mainly developed country parties to the Convention have, since the mid-1990s, published annual or periodic inventories of emissions and removals, and continued to do so after the Kyoto Protocol to the Convention ceased in 2012. Policymakers use these inventories to develop strategies and policies for emission reductions and to track the progress of those strategies and policies. Where formal commitments to limit emissions exist, regulatory agencies and corporations rely on emission inventories to establish compliance records.

However, as increasing international concern and cooperation aim at policy-oriented solutions to the climate change problem, a number of issues circulating around uncertainty have come to the fore, which were undervalued or left unmentioned at the time of the Kyoto Protocol but require adequate recognition under a workable and legislated successor agreement. Accounting and verification of emissions in space and time, compliance with emission reduction commitments, risk of exceeding future temperature targets, evaluating effects of mitigation versus adaptation versus intensity of induced impacts at home and elsewhere, and accounting of traded emission permits are to name but a few.

The *4th International Workshop on Uncertainty in Atmospheric Emissions* is jointly organized by the *Systems Research Institute of the Polish Academy of Sciences*, the Austrian-based *International Institute for Applied Systems Analysis*, and the *Lviv Polytechnic National University*. The 4th Uncertainty Workshop follows up and expands on the scope of the earlier Uncertainty Workshops – the *1st Workshop* in 2004 in Warsaw, Poland; the *2nd Workshop* in 2007 in Laxenburg, Austria; and the *3rd Workshop* in 2010 in Lviv, Ukraine.

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Modeling uncertainty in ammonia emissions from agriculture: Regional upscaling by Monte Carlo analysis

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Abstract

Assessment of NH_3 emissions and related uncertainties is required for both the inventory of air pollutants as well as the inventory of greenhouse gases, since N deposition leads to formation of indirect N_2O emissions. In Switzerland, the nitrogen mass-flow model Agrammon provides data on farm-specific NH_3 emissions and derives the national total by upscaling based on total livestock numbers. So far, related uncertainties relied solely on expert judgement.

We show an approach for assessing model uncertainty by a combination of Monte Carlo simulations and Gaussian error propagation. This approach allows accounting for large, asymmetric uncertainties and correlations across regional scales and therefore permits a robust assessment of aggregated uncertainties. A particular focus lies on aggregation of uncertainties in process-specific model parameters to the categories that are reported to UNECE.

The new approach permits a more detailed analysis of model uncertainties and thus a more accurate reporting of NH_3 emissions and indirect N_2O emissions.

Keywords: Monte Carlo, Ammonia emissions, Nitrogen mass-flow model, Inventory uncertainty

1. Introduction

Atmospheric nitrogen deposition currently exceeds critical loads in a large part of natural ecosystems in Switzerland [1]. Additionally, ammonia (NH_3) emissions increase the formation of secondary aerosols. Atmospheric nitrogen depositions induce substantial indirect gaseous nitrogen losses due to microbial processes in the soil, thereby leading to an increase of indirect nitrous oxide (N_2O) emissions ([2], [3]). Emissions of NH_3 and N_2O have to be reported annually by Switzerland to Convention on Long-range Transboundary Air Pollution (CLRTAP/UNECE) and United Nations Framework Convention on Climate Change (UNFCCC) in the respective inventories.

Thus, climate change mitigation and air pollution control require measures to reduce NH_3 emissions. Knowledge of related uncertainties is an important prerequisite for designing effective abatement measures.

In Switzerland, NH_3 emissions from agriculture amounted to 57.3 kt in 2013. With a share of 93.1%, agriculture is by far the largest source of Switzerland's total NH_3-emissions. Within this source, the category 3B Manure management contributes with 46% to the agricultural emissions in the year 2013 and the remaining 54% occur in category 3D Crop production and agricultural soils [4]. Thus, accurate assessment of agricultural NH_3 emissions and related uncertainties is of particular importance.

So far, considerable effort was invested in modelling agricultural ammonia emissions in Switzerland by means of the nitrogen mass flow model Agrammon, which simulates Switzerland's national NH_3 emission that are reported to UNECE and that provide a basis for calculating N_2O emissions reported to UNFCCC. Since NH_3 volatilization is highly dependent on manure management techniques as well as environmental parameters (e.g. [5], [6], [7], [8], [9]), it is crucial to take into account individual farm characteristics as much as possible. Therefore, the Agrammon model applies a detailed bottom-up approach that accounts for technical aspects in the manure handling, housing and yard characteristics as well as composition of animal feed ([10], [11], [12]). Due to the large number of model parameters, assessment of underlying model uncertainties and their aggregation to the national level is not straightforward. So far, the uncertainties reported to UNECE relied solely on expert judgement.

Commissioned by the Swiss Federal Office for the Environment, we developed a model that assesses uncertainties of Switzerland's nitrogen mass-flow model Agrammon and aggregates uncertainties in the emissions at the farm level to the national scale as required in the annual reporting to UNECE. It addresses the issue of correlated model parameters and large uncertainties by Monte Carlo simulations. Subsequently, it performs a stepwise aggregation of process specific uncertainties at the farm level to the national scale by a combination of Monte Carlo simulations and Gaussian error propagation.

2. Data and Methods

Agricultural NH_3 emissions from livestock production in Switzerland are estimated from the nitrogen mass flow model Agrammon (www.agrammon.ch, [10], [12]). In this study, we developed a model that assesses related uncertainties as part of the post-processing of the Agrammon model output. Even though only the model output is used, a brief overview of the Agrammon model is provided in section 2.2 for illustrative purposes. Subsection 2.3 describes the methodological approach implemented in the uncertainty simulation model and subsection 2.4 shows how the process specific emission factors are aggregated to the CLRTAP categories.

2.1 Data

The Agrammon model simulations are based on data from a regularly conducted survey, which covers around 3000 farms, representing around 5% of all farms in Switzerland. The survey provides detailed data on farm-specific technical parameters that are influencing emission factors, such as timing and method of manure application, type of manure storage as well as composition of animal feed. The survey is stratified according to three geographical regions (East, Central, West/South), three altitude zones (valley, hills, mountains) and five farm types. Detailed information on the survey conducted in 2010 is provided in [12]. The present study applies data from this survey. The Swiss Federal Statistical Office conducts an annual census on livestock numbers, which provides the necessary activity data for the present study. Related uncertainties are estimated to be in the order of 6% [13].

A previous study performed sensitivity analyses with respect to the technical parameters for selected farm classes and livestock categories [14]. In the present study, we used the resulting sensitivities of the simulated emissions as input to the uncertainty simulation model.

2.2 NH_3 emission modeling

The NH_3 emission model applied in Switzerland simulates emissions from livestock farming by partitioning total excretion into different processes that are relevant for simulating emissions. The model distinguishes different 24 livestock categories and 32 farm classes, which were derived from 3 geographic regions and 3 altitude zones and 5 farm types. In addition, it accounts for emissions related to use of fertilizers in crop production. It calculates farm-specific NH_3 emission from nitrogen fluxes along the manure management chain (housing, storage, grazing, manure application) based on data gathered from stratified surveys on farm and manure management (see subsection 2.1). For each stage in the manure management chain, specific emission factors are defined as a share of total soluble nitrogen (total ammoniacal N – TAN) present at a given stage. The model also allows for adjustment of these standard emission factors by a set of correction factors that take into account farm-specific manure management practices. These parameters account for differences in composition of animal feed (e.g. protein contents), manure storage systems (size, type, mixing frequency and coverage), manure application (timing, application rate and technique) as well as technical aspects of housing and yard that are influencing NH_3 emissions.

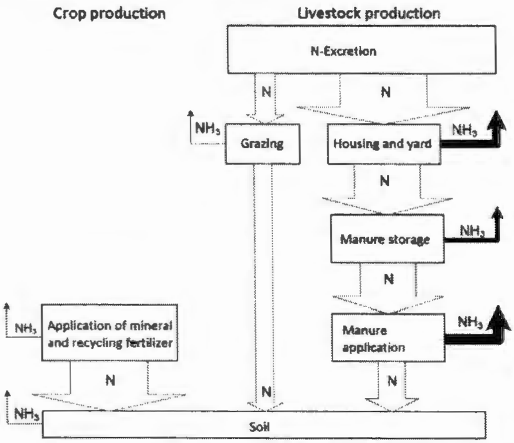

Figure 1. Model illustration: simulations account for NH_3 emissions from different stages such as housing and yard, storage of solid and liquid manure, application of manure and grazing.

Based on the survey data, the Agrammon model simulates farm-specific emissions for each livestock category (l) and each emission stage (s) in the manure management chain. Within a given farm class, a mean emission factor ($EF_{s,l}$) is derived by a linear regression of farm-specific emissions ($Em_{f,s,l}$) and corresponding activity data ($AD_{f,l}$), which consist of the livestock numbers of the surveyed farms.

$$Em_{f,s,l} = EF_{s,l}\ AD_{f,l}, \tag{1}$$

Regression analysis is performed separately for each manure management stage (s) and each livestock category (l), resulting in stage specific emission factors for each farm class ($EF_{s,l}$). Total emissions from a specific livestock category and manure management stage in a given farm class result from multiplying these mean emission factors with the total livestock numbers (AD_{tot}) of this class. The regional total of NH_3

emissions (Em_{tot}) consists of the sum of the simulated emissions over all livestock categories and manure management stages.

$$Em_{tot} = \sum_s \sum_l EF_{s,l} \, AD_{tot} \, , \tag{2}$$

While deriving the national total emissions is straightforward, assessment of the propagation of related model uncertainties is more challenging. The following section presents the simulation model that estimates related model uncertainties for each livestock category by means of Monte Carlo simulations.

2.3 Uncertainty assessment by Monte Carlo simulation

As described in the previous subsection, the nitrogen mass flow model Agrammon provides farm-specific (f) emission data ($Em_{f,s,l}$) for each livestock category (l) and manure management stage (s). Uncertainties in the mean emission factors estimated by linear regression of farm-specific emissions and corresponding livestock numbers are the result of uncertainties in the simulated emissions at the level of individual farms. Previous research shows that uncertainties in the emissions at the farm level are dependent on farm types and thus the data set exhibits a non-constant variance [14].

Linear regression models require that the errors in the data set fulfill certain assumptions, which are the statistical independence of the errors, constant variance in the errors and normality of the error distribution. Farm-specific emissions simulated by Agrammon violate in particular the second assumption since variance in the error terms is larger for farms with high emissions. In addition, there are correlations in the error terms since some of the underlying technical parameters are identical for all farm classes. Thus, confidence intervals estimated by conventional linear regression analysis are biased.

Therefore, we implemented an approach based on Monte Carlo simulations that provides a robust estimate of the standard errors and estimates confidence intervals. The uncertainty simulation model is implemented in the statistics program R. The model allows accounting for correlated error terms and non-constant variance.

When the assumption of constant variance is violated, conventional estimation of standard errors can be biased. Therefore, we adopted an approach for estimating robust standard errors in the estimated coefficients that takes into account the heteroscedasticity in the data. Instead of using the root mean square error, the standard error is estimated based on the squared residual (e_i) of each observation [15].

$$SE = \sqrt{\textstyle\sum_i w_i^2 \, e_i^2} \, , \tag{3}$$

Where w_i indicates the observation weights. Besides accounting for heteroscedasticity in the data set, the uncertainty simulation model addresses the issue of correlated error terms. In each simulation run, emission data (Em_{sim}) are generated by adding a farm-specific error term (ε), which is uncorrelated, and a correlated error term (ε_{corr}), which is identical for all data points in a given model run.

$$Em_{sim} = Em_{s,l} \, (1 + \varepsilon + \varepsilon_{corr}) \, , \tag{4}$$

From the distribution of the simulated emission data, we estimate the 95% confidence interval, from which we derive relative uncertainties for each emission factor provided by the Agrammon model.

In order to estimate the total uncertainty in NH_3 emissions in Switzerland for the national inventory, uncertainties are required at the national scale as a total for each livestock category. Thus in a next step, uncertainties in the specific emission factors have to be aggregated to the national scale and to the categories required for the reporting under the CLRTAP.

2.4 Aggregation of uncertainties

In analogy to the aggregation of emissions from specific farm classes and emission stages to the national level and to the categories required for the informative inventory report (see equation (2)), related uncertainties need to be aggregated as well. Uncertainties in emission factors of different manure management stages and across regions are correlated and therefore Gaussian error propagation is not applicable. Instead, the model aggregates uncertainties in a stepwise procedure by means of an additional Monte Carlo simulation that allows accounting for correlation in the uncertainties at the regional scale. This step results in uncertainties of stage and livestock specific emission factors at the national scale.

Since the Agrammon model distinguishes more livestock categories and manure management stages than required for the reporting under CLRTAP, further aggregation of manure management stages and livestock categories is required. Thus, in a next step the model aggregates uncertainties over all emission stages (s) and livestock categories (l) of a given CLRTAP Category (Cat). For example, category 3 B 1 b Cattle non-dairy subsumes all manure management stages (except manure application and grazing) and several livestock categories such as calves, heifers and beef cattle. At this level, uncertainties are assumed to be independent and they are aggregated by means of Gaussian error propagation.

$$U_{EF,Cat} = \sqrt{\sum_{l \in Cat} \sum_{s \in Cat} U^2_{EF,l,s}} \qquad (5)$$

In the final step, the uncertainties in the resulting emissions ($U_{Em,Cat}$) are estimated for each CLRTAP category again by means of Gaussian error propagation from the uncertainties in the corresponding emission factors ($U_{l,Cat}$) and in the livestock numbers ($U_{l,Cat}$), which is estimated to be in the order of 6% [13].

$$U_{Em,Cat} = \sqrt{{U_{l,Cat}}^2 + {U_{l,Cat}}^2} \qquad (6)$$

3. Results and Discussion

The simulations provide model uncertainties according to livestock categories as defined in the CLRTAP (see Figure 2). Relative uncertainties range between 20% and 80%. The results show largest uncertainties for poultry, goats as well as mules and asses. Emissions of cattle, swine and horses have considerably lower uncertainties.

Generally, high uncertainties are observed for those categories that are modelled by Agrammon with a low degree of regional differentiation. For example in the category turkeys, the Agrammon model does not apply any regional stratification at all, since the number of observations would not allow for a regionalization. This explains the rather large uncertainties observed for this livestock category.

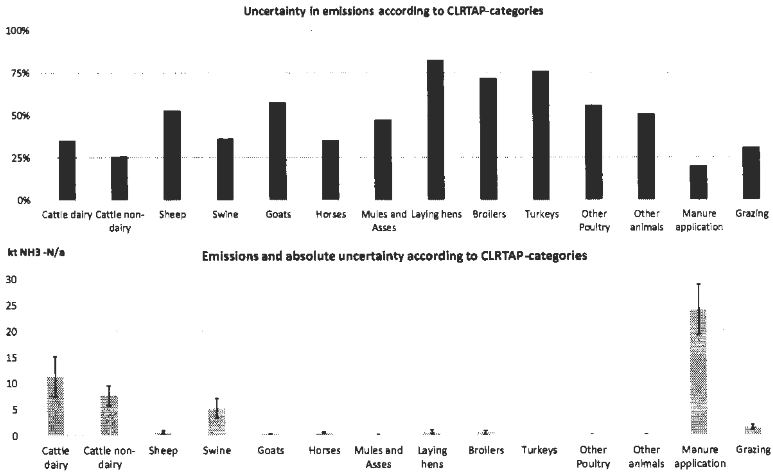

Figure 2. Upper part: Relative uncertainty in NH_3 emissions according to CLRTAP categories. Lower part: Annual emissions in kilotonnes (kt NH_3-N/a) and absolute uncertainty (as error bars).

Table 1. NH_3 emissions (Em) in kilotonnes reported in 2011 and related uncertainties in activity data (U_{AD}), emission factors (U_{EF}) and Emissions (U_{Em}) according to UNECE/CLRTAP categories.

Category UNECE/CLRTAP	Em in kt	U_{AD}	U_{EF}	U_{Em}
3B1a Manure management - Dairy cattle	11.3	6%	34%	35%
3B1b Manure management - Non-dairy cattle	7.6	6%	25%	26%
3B2 Manure management - Sheep	0.6	6%	52%	53%
3B3 Manure management - Swine	5.2	6%	36%	36%
3B4d Manure management - Goats	0.2	6%	57%	57%
3B4e Manure management - Horses	0.5	6%	34%	35%
3B4f Manure management - Mules and asses	0.1	6%	47%	47%
3B4gi Manure mangement - Laying hens	0.6	6%	82%	82%
3B4gii Manure mangement - Broilers	0.5	6%	72%	72%
3B4giii Manure mangement - Turkeys	0.0	6%	76%	76%
3B4giv Manure management - Other poultry	0.1	6%	55%	56%
3B4h Manure management - Other animals	0.0	6%	50%	50%
3Da1 Inorganic N-fertilizers (includes also urea application)	2.0	25%	50%	56%
3Da2a Animal manure applied to soils	24.1	6%	19%	20%
3Da2c Other organic fertilisers applied to soils	0.4	6%	50%	50%
3Da3 Urine and dung deposited by grazing animals	1.4	6%	30%	31%
3Db Indirect emissions from managed soils	2.8	6%	50%	50%
Total Uncertainty in agricultural NH_3-Emissions	**57.3**			**12%**

Due to the large share of dairy and non-dairy cattle and swine in the total livestock production of Switzerland, the contribution to the overall uncertainty is dominated by these categories [4]. The total uncertainty in Switzerland's ammonia emissions from livestock production amounts to about 13%. Uncertainties from dairy cattle account for 43% of the total variance, other cattle 21%, swine 20%, laying hens and broilers 9% and all other animal categories account for the remaining 7%.

In addition, the emissions from use of synthetic fertilizers and farm-level agricultural operations are estimated based on the statistics provided by the Swiss farmer's association and related uncertainties are based on expert judgement [16] (see Table 1). This results in a total uncertainty in agricultural NH_3-Emissions of around 12%.

4. Conclusions and Outlook

The new uncertainty simulation model permits a robust and standardized assessment analysis of model uncertainties, as it is able to account for large, asymmetric uncertainties and correlations among the technical model parameters and across regional scales. Thus, it allows a more accurate monitoring and reporting of NH_3 emissions, which indirectly improves also the assessment of related indirect N_2O emissions. By identifying the most uncertain sources and their contribution to the total uncertainty in NH_3 emissions, the new uncertainty simulation model can serve as a basis for further improvements in Switzerland's air pollutant and greenhouse gas inventories.

Previously reported uncertainties of Switzerland's NH_3 emissions from livestock production based on expert judgement were estimated to be in the order of about 50% in each category [16]. The results of the present study indicate that uncertainties are considerably lower for cattle and swine. Since these livestock categories contribute substantially to the total uncertainty of NH_3-emissions from livestock production, the results indicate that total uncertainty has been overestimated in previous inventories. Future research aiming at reducing existing uncertainties should therefore primarily address those livestock categories.

The updated uncertainties of the ammonia emissions were integrated into the uncertainty level and trend analyses of Switzerland's air pollutant inventory in 2013 [17] in line with the reporting obligations to UNECE under the CLRTAP [18]. For submission in 2015 [4], we modified the uncertainty simulation model such that it aggregates uncertainties to the new categories in line with the new EMEP/EEA Guidelines of 2013 [19]. Future work will focus on a refined assessment of uncertainties at the level of process specific parameters and on assessing correlations among technical parameters.

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