Review scientific underpinning of ammonia emission factors and ammonia deposition models

The Netherlands scientific community has been very active in research on ammonia emission in livestock farming and the efficiency of different mitigation measures during the last decades, as well as on ammonia fate in the atmosphere and subsequent deposition to agricultural and natural ecosystems. More particularly, a large number of experiments has been performed, especially in the 80s and 90s. Recognizing this experience, the Dutch results have widely been used in the European guidebooks for ammonia emission control, *e.g.* in the frame of the Gothenburg protocol. Moreover, The Netherlands were one of the few European countries which put a significant effort in developing atmospheric modeling of ammonia in support to decision making and policies.

1. Are the emission factors for application of manure as used in the Netherlands based on scientifically sound research?

- A much valuable initiative was to choose, after thorough assessment, a reference method which has been used for a large part of the experiments on ammonia emissions. This choice is a good compromise, certainly the best at this period, even though its application is not straightforward.
- The numerous experiments clearly showed the large variability in the emissions, largely due to the conditions of application (soil and canopy conditions, machinery) and, after application, to the influence of soil and meteorological conditions. This variability is mainly linked to the above-mentioned effects and not to uncertainties in measurements.
- Emissions factors (EF) based on TAN (total ammoniacal nitrogen) is a coarse approach, used in almost all countries for ammonia emission inventories. The NEMA approach could be a significant improvement, because it makes the links between the different steps of manure management.
- EF could be further improved by accounting for meteorological, soil and agronomic conditions, including the mitigation techniques. This should be based on both synthesis of experimental values and modeling. Using mechanistic modeling could be the way to consider the relative effects of soil, climate and agronomic conditions.
- Dutch experts contributed to a large extent to European expert groups and to different references and guidebooks for ammonia emission. Their contribution should be further supported at national level.

2. Is the scientific underpinning for the differences between broadcast application and other application techniques, such as sod injection, deep injection, and trailing shoe, sufficient to use different ammonia emission factors for these techniques?

- A large number of experiments, not only in The Netherlands, but also in Denmark, UK, Germany, France, *etc.*, clearly showed the efficiency of the above mentioned methods (hereafter mentioned as “mitigation techniques”) in comparison with the broadcast application.
- The large number of experiments provided robust averages. Despite large variability due to interactions with soil conditions and crop canopy, there is limited doubt on the

efficiency and the relevance of mitigation techniques and hence, the possibility to use different emission factors.

- Despite a large number of references under experimental farms conditions, there is a general (not only in The Netherlands) lack of references obtained under the conditions of real agricultural practice. Many technical and human factors may lead to decrease the efficiency of mitigation techniques or increase the variability.

3. What are the gaps in knowledge in the scientific underpinning of ammonia emission factors, which demands for field measurements of ammonia emission?

- Assessment of emission reduction technique under real agricultural practice (real farmers, real fields) in a range of conditions (soil, crop, meteorology, *etc.*). This would be complementary of experiment in controlled conditions or experimental farms.
- More effort should be put on developing, testing and comparing flux measurement methods. The priority should be on methods working at field scale which may require sensor development.
- Have a focus on screening the influence of soil and climate conditions under both field and lab conditions.
- Support modeling of ammonia emission.
    - At field scale to help interpreting the differences between soils, crops and meteorological conditions and the implementation of mitigation techniques. This should include accounting for canopy effects and emission from crop residues.
    - Modeling at farm scale in order to assess ammonia emission at the different steps of manure management
- Get more references on solid manures, especially due to the increase of "new" organic manures applied to farmland (compost from urban wastes, water treatment plants, *etc.*)
- Due to the multiple impacts of reactive nitrogen, it is necessary to consider also the emission of other compounds. A specific topic would be to analyze the interactions between ammonia, nitrous oxide (N_2O) and nitrate emissions.

4. Is the scientific underpinning of the Dutch modeling of the dispersion and deposition of ammonia sufficient and scientific sound?

- The Dutch modeling of the dispersion and deposition of ammonia has been developed for long with both research and operational objectives. It is based on well-know and sound concepts of dispersion modeling.
- As a whole, the Dutch modeling meets the relevant level of complexity for operational application. Recent developments on surface interactions make it better adapted to accounting for ammonia exchange in the environment.
- The Dutch model has been extensively tested, and different reports are available for describing its functioning. However, it could be more disseminated in peer-review journals. Comparisons with other dispersion/deposition models both at local scale (short-term version) and national/European scale would be much valuable.

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0. Preamble

This review has been prepared based on the synthesis and scientific articles provided by Gerard Velthof as well as my personal scientific document and previous knowledge on the processes and modeling of ammonia emission and deposition in the context of Western Europe.
This review goes through the 4 questions with several additional comment and links between questions which cannot be fully independent.

The Netherlands scientific community has been very active in research on ammonia emission during the last decades as well as on ammonia fate in the atmosphere and subsequent deposition to agricultural and natural ecosystems. More particularly, a large number of experimental references has been collected, especially in the 80s and 90s, to investigate the order of magnitude of ammonia emissions in livestock farming system and the efficiency of different mitigation measures applied mainly at field scale, but also at farm scale. Moreover, The Netherlands were one of the few European countries which put a significant effort in developing atmospheric modeling in support to decision making and policies.

5. Are the emission factors for application of manure as used in the Netherlands based on scientifically sound research?

- The Dutch scientific community has an extensive experience in measuring ammonia emission especially following field application of organic manures. A large number of experiments has been performed in The Netherlands for assessing the efficiency of mitigation measures at plot scale. Recognizing this experience, the Dutch results have widely been used in the European guidebooks for ammonia emission control, *e.g.* in the frame of the Gothenburg protocol.
- A much valuable initiative was to choose, after thorough assessment, a reference method which has been used for a large part of the agronomic experiments on ammonia emissions from the 90s. This choice looked like a good compromise between simpler methods like chambers, which suffer from modifying too much the emission conditions (wind speed, air temperature and relative humidity) and from wall effects (ammonia is a sticky gas), and more sophisticated methods like micromet methods which are complex to implement and require large homogeneous fields. Its implementation, including different measurement levels, requires human resources but this is necessary for accuracy and confidence in the results.
- New results on the influence of measurement techniques on ammonia emission factors, based on a synthesis of experiments during the last decades by Sintermann et al. (2011) gives a new insight on this question. This was made possible by both a large number of studies since the 80s and new developments of measurements methods (mainly micromet methods) after 2000. But this information was not available when the Dutch scientists

chose the IHF method as a reference. I consider that this choice was the best at this period, even though its application is not straightforward.

- The numerous experiments on mitigation measures for ammonia emissions in The Netherlands and in other UNECE countries clearly showed the large variability in the efficiency of these measures. This can be linked to measurement uncertainty, but the main reasons are linked to the influence of climate, soil and agronomic factors. Climate is certainly not the main source of variation for The Netherlands, as it is relatively homogeneous, compared to other countries (e.g. France), but meteorological conditions before or at the period of fertilizer application can have a strong influence on the emission levels (*e.g.* temperature, soil water content following rainfall) and on the efficiency of specific measures. For the soil conditions, the situation must be similar to that of most other countries, even though the expected variability is certainly less than over countries with largest variability in topography and ecoclimatic zones. The interaction between soil and meteorological conditions, which determines the soil conditions at application is an important source of variability. Considering the agronomic factors, the skills of experimentalist is indubitable, but the conditions of application linked to soil conditions or machinery can induce large uncertainty. The above considerations mean that the observed variability is, to a large extent, linked to random conditions and not to uncertainties in measurements.
- Few information is given on emission from animal housings and storage facilities, even though lots of experimental references are available from Dutch research. This is certainly due to the fact that it is not within the scope of this review. However it must be recalled that it is a similar source to field application, with also large uncertainty due mainly to infrastructure characteristics and manure management.
- Emissions factors (EF) are based on TAN (total ammoniacal nitrogen). This is a coarse approach, but is what is done is almost all countries for ammonia emission inventories. The NEMA approach could be a significant improvement, as it makes the links between the different steps of manure management, which is promoted (but often not implemented) in many countries and at UNECE level.
- There is still room for significant progress in the field of improving EF. This should be based on accounting for meteorological, soil and agronomic conditions, and should include the mitigation measures. However, this is still a field of research at European level, even though large efforts in synthesis have already been done in the recent years, *e.g.* the Alfam project.
- This should be based on both synthesis of experimental values and modeling. For the former, the Dutch scientific community has large possibilities, based on the large number of experiments performed in a range of soil, climate and agronomic conditions. But, as mentioned above, the interactions between these conditions and ammonia volatilization often makes it difficult to interpret the conditions and derive methods with a good level of confidence. Using mechanistic modeling could be the way to progress. To my opinion, it should be a research effort at European scale.
- Dutch experts have been widely involved in European expert group and contributed to a large extent to knowledge and different references and guidebooks for ammonia emission estimate. It seems to be less the case for their present contribution in the groups based on voluntary approach (e.g. Unece expert groups), even though some of them contribute at an excellent level. This might be due to funding of this contribution. Considering the excellent level of expertise of the Dutch scientific community, I would suggest to find a way to support this contribution at national level.

6. Is the scientific underpinning for the differences between broadcast application and other application techniques, such as sod injection, deep injection, and trailing shoe, sufficient to use different ammonia emission factors for these techniques?

- A large number of experiments, not only in The Netherlands, but also in Denmark, UK, Germany, France, *etc.*, clearly showed the efficiency of the above mentioned methods (hereafter mentioned as "mitigation techniques"). In most cases, this has been established using the broadcast application as a reference. The difference between this reference and the different mitigation techniques are, in most cases, clearly significant. However, the difference between the mitigation techniques is not so clear, except deep injection which decrease dramatically the ammonia emission, but is not easily applicable in all cases and is energy consuming.
- As a matter of fact, as mentioned under question 1, there is a large variability in the response of the different techniques. All application techniques which perform a surface incorporation are subject to strong interactions with soil conditions (soil water content, soil texture, stoniness, *etc.*) and canopy (crops *vs.* grass, plant and root density, *etc.*) which explain to a large extent this variability. For surface application, the efficiency depends not only on the application technique and its implementation, but also on the ability of the crop to recapture ammonia emission, and on its influence on local microclimate (especially temperature and humidity at the soil surface, where the slurry/mineral fertilizer is applied).
- Despite a large number of references under experimental farms conditions, there is a general (not only in The Netherlands) lack of reference obtained under the real conditions of agricultural practices. Many technical and human factors may lead to decrease the efficiency of mitigation techniques or increase the variability. *E.g.* under practical conditions the slurry is not applied nor incorporated homogeneously and can be still presentat the surface in some places, due to soil conditions and speed/tuning of the engine. Consequently, a strong focus should be put on assessing mitigation technique under the conditions of real agricultural practices in a range of conditions (soil, crop, meteorology, *etc.*)
- All the above arguments explain the large variability in the mitigation techniques efficiency and hence a range of values for the emission factors. However, considering average values (based on a large number of experiments) there is limited doubt on their efficiency and the relevance and hence, the possibility to use different emission factors.
- Improvements could be obtained by having in some cases a more analytical approach of the processes involved in ammonia emission reduction. For example using trailing hose or trailing shoe first aims at diminishing the contact area between the applied slurry and the atmosphere. It also decreases the transfer coefficient to the air by placing the slurry below the canopy. Moreover, the canopy significantly modifies the microclimatic condition at the soil surface (i.e. where the slurry or the mineral fertilizer is applied). Making the balance between these effects and their range of influence according to application conditions requires a modeling approach of the volatilization processes at the soil surface, including accounting for the presence of the vegetation when relevant.
- When coming to application, care must be taken to the conditions of application (soil, climate, vegetation) and to a good tuning of the equipment. This means that research must focus not only on technical issues, but also on sociological aspect (*e.g.* how a farmer or a farmer advisor put in practice a given technique, what must be done to ensure good efficiency at different levels (farmer, groups of farmers, regions, *etc.*). This point could also be added under question 3.

7. What are the gaps in knowledge in the scientific underpinning of ammonia emission factors, which demands for field measurements of ammonia emission?

Considering the review made by the Dutch group and my own views on this topic, I would suggest the following (see comments above when relevant):

- Assessment of emission reduction technique under real field conditions (real farmers, real fields). This should be complementary (not concurrent) of experiment in controlled conditions or experimental farms.
- More effort should be put on developing, testing and comparing flux measurement methods. According to the preceding point, the priority should be on methods working at field scale. This especially addresses micromet methods. It means that there is also a need to support instrumentation development and testing, as these methods require sensitive and (often) rapid sensors.
- Have a focus on the influence of soil conditions, including interactions with meteorological conditions. This should include systematic analysis (screening) using both field and lab conditions.
- Support modeling of ammonia emission from different points of view and at different scales. This would help interpreting the range off variation of emission factors.
    - At field scale (homogeneous conditions) to be able to integrate and share between the different possible effects related to the volatilization process (*e.g.* soil pH, soil water content, presence of vegetation). This would help interpreting the differences between soils, crops and meteorological conditions. This modeling should also be able to simulate the implementation of mitigation techniques.
    - Simulate plant canopy effects: ammonia recapture of ammonia emitted in the field, modification of surface conditions by the canopy, emission from litter (dead leaves and stems) and crop residues.
    - Modeling at farm scale in order to assess ammonia emission at the different steps of manure management; this looks essential as nitrogen management and related decision making is made at farm scale rather than at plot scale
    - Modeling at landscape scale: for comparing with atmospheric measurements (question 4), it is necessary to account for all processes which the atmospheric concentrations are inferred from. This includes variability in soil conditions, recapture by neighbor ecosystems, hedges or surface waters, *etc.* This type of development should include further development of measurement at this scale
- Solid manures: there are much less references on solid manures than on slurry. It would be important to get more and new references, especially due to the rapid increase of "new" organic manures applied to farmland (compost from urban wastes, water treatment plants, *etc.*)
- Due to the multiple impacts of reactive nitrogen, it is now necessary to consider not only ammonia volatilization but also the emission of other compounds. A specific topic would be to analyze the interactions between NH_3, N_2O and nitrate emissions.
- It would also be informative to analyze whether the implementation of mitigation techniques changed over the past years or decades, and could explain a trend in ammonia emission. This might be due to changes in the equipment or in the way they are managed (individual farmer *vs.* company).

8. Is the scientific underpinning of the Dutch modeling of the dispersion and deposition of ammonia sufficient and scientific sound?

- The Dutch modeling of the dispersion and deposition of ammonia has been developed for long with both research and operational objectives. It is based on well-know and sound concepts of dispersion modeling. Recent developments on surface interactions make it better adapted to accounting for ammonia exchange in the environment.
- A specificity of the work done by the Dutch groups is the adaptation of these well-known concepts to support policy making and decision at national or local level. This required making a compromise between a detailed description of processes and the possibility to use the model for operational applications. As a whole, the Dutch modeling is sound from a scientific point of view and meets the relevant level of complexity for operational application.
- An important point is the ability of this modeling to consider, with a more or less common approach both local (landscape) and national scales. As a matter of fact, landscape scale is the scale (groups of farms, small agricultural regions) where most measures are implemented. An atmospheric model can be used to test their effect under real conditions.
- The Dutch model has been extensively tested, different reports are available for describing its functioning, but it seems to have a deficit of publication in peer-review journals. This certainly could be done rapidly. I am not fully aware of what has been done in this field, but it seems that it could include more comparisons with other dispersion/deposition models both at local scale (short-term version) and national/European scale. This topic, which certainly still requires research activity, could be added to the list under question 3.