

Modelling ammonia emissions in European regional models

Summary

A prototype ammonia emission model has been developed and incorporated into the EMEP atmospheric transport model. Example simulations from this model are presented here. A model of manure management practices has also been developed but has not been fully implemented. Work on this model is ongoing, within the context of an EU integrated project.

When considering how the ammonia and manure management models might be used when fully operational, it is necessary to consider the international regulative framework for limiting ammonia emissions. Within both the CLRTD and NEC, when modelling the current and past years the emission data used must be those submitted by the parties/member states. The dynamic ammonia emission and manure management models could therefore be used in three ways:

- Individual countries could choose to use the model, using a parameterisation tailored to the local circumstances.
- EMEP could normalise the emissions predicted by the model to those submitted by the individual countries.
- The dynamic model could be used in reviewing country emissions..

The work of this project highlights the need when assessing the impact of abatement measures, to take account of the interactions between ammonia emission sources and their effect on manure management.

1.

Introduction

The emission of ammonia to the atmosphere has a number of detrimental effects. In the atmosphere, the ammonia combines with acidic compounds such as sulphur dioxide and combustion products from transport and industry, to form fine airborne particulates. These particulate, particularly those below 2.5µm in size, can enter the human lung and damage health. The ammonia and ammoniacal compounds in the atmosphere are deposited to earth's surface, either by atmospheric turbulence or by the scrubbing effect of rain and snow. If this deposition occurs to ecosystems that are naturally nutrient-poor, the nitrogen in the deposition can act as a fertiliser

(i.e. eutrophication). In aquatic ecosystems, this can contribute to algal blooms. In terrestrial ecosystems, this can encourage the growth of some plant species, to the detriment of others, causing an unwanted change in the species composition. In base-poor terrestrial ecosystems, the nitrogen that is deposited may be subsequently leached out of the soil, a process that leads to acidification of the soil.

In recognition of the acidifying and the eutrophying effect of ammonia emissions, the 1999 Gothenburg Protocol added ammonia to the list of compounds to be included in the United Nations (UN) Convention on Long-Range Transboundary Pollution (CLTRP). The Gothenburg Protocol established limits to be achieved in 2010 on the annual emission of a number of compounds, including ammonia, for all parties to the Convention. Parallel to the UN CLTRP process, the European Union (EU) implemented the National Emission Ceilings (NEC) Directive. The NEC Directive adopted the same national emission ceilings as CLTRP but included additional requirements for reporting. The NEC Directive, like CLTRP, is legally binding but unlike CLTRP only applies to EU member states and can be enforced by referral to the EU judicial system. The reduction of ammonia emissions as included in the NEC directives and the Gothenburg Protocol targets the impact of these emissions on acidification and eutrophication over European ecosystems but does not consider the effect of ammonia emissions on human health. The health impact aspect from ammonia emissions will be in focus both for the review of the NEC Directive due by 2005 and of the Gothenburg Protocol scheduled for 2006.

Ammonia emissions are the gaseous precursor of ammonium aerosol that can be transported over long distances and affect Particulate Matter (PM) levels over thousands of kilometers. Ammonium aerosol can be found in the form of ammonium sulphates and ammonium nitrate, which together contribute between 30-50% of the PM mass over Europe. Through ammonium formation, ammonia emissions from agriculture in rural areas determine to a large extent the concentrations of secondary inorganic particles in urban areas, thus affecting also the population exposure to adverse health effects. Ammonia also affects aerosol formation indirectly by enhancing the dry deposition of sulphur dioxide thereby affecting the formation and transport of sulphate aerosol.

Agricultural systems based on the production of animal products (meat, milk, fibre) are the major source of ammonia emissions within Europe, accounting for about 84% of the total emission (Vestreng, 2001). Agriculture related emissions of wind-blown dust and erosion of soils also directly contribute to emissions

of particulate matter. The proposed analysis of the processes leading to ammonia emissions from agricultural practices (animal housing, manure storage and field application of manure and fertilisers) will also facilitate the evaluation of the extent and relative importance of wind blown PM from agriculture.

Both ammonia and wind-blown dust emissions from agricultural practices are dependent on meteorological conditions. In particular, surface temperature, soil moisture and surface winds determine the extent and temporal variation of these agricultural emissions. The strong dependence of these emissions on meteorological conditions recommend to include these as a intrinsic part (subroutine) of chemical transport models, in a similar way as it is already done with biogenic VOC emissions from forest areas or wind driven sea-salt emissions.

The ammonia emissions presently included in the EMEP model are national sector totals officially reported by the countries to UNECE/EMEP and are not linked to specific meteorological variations. The reported data are yearly totals. These emissions are then distributed over the year using a function that is very similar across Europe, despite very different agricultural practices over Europe. The introduction of the new modelling emission routine is expected to improve the characterisation of ammonia emissions and the model's ability to reproduce observed ammonium concentrations.

This project described here was proposed as a feasibility study for a parameterised model for agricultural emissions. The project was also intended to contribute to the work of the Expert Panel on Agriculture under Task Force on Emission Inventories and Projections. The Expert Panel on Agriculture has been re-examining the methods recommended in the Emission Inventories Guidebook for use in the national assessment of agricultural emissions. This re-examination includes the methods that could be used to achieve a time resolution for ammonia emissions of less than one year.

2.

Ammon

The estimates of nitrogen deposition across Europe were made using models of the emission of nitrogenous compounds and of their subsequent atmospheric transport. This work is carried out by EMEP (www.emep.int), which is part of the organisation under the UN Economic Committee for Europe (UNECE) that provides the secretariat for CLTRP. The EMEP model operates uses a 50 x 50

km horizontal grid, to take account of the spatial dynamics of ammonia emission and atmospheric chemistry.

The emission ceilings in the current CLRTD and NEC Directive are absolute rather than values, based on the best information that was available at the time of the negotiation of the Gothenburg Protocol. In the intervening decade, better information and techniques have become available for assessing the atmospheric transport of ammonia. This has led to improvements in EMEP atmospheric transport model. In contrast, the modelling of ammonia emission remains relatively primitive. Parties to the Convention are required to report annual ammonia emissions but the EMEP model operates with time steps of 3 hours, so the annual emissions must be temporally disaggregated to give emission estimates at this time scale. Initially, a sine function was used, giving a peak in emission in midsummer. However, based on the results of GENEMIS project, emission data are now distributed over the year using a bimodal function, to give a seasonal emission profile with a main peak in spring and a secondary peak in autumn. The logic of this choice of distribution is that peaks in ammonia emission occur in association with manure application to fields and this generally occurs in spring and autumn. Whilst this is generally true, it will be shown later that this distribution is dependent on both climate and the local regulation of nitrogen use in agriculture. Consequently, the major aim of the current project was to provide the EMEP atmospheric transport model with an improved model of ammonia emission from animal husbandry.

Ammonia emissions from animal husbandry account for about 90% of ammonia emissions from agriculture, which in turn accounts for 80-90% of total emissions. The emissions associated with animal husbandry arise from three types of source; animal housing, manure storage and field-applied manure (including manure deposited during grazing). The manure is an ammonia source because it contains relatively high concentrations of ammonium in solution and exposes a large surface area to the atmosphere. The concentration of ammonia in the atmosphere is normally low, so air passing over the manure surface draws ammonia out of solution.

A requirement for the model was that it should be capable of incorporating the effect of measures taken to abate ammonia emissions. In addition to reducing emissions, these measures alter the temporal distribution and so in a way that varies with variations in climate. This is because such measures are often associated with one particular ammonia source e.g. animal housing, and each source has a different diurnal and seasonal emission profile. Furthermore, the rate at which ammonia is drawn out of the manure depends on the

speed and temperature of the air passing over the surface. This meant that the ammonia emission model needed to include a description of the processes controlling this interaction. A second consequence of the need to examine the effect of abatement measures arises from the nature of manure management systems. Manure passes from animal housing, through manure storage and is then applied to the field, which means these sources interact; emissions from one source reduce the pool of ammonium from which emission can occur in downstream sources. This requires the model to follow the fate of ammonium in the manure as it passes through the manure management system.

3.

Progress

The main objective of the project was the development of a prototype ammonia emission model, with a secondary objective of associating costs with the abatement measures. The main objective was achieved. The second objective was not achieved, as the partner responsible for providing the cost estimates was unable to provide the cost database due to reduced core funding.

A major issue that became apparent during the project was the lack of management data to allow testing of the model. Some progress has been made on methods to estimate the structural input data required by the model and significant progress made on a model to estimate the operational input data required.

4.

Ammonia

The following description is of a model of ammonia (NH_3) emission from a single grid cell of an atmospheric transport model such as that used by EMEP.

The seasonal ammonia emission will vary between farms with different animal types (e.g. pig, cattle, sheep) and manure handling type (e.g. liquid or solid), due to differences in N input and farming practice, and between geographic locations, due to differences in climate. The model described below is specified separately for each combination of M animal types and J manure types (slurry = 1 and solid manure = 2), and assumes that on farms with a mixture of livestock types, there is no interaction between types. Within each combination, the sources of ammonia emission modelled here are:

- Animal housing and outdoor impermeable yard areas used by livestock.
- Manure storage.

- Field-applied manure.
- Grazing animals.

The general structure of the model is shown in Fig 1.

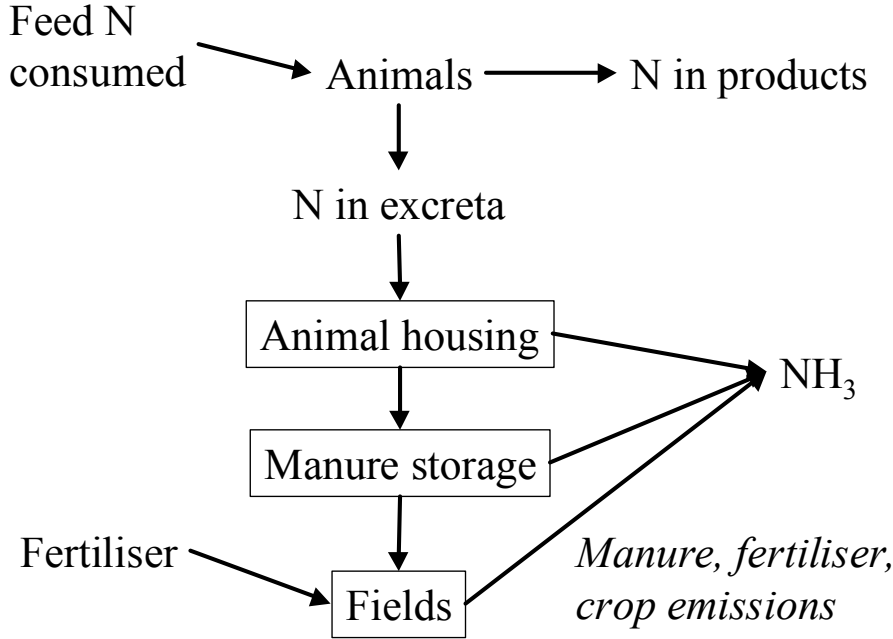


Fig 1 Schematic of the manure ammonia emission model.

Unlike Gyldenkærne et al. (2005), the emission of ammonia from crops is not modelled here. The emission from crops depends on the NH_3 concentration difference between the intra-cellular space of the leaves of the crop and the atmosphere above the crop. Since the NH_3 concentration above the crop is dependent on the emitting environment, it is more appropriate for crop emissions to be estimated within the atmospheric transport model.

The submodels describing the emission from manure in animal housing, manure storage, field-applied manure and grazing are linked. For these four submodels, the state variables are the manure organic nitrogen ($N_{i,D}$; kg), ammoniacal nitrogen ($N_{i,A}$; kg) and the volume of manure (V_i ; m^3), where the subscript $i = 1$ to 4 refers to animal housing, manure storage, field-applied manure and grazing respectively. The submodel describing emission from mineral fertilisers ($i = 5$) operates independently.

The emission (E_t ; kg d^{-1}) from any given cell of a horizontal grid at time t (d) will be:

$$E_t = \sum_{l=1}^L \sum_{j=1}^2 \sum_{i=1}^5 E_{t,l,j,i} \quad (1.1)$$

For clarity, the subscripts l and j are omitted from the subsequent sections.

4.1 *Animal excretion*

The total excretion rate by animals of a given category m within a grid cell is defined as n_F (kg d⁻¹) organic N and n_A (kg d⁻¹) ammoniacal N. Using an assumption that excretion is evenly distributed throughout the year, these values are calculated as follows:

$$n_A = \frac{S\mu n_T}{365} \quad (1.2)$$

$$n_F = \frac{S(1-\mu)n_T}{365} \quad (1.3)$$

where S is the number of animals of the relevant category that are present within the grid cell, averaged over the year, n_T is the total amount of N excreted per year by the category of animal (kg) and μ is the proportion of the manure N that is in the ammoniacal form. The dry matter (DM) in the faeces excreted (D_0 ; kg d⁻¹) is calculated as:

$$D_0 = \frac{SD_T}{365}$$

where D_T is the total annual excretion of DM.

The rate of production of water in the excreta (V_0 ; m³ d⁻¹) is given by:

$$V_0 = \frac{SY(1-D_0)}{365\gamma} \quad (1.4)$$

where Y (kg yr⁻¹) is the total annual mass of manure excreted per animal of the relevant category and γ is the density of the water (kg m⁻³).

A proportion g_t of the manure is deposited during grazing and the remaining $(1-g_t)$ is deposited in the animal housing.

4.2 *Animal housing*

The animal housing model is defined separately to describe two situations; housing that produces slurry ($m=1$) and housing that produces solid manure ($m=2$). Animal housing losses are here considered to be the losses that occur from the surface to which dung and urine are deposited, plus slurry channels (if present). If manure is stored inside the animal house, the losses from this source are considered in the storage submodel. Manure is assumed to be transferred to the storage on a daily basis, irrespective of the storage type. A schematic representation of the housing model is shown in Fig 2.

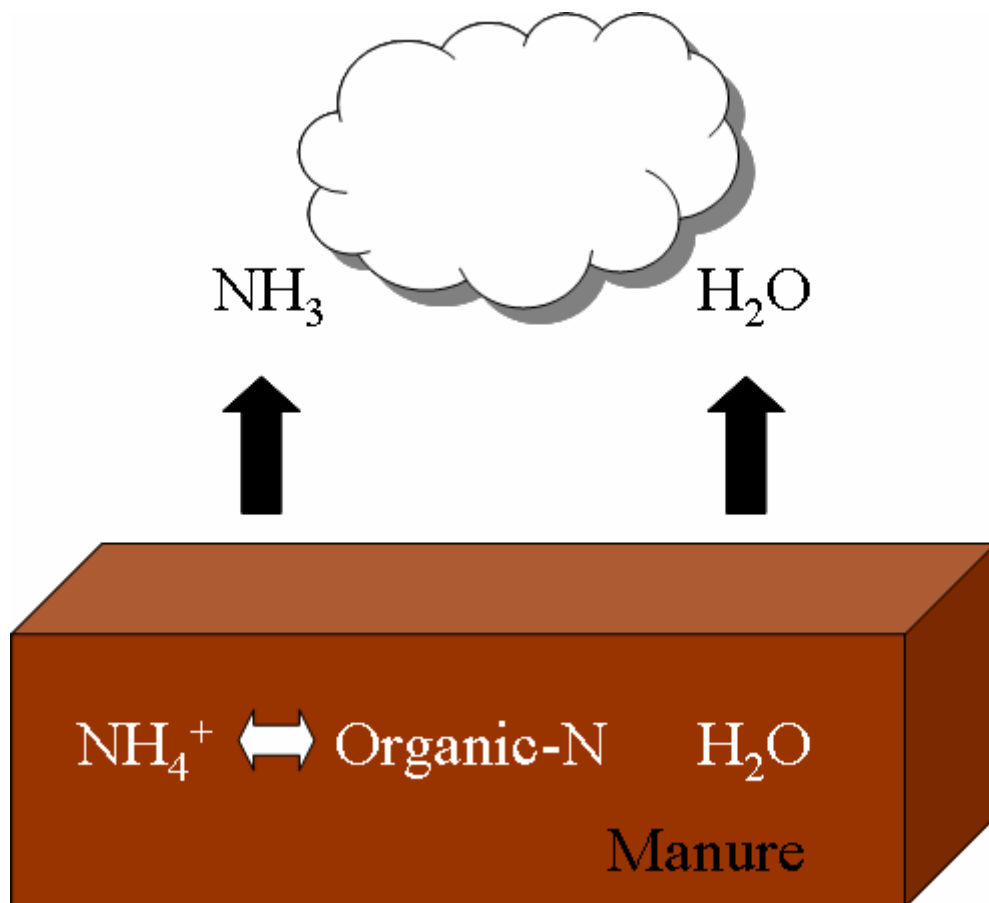


Fig 2 Schematic representation of housing and storage model.

In addition to dung and urine, nitrogen and water enters the animal housing in bedding material and water used for cleaning the floors. The N excreted in urea is assumed to be hydrolysed rapidly into ammonium. The dynamics of the volume of manure in the animal housing ($V_{1,t}$; m^3) are as follows.

$$\frac{dV_{1,t}}{dt} = (1 - g_t)(V_0 + k_{p,1}S) - k_{L,1,t} - k_{E,1,t}A_1 \quad (1.5)$$

where $k_{L,1,t}$ is the rate at which manure passes from the animal housing to the manure storage ($\text{m}^3 \text{s}^{-1}$), $k_{E,1,t}$ is the evaporation rate ($\text{m} \text{s}^{-1}$), $k_{p,1}$ is the rate of addition of other water (mainly washing water but also spilt drinking water and moisture in animal feed) ($\text{m}^3 \text{animal}^{-1} \text{s}^{-1}$) and A_1 is the area of flooring soiled by excreta (m^2).

The change in DM in the animal housing ($D_{1,t}$) is:

$$\frac{D_{1,t}}{dt} = (1 - g_t)(D_0 + \tau S) - k_{L,1,t} \frac{D_{1,t}}{V_{1,t}} \quad (1.6)$$

where τ is the mass of DM added in bedding and split feed ($\text{kg animal}^{-1} \text{s}^{-1}$).

The dynamics of the ammonium N ($N_{A,1,t}$; kg) are as follows:

$$\frac{dN_{A,1,t}}{dt} = (1 - g_t)n_A - E_{1,t} - \alpha N_{A,1,t} - k_{L,1,t} \frac{N_{A,1,t}}{V_{1,t}} \quad (1.7)$$

The terms reflect in order; the addition via animal excretion, the removal by volatilisation, the immobilisation of ammonium N in organic matter and the removal in manure sent to the manure storage. The factor α (s^{-1}) is the rate at which ammonium N is incorporated in microbial biomass or absorbed into the matrix of any bedding material added in the animal housing.

The emission ($E_{1,t}$; kg s^{-1}) is calculated as follows:

$$E_{1,t} = \frac{A_1 H_{1,t} N_{A,1,t}}{r_{1,t} V_{1,t}} \quad (1.8)$$

where $H_{1,t}$ is the Henry's Law variable and $r_{1,t}$ is the resistance to ammonia transport to the free atmosphere (s m^{-1}). $H_{1,t}$ is defined in Appendix A.

Substituting (1.8) into (1.7) gives:

$$\frac{dN_{A,1,t}}{dt} = n_A - \left(\left(\frac{A_1 H_{1,t}}{r_{1,t}} + k_{L,1,t} \right) \frac{1}{V_{1,t}} + \alpha \right) N_{A,1,t} \quad (1.9)$$

The temperature of the manure $\theta_{1,t}$ is, with one exception, equated with the inside air temperature. This is defined below. The manure pH is here considered a constant, specific to a manure and animal type.

The emitting area is identified with the area soiled with excreta and is calculated as:

$$A_1 = Sb \quad (1.10)$$

where b is a parameter constant, specific to an animal type ($\text{m}^2 \text{ animal}^{-1}$). The resistance $r_{1,t}$ represents the ineffectiveness of air flow and turbulence in transporting ammonia from the inside of the animal housing to the outside. As such, it is a function of the design of the housing and the ventilation rate. The effect of the former is described using an empirical, housing-specific parameter δ whereas the latter is modelled explicitly (see below):

$$r_1 = \frac{\delta A}{Q} \quad (1.11)$$

Where Q_t is the ventilation rate ($\text{m}^3 \text{ s}^{-1}$) and δ is a dimensionless constant. The ventilation rate in housing with both forced and unforced ventilation systems is related to outside temperature (see below).

The change in organic N in the animal housing ($N_{F,1,t}$) is:

$$\frac{dN_{F,1,t}}{dt} = (1 - g_t)(n_D + \varepsilon S) + \alpha N_{A,1,t} - k_{L,1,t} \frac{N_{F,1,t}}{V_{1,t}} \quad (1.12)$$

where ε is the mass of N added in bedding and split feed ($\text{kg animal}^{-1} \text{ s}^{-1}$).

4.1.1 *Inside temperature and ventilation rate*

The inside temperature ($\theta_{h,t}$) and ventilation rate (Q_t) of housing with forced ventilation are simulated using a simple energy model. This model assumes that generally, Q_t is managed to maintain θ_h at a target temperature (θ_{targ} ; K) and that the only factors determining the Q_t necessary to achieve this objective are the outside temperature and the sensible heat production of the animals. The ventilation rate is defined as:

$$Q_t = \frac{(1 - g_t) Sh}{C_p \rho (\theta_{\text{targ}} - \theta_t)} \quad (1.13)$$

where h is the sensible heat production of an individual animal of type M (MJ d^{-1}), ρ is the density of air (kg m^{-3}), C_p is the specific heat capacity of the air ($\text{J kg}^{-1} \text{ K}^{-1}$), which here ignores humidity effects, and θ_t is the outside air temperature (K).

For welfare and engineering reasons, the value of Q_t is assumed to be constrained between the lower and upper limits of Q_l and Q_u respectively (). If $Q_l \geq Q_t \leq Q_u$ then $\theta_{h,t}$ equates to θ_{targ} . If Q_t is predicted to fall below Q_l , $Q_t = Q_l$ and it is assumed that supplementary heating is provided to maintain $\theta_{h,t} = \theta_{\text{targ}}$. If Q_t is predicted to exceed Q_u , no mechanical cooling is assumed, $Q_t = Q_u$ and $\theta_{h,t}$ then exceeds θ_{targ} :

$$\theta_{h,t} = \frac{h}{C_p \rho Q_u} + \theta_t \quad (1.14)$$

For freely ventilated housing, it is assumed as in Gyldenkærne et al (2005) that $\theta_{h,t}$ is maintained at a constant temperature θ_{delta} above θ_t . Q_t is then a constant that is estimated from Equation (1.13), substituting θ_{delta} for $(\theta_{\text{targ}} - \theta_t)$. Also following Gyldenkærne et al (2005), it is assumed that the efforts of the farmer, combined with the ground heat flux and deposition of warm excreta, is sufficient to

ensure that θ_h never falls below freezing. Consequently, if $\theta_h + \theta_{\text{delta}} < 273\text{K}$, $\theta_{h,t} = 273\text{K}$.

The sensible heat production is calculated from the total heat production, using the methods described in CIGR (2002).

4.3 *Manure storage*

A schematic representation of the storage model is shown in Fig 2.

The dynamics of the volume of water for the manure storage are as follows:

$$\frac{dV_{2,t}}{dt} = k_{L,1,t} - k_{L,2,t} - \varphi_E k_{E,t} A_2 + \varphi_P k_{P,t} A_2 \quad (1.15)$$

where $k_{L,2,t}$ is the volume of manure removed for field application ($\text{m}^3 \text{s}^{-1}$), $k_{E,t}$ is the open water evaporation rate (m s^{-1}) and $k_{P,t}$ is the precipitation rate (m s^{-1}). To allow for the effect of covering manure storage on water losses, φ_E and φ_P are cover-specific constants that equate to the proportionate reduction of open water evaporation and precipitation. It is assumed that the storage is sufficiently watertight that infiltration into the soil is insignificant.

The dynamics of the DM in storage are:

$$\frac{dD_{2,t}}{dt} = k_{L,1,t} \frac{D_{1,t}}{V_{1,t}} - \left(0.4\beta + \frac{k_{L,2,t}}{V_{2,t}} \right) D_{2,t}$$

where β is the rate of decomposition of DM (s^{-1}) and it is assumed that about 40% of the decomposed DM is C that is emitted as CO_2 .

The dynamics of the ammonium N for the manure storage are as follows:

$$\frac{dN_{A,2,t}}{dt} = k_{L,1,t} \frac{N_{A,1,t}}{V_{1,t}} + \beta N_{D,2,t} - E_{2,t} - \left(\sigma + \frac{k_{L,2,t}}{V_{2,t}} \right) N_{A,2,t} \quad (1.16)$$

where σ is the rate at which ammonium N is removed by nitrification (s^{-1}). The terms reflect in order; the addition from animal housing, the input due to the mineralization of organic N, the removal

by volatilisation, the removal of ammonium via nitrification and the removal in manure removed for field application. It is assumed here that there is no accumulation of N as nitrate; all nitrate N is emitted as NO, N₂O or N₂. For simplicity, the decomposition rate of protein is assumed to be the same as for DM.

The emission is calculated as follows:

$$E_{2,t} = \frac{A_2 H_{2,t} N_{A,2,t}}{r_{2,t} V_{2,t}} \quad (1.17)$$

where $H_{2,t}$ is calculated as described in Appendix A, using the manure pH and outside air temperature. A_2 is the total area of the manure storage (m²).

Substituting (1.17) into (1.16) gives:

$$\frac{dN_{A,2,t}}{dt} = k_{L,1,t} \frac{N_{A,1,t}}{V_{1,t}} + \beta N_{D,2,t} - \left(\sigma + \left(\frac{A_{2,t}}{H_{2,t} r_{2,t}} + k_{L,2,t} \right) \frac{1}{V_{2,t}} \right) N_{A,2,t} \quad (1.18)$$

A_2 is calculated assuming a constant maximum storage depth (d ; m):

$$A_2 = \frac{FSY}{d\gamma} \quad (1.19)$$

where F is the capacity of the manure store, expressed as the number of days manure production, a model input. For liquid manure and solid manures stored within the animal housing, this is not unrealistic. For solid manure stored externally, the assumption is less valid but is used here for convenience.

For the calculation of ammonia emission from liquid manure and from non-composting solid manure, the manure temperature is equated to the air temperature. In composting manure, the emitting surface lies within the manure stack and the temperature here is largely independent of the air temperature. In this case, the temperature is assumed to be a constant (θ_c), which is set at a value that typical of composting manure. The manure pH is a slurry-specific parameter. The transport resistance for liquid manure and

for non-composting solid manure is calculated as described in Olesen and Sommer (). $r_{2,t}$ is thus the sum of a cover resistance (r_c ; s m^{-1}), which is constant for a particular type of tank or stack cover, and an aerodynamic resistance ($r_{a,2,t}$; s m^{-1}), which varies according to the meteorological conditions. For composting manure, $r_{2,t}$ is a constant parameter.

The denitrification constant (β) is storage-specific parameter. The manure removal rate ($k_{L,2,t}$) is described below.

4.4 *Field application*

Whereas the area that can emit NH_3 in animal housing and manure storage remains constant with time, the emitting area resulting from the field application of manure varies with time. The area is increased by farmers applying manure to new fields and is decreased when the applied manure dries out, either by evaporation or infiltration into the soil. Wishing to avoid the simulation of individual fields, the emitting area is modelled as though it were a tank that can expand and contract horizontally. When considering a single manure application, the mechanism for increasing the area is conceptually straightforward; the tank has an area and depth equal to that of the applied manure. The reduction in the area of the tank is conceptually more complex, since it must simulate the reduction in the emitting area that occurs through both ploughing and drying. Ploughing is simulated by introducing a rate constant representing the proportion of the current emitting area that is ploughed in per unit time. For drying, the mechanism adopted is to introduce a parameter constant that represents the DM content (ξ ; $\text{kg DM (fresh manure kg)}^{-1}$) above which any subsequent net loss of water (evaporation + infiltration > water in newly added manure) is assumed to result in a decrease in the emitting area.

A schematic representation of the field model is shown in Fig 3.

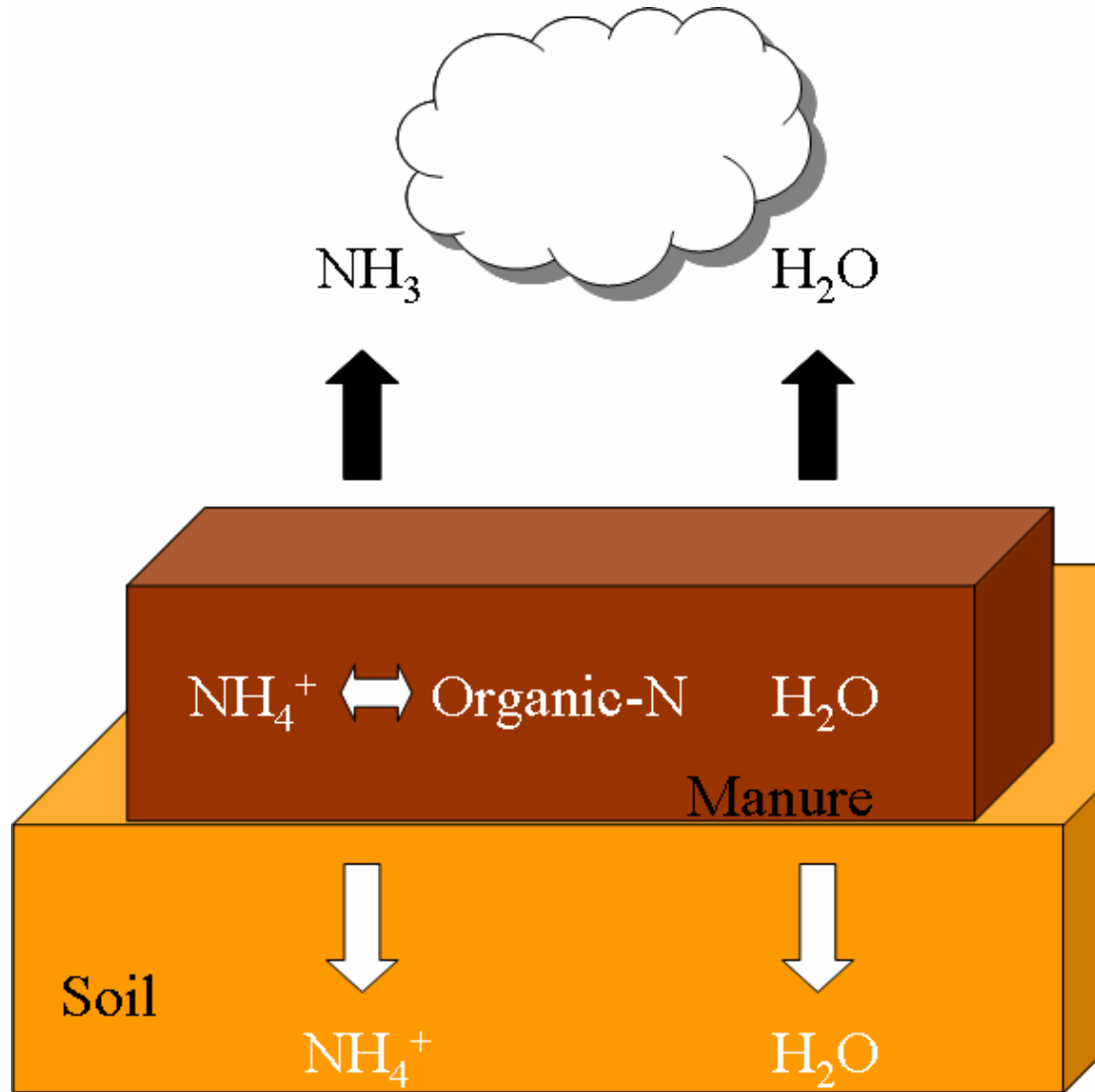


Fig 3 A schematic of the field model.

The dynamics of the volume of water for field application are as follows:

$$\frac{dV_{3,t}}{dt} = \eta k_{L,2,t} - (k_{E,3,t} - k_{P,3,t} + k_{I,t}) A_{3,t} - k_B V_{3,t} \quad (1.20)$$

where η is the proportion of $k_{L,2,t}$ that is buried at the time of application (e.g. by injection), $k_{E,3,t}$ is the evaporation rate (m s^{-1}), $k_{P,3,t}$ is the rate of precipitation (m s^{-1}), $k_{I,t}$ is the infiltration rate (m s^{-1}) and k_B is the rate at which manure is buried (e.g. by ploughing) (s^{-1}).

The DM in the manure is assumed to remain on the surface of the field (DM in the liquid phase of the manure is ignored here), unless ploughed. The dynamics of the emitting area are then:

If $\frac{D_{3,t}}{\gamma V_{3,t} + D_{3,t}} < \xi$ then

$$\frac{dD_{3,t}}{dt} = \eta k_{L,2,t} \frac{D_{2,t}}{V_{2,t}} - k_B D_{3,t}$$

Else

$$\frac{dD_{3,t}}{dt} = \eta k_{L,2,t} \frac{D_{2,t}}{V_{2,t}} + \frac{\gamma \xi}{1 - \xi} \frac{dV_{3,t}}{dt} - k_B D_{3,t}$$

The dynamics of the ammonium N for the field application are as follows:

$$\frac{dN_{A,3,t}}{dt} = \eta k_{L,2,t} \frac{N_{A,2,t}}{V_{2,t}} - E_{3,t} - \left(\frac{k_{I,t} A_{3,t}}{V_{3,t}} + k_B \right) N_{A,3,t} \quad (1.21)$$

Ammonia emission from all manure types after field application is simulated as follows:

$$E_{3,t} = \frac{A_{3,t} N_{A,3,t}}{H_{3,t} V_{3,t} r_{3,t}} \quad (1.22)$$

where the temperature used in calculating $H_{3,t}$ is assumed to be the air temperature. The manure pH is a slurry-specific parameter. $r_{3,t}$ is the sum of the aerodynamic resistance ($r_{a,3,t}$; m s^{-1}) and a resistance (r_{app} ; m s^{-1}) that is specific to an application method.

Substituting equation (1.22) into equation (1.21) and re-arranging, gives:

$$\frac{dN_{A,3,t}}{dt} = \eta k_{L,2,t} \frac{N_{A,2,t}}{V_{2,t}} - \left(\left(\frac{1}{H_{3,t} r_{3,t}} + k_{I,t} \right) \frac{A_{3,t}}{V_{3,t}} + k_B \right) N_{A,3,t} \quad (1.23)$$

The infiltration rate k_i is made a function of the clean water infiltration rate of the soil (I_s ; m d^{-1}) and the manure DM content:

$$k_{I,t} = I_s e^{\left(\frac{\varpi D_{3,t}}{V_{3,t} + D_{3,t}} \right)} \quad (1.24)$$

where ϖ is a parameter constants, specific to an animal type. A single exception is when the air temperature is below 0C, when k_1 is set to zero.

As mentioned earlier, the emitting area is reduced to simulate drying, if the DM concentration exceeds ξ :

If $\frac{D_{3,t}}{\gamma V_{3,t} + D_{3,t}} < \xi$ then:

$$\frac{dA_{3,t}}{dt} = \frac{k_{L,2,t}}{\lambda} - k_B A_{3,t}$$

Else

$$\frac{dA_{3,t}}{dt} = \frac{dD_{3,t}}{dt} \frac{A_{3,t}}{D_{3,t}}$$

where λ is the application rate of the manure ($\text{m}^3 \text{m}^{-2}$). Note that in specifying λ , only the area that physically receives manure is considered. This means, for example, that for manure applied using bandspreading techniques, only the area within the bands is considered.

4.5 Emission during grazing

The ammoniacal N in the moisture in dung is a small proportion of the total ammoniacal N excreted and is ignored here. The volume of urine deposited during grazing is $g_t V_0$ and the ammoniacal N deposited during grazing is $g_t n_A$. The urine deposited during grazing is by definition deposited onto cropped land and a proportion will be intercepted by the canopy of the crop. Emission losses during grazing are simulated here by assuming that all the ammoniacal N in this intercepted urine is immediately volatilised.

5.1 Key features of manure management

Two types of data needed in order to model nutrient flows at the farm scale, structural and operational. The structural data are here defined to include agricultural features that require substantial investment of resources (e.g. building new animal housing), so can be expected to remain constant for several years. The operational data changes over a shorter timespan e.g. choice of manure application method, time of ploughing.

The main structural aspects of manure management systems that are relevant to ammonia emissions are:

- The form of the manure (solid or liquid) produced by the housing. This determines the options for method of storage and field application.
- The type of animal housing. This defines whether the housing is free or forced ventilated, the type of flooring in the animal housing and the type of manure produced. This influences the magnitude and time-course of emissions of ammonia, dinitrogen and nitrous oxide.
- The presence or otherwise of an exhaust air scrubbing facility.
- The type of manure storage facility. For liquid-based systems, this influences the dynamics of the exchange of heat, water and ammonia with the atmosphere. Particularly important are the exposed surface area of manure and whether the storage is inside or outside the animal housing. For solid manures, this determines the access of air to the base of the manure and therefore the extent to which the manure may become aerobic or anaerobic. The former will encourage aerobic mineralization and ammonia emission while the latter will encourage anaerobic mineralization and the emission of nitrous oxide.
- The presence or otherwise of a cover on the manure storage. Covers will reduce the ammonia emissions.
- The size of the manure storage facility relative to the number of animal places in the animal housing. This determines the extent to which farmers may be forced to apply manure due to the storage being filled to capacity.
- The method of manure application to the field. For liquid manures, this determines the surface area of manure that is exposed to the atmosphere and the extent to which contamination of the canopy, both of which influence ammo-

nia emissions. The application method also determines the extent to which the liquid manure is concentrated in strips or buried, both of which influence ammonia emission.

The operational management factors that are most relevant to losses of nutrients from farming systems are:

- When and for how long livestock are in animal housing. This largely determines the proportions of the annual excretion that are deposited in the animal housing, on hard standings and on pasture. Manure N deposited in animal housing and on hard standings has a greater risk of being emitted as ammonia whereas that deposited on pasture has a greater risk of being lost via nitrate leaching.
- The timing of manure removal from storage and application to fields. Manure applied in the autumn and winter has a greater risk of being lost via nitrate leaching while that applied in the spring and summer has a greater risk of being emitted as ammonia.
- The manure application rate. This influences the area and duration of manure exposed to the atmosphere, which in turn influences the emission of ammonia. It also influences the extent to which the nutrients applied in the manure satisfy or exceed the uptake capacity of the crop.
- The time between manure application and cultivation (if any). This influences the period during which ammonia can be emitted from field-applied manure.

5.2 *Structural data*

Structural data are the most difficult to model, since farm structure is the result of a wide range of influences (see above). In order to make progress, it is necessary to make extensive assumptions concerning the nature of European agriculture and then modify those assumptions where the available data suggest this is necessary. The assumption is therefore that 60 years ago, mixed livestock/arable farming was ubiquitous. At this time before the ready availability of high-powered farm machinery and inorganic fertilisers, most manure was stored as solid manure (more specifically, a mixture of faeces, urine and bedding). The last 50 years have seen a trend towards larger farms and greater specialisation. Slurry is generally the cheapest form in which to manage large quantities of manure, so farms that have expanded or intensified are more likely to manage their manure as slurry. Solid manure requires little investment in containment and can be applied to land using relatively low-cost

machinery, so small farms are likely to have retained this method of manure handling. A preliminary investigation of Danish data supports this view (see Fig 4).

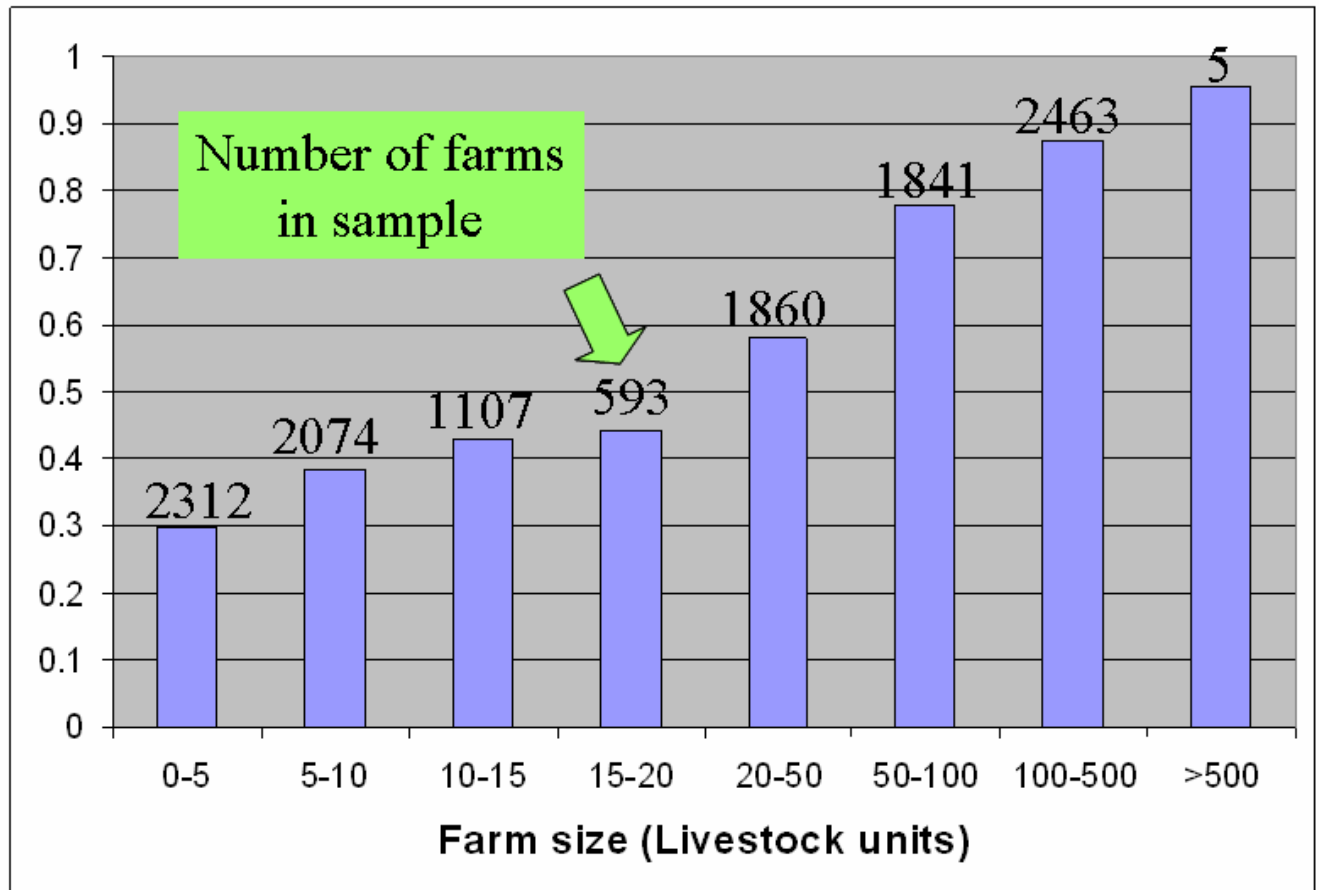


Fig 4 Proportion of manure managed as a liquid (Y axis) v farm size.

Large animals, such as cattle and horses, or those with thick coats, such as sheep, are usually kept in housing without forced ventilation or heating. In contrast, smaller animals such as pigs and poultry, are kept in housing with forced ventilation and heating.

Slurry is generally stored in tanks and the storage facilities are usually outside the animal housing. Solid manure is often stored for a period inside the housing. Some is then stored in heaps for a further period outside whilst the remainder is applied directly to the field. The capacity of the manure storage is to a large extent determined by the longest period during which field application is not possible. In the absence of legislation, applications can be prevented during some periods by the trafficability of the soil, the presence of a well-

developed arable crop or competition for labour from other farming activities. For EU countries, there may also be prohibition or discouragement of application of manure outside the growing season, due to the EU Nitrates Directive.

Manure storage is usually only covered if this is demanded by national legislation, with the exception of farms in areas with high precipitation, where the saving on storage and application capacities may be sufficient to offset the investment cost of the cover. Broadcast spreading is the cheapest method of application and will normally be used unless farmers are obliged either directly or indirectly by legislation to use other means.

In the absence of better information to the contrary, we propose the following:

- All ruminant livestock on farms larger than E_1 (ESU*) are, when housed, in freely ventilated housing producing slurry, where E_1 varies between animal type. The remainder are housed in freely ventilated housing producing solid manure.
- All pigs and poultry on farms larger than E_2 (ESU) are housed in forced ventilated housing producing slurry. The remainder are housed in freely ventilated housing producing solid manure.
- All remaining livestock are kept in freely ventilated animal housing and produce solid manure only.
- Slurry is stored in tanks outside the animal housing. Half the solid manure is stored in the animal housing and half outside in heaps. Except for poultry, storage facilities are located outside the animal housing.
- All manure is spread using broadcast spreader.

* ESU = economic size unit, as defined by EUROSTAT.

5.3 *Operational data*

The volume and composition of manure depends on the excretion of the livestock and the extent to which material is added (e.g. in bedding, spilt feed, washing water, rain) or lost (e.g. by evaporation, volatilisation or leaching). Excretion by livestock is not considered here since standard values for a range of livestock categories are often available at the country level and if they do not, there already exist methods to calculate excretion (e.g. IPCC). The ob-

jective here is to simulate the regionally-averaged grazing and manure management in animal housing, storage and on fields, with a temporal resolution of one hour. The manure is described in terms of the dry matter (DM) and water it contains. The duty of the model is to follow the dynamics of DM and water as it passes through the manure management system.

Time is defined in terms of d , the day number, counting from 1 January, and h , the hour of the day. All variables are defined on an hourly basis throughout the year but for clarity, the relevant sub-scripting has been omitted from the model definition. Constants are explicitly named as such. The following model definition is specific to a particular animal type i.e. a production subset of a species e.g. dairy cattle, and to a particular housing/manure type e.g. straw-based pig housing.

5.3.1 *Housed versus grazed livestock*

Some livestock are typically housed all year e.g. pigs and chickens, although there are notable exceptions (e.g. organically reared pigs). It is assumed here that all non-ruminant animals are housed throughout the year. For other livestock, it is assumed that the amount of time animals are at pasture generally decreases as the intensity of production increases. This assumption is based partly on the greater ease of feeding livestock in animal housing, partly on the logistical difficulties associated with the increased distances livestock must travel to reach the pasture. The assumption here is that the proportion of other livestock (principally cattle, sheep, goats and horses) that are grazed (g) is dependent on the mean economic farm size (E):

If $E < E_L$, $g=1.0$.

If $E > E_U$, $g=0.0$.

otherwise:

$$g = 1 - \frac{E}{E_H - E_L}$$

where E_L and E_U are constants for a given type of livestock.

The grazing period is assumed to coincide with the growing season of grass. In situations where drought reduces grass growth, it is assumed that the livestock are fed outside the animal housing and so excreta continues to be deposited on pasture, rather than in the

animal housing. Grazing commences on day $D_{g,1}$ and finishes on day $D_{g,2}$. Outside this period, the animals are housed 24 hours per day. The date associated with the start of growth may be calculated with an independent crop growth model or from the simple model described in Appendix B. During the grazing period, the proportion of the day spent in animal housing (H ; d) is assumed to be 0.5 for dairy livestock of all species and 0 for all other ruminant animals. The time H is assumed to be centred on midnight. The diurnal variations in the activity of livestock that are seen in animal housing (ref) are assumed to also occur in the field and to translate into a corresponding diurnal variation in excretion. During the grazing period, the proportion K of all DM and water excreted by the livestock that is deposited on grazed pasture is:

$$\begin{aligned} &\text{If } H/2 > h < (24-H/2) \text{ then} \\ &K = g \sin \\ &\quad (1.25) \end{aligned}$$

Otherwise, $K=0$.

5.3.2 Animal Housing

Water enters the animal housing both as liquid water and as moisture in animal feed and bedding material, whereas DM only enters in the latter two. The dynamics of water in the animal housing ($W_{1,t}$; kg) are:

$$\frac{dW_{1,t}}{dt} = w_{F,t} + w_{D,t} + w_{P,t} - w_{M,t} - e_{1,t} - k_{w,1,t}$$

where $w_{F,t}$ (kg hr^{-1}) is the water in feed (including chemically bound water), $w_{D,t}$ (kg hr^{-1}) is the drinking water supplied, $w_{P,t}$ (kg hr^{-1}) is the water used for washing, $w_{M,t}$ (kg hr^{-1}) is the water exported in animal products (e.g. milk), $e_{1,t}$ (kg hr^{-1}) is the loss of water by evaporation from the animals and wet floor surfaces and $k_{w,1,t}$ (kg hr^{-1}) the rate of removal of water in manure transferred to storage. The corresponding equation for DM ($B_{1,t}$; kg) is:

$$\frac{dB_{1,t}}{dt} = b_{F,t} + b_{S,t} - b_{E,t} - b_{M,t} - k_{B,1,t}$$

where $b_{F,t}$ (kg hr^{-1}) is the DM supplied in animal feed, $b_{S,t}$ (kg hr^{-1}) is the rate of addition of DM in bedding material, $b_{E,t}$ (kg hr^{-1}) is the DM emitted in gaseous forms (principally water and CO_2), $b_{M,t}$

(kg hr⁻¹) is the DM exported in animal products and $k_{B,1,t}$ (kg hr⁻¹) the DM in manure transferred to storage.

$b_{S,t}$ and $w_{P,t}$ can be related to the number of livestock present in the housing (S_t):

$$b_{S,t} = \beta S_t$$

$$w_{P,t} = \varepsilon S_t$$

where β (kg DM animal⁻¹ hr⁻¹) and ε (kg animal⁻¹ hr⁻¹) are constants for a given animal species in a given type of animal housing.

$w_{M,t}$ and $b_{M,t}$ can be calculated from the following equations:

$$w_{M,t} = S_t \left((1 - d_m) P_m + (1 - d_g) P_g \right)$$

$$b_{M,t} = S_t \left(d_m P_m + d_g P_g \right)$$

where d_m and d_g are the concentrations DM in milk and growth respectively, and are constants specific for a livestock type. P_m and P_g are the milk yield and animal growth (kg animal⁻¹ hr⁻¹) and are also constants specific for a livestock type.

CIGR (2002) provides a convenient method for calculating the total daily energy expenditure of livestock and its subsequent portioning between sensible and latent heat.

It is assumed here that this demand is spread evenly throughout the day and that the corresponding hourly values are $\Omega_{T,t}$, $\Omega_{S,t}$ and $\Omega_{L,t}$ (MJ hr⁻¹).

If the typical feed for an animal of a given type (e.g. dairy cattle) has concentrations of energy and DM of δ (MJ (kg fresh weight)⁻¹) and d_F (kg DM (kg fresh weight)⁻¹) respectively, then:

$$w_{F,t} = \frac{S_t (1 - d_F) \Omega_{T,t}}{\delta}$$

$$b_{F,t} = \frac{S_t (1 + \tau) d_F \Omega_{T,t}}{\delta}$$

where τ is the proportion of feed DM supplied that is spilt and is a constant for an animal housing type.

$\Omega_{L,t}$ includes energy used to evaporate water vapour from the animals and from the feed and floor surfaces. CIGR (2002) provides a

method to estimate the latent heat loss from the animals ($\Omega_{L,a,t}$; MJ hr^{-1}). $w_{D,t}$ can then be estimated by the following equation:

$$w_{D,t} = \frac{S_t (1 + \alpha) \Omega_{L,a}}{C_v}$$

where C_v is the specific heat of vaporisation of water at animal body temperature (MJ kg^{-1}) and α is the proportion of drinking water that is spilt. The value of $e_{l,t}$ can be estimated from the latent heat loss:

$$e_{l,t} = \frac{S_t \Omega_{L,t}}{C_v}$$

$b_{E,t}$ is the mass vaporised by animals and excreted in exhalation and the gaseous emissions from the manure. The former is here assumed to be the difference between the digestible DM in the feed consumed and the DM in animal products. b_E can then be calculated as follows:

$$b_{E,t} = \gamma b_{F,t} - b_{M,t} + \varsigma_1 B_{l,t}$$

where γ (kg kg^{-1}) is the DM digestibility of the animal feed and ς_1 (hr^{-1}) is a constant, describing the decomposition rate of the manure DM in the animal housing.

5.3.3 Manure storage

The dynamics of the mass of water in the manure storage ($W_{2,t}$; kg) are as follows:

$$\frac{dW_{2,t}}{dt} = k_{W,1,t} - k_{W,2,t} - \varphi A_2 (k_{E,2,t} + k_{P,t}) \quad (1.26)$$

where $k_{W,2,t}$ is the volume of manure removed for field application (kg hr^{-1}), A_2 (m^2) is the surface area of the manure storage, $k_{E,2,t}$ is the evaporation rate ($\text{kg m}^{-2} \text{hr}^{-1}$) and $k_{P,t}$ is the precipitation rate ($\text{kg m}^{-2} \text{hr}^{-1}$). φ is zero if the storage is equipped with a cover that excludes precipitation, otherwise unity. It is assumed that the storage is sufficiently watertight that infiltration into the soil is insignificant.

The dynamics of the DM in the manure in storage ($B_{2,t}$; kg) are:

$$\frac{dB_{2,t}}{dt} = k_{B,1,t} - \varsigma_2 B_{2,t} - \frac{k_{W,2,t} B_{2,t}}{W_{2,t}}$$

where ς_2 is the decomposition rate of DM in storage (hr^{-1}) and the last term describes the mass of DM removed for field application.

A_2 is calculated assuming a constant maximum storage depth (D ; m):

$$A_2 = \frac{F}{D} \quad (1.27)$$

where F is the capacity of the manure storage (kg). The manure storage capacity is expressed in terms of the number of days of manure production (n ; days):

$$F = \frac{n}{24} \sum_{t=0}^T S_t (k_{W,1,t} + k_{B,1,t})$$

where T is a production cycle (hr).

5.3.4 *Manure applications*

The management of manure applications to cropland depends to a large extent on whether the manure is considered a waste or a resource. If the manure is considered a waste, it is likely to be applied at a rate, time and with a technique that incurs the least cost and inconvenience to the farmer. This will generally mean application by broadcast spreader, as close as possible to the manure storage, at as high a rate as the soil, crop and environmental authorities will permit. Within these constraints, the applications will be timed to coincide with periods of low demand for labour or when the manure store is nearing the maximum storage capacity. Typically, this will be wintertime or immediately after harvesting arable crops.

In Europe, farmers are encouraged to consider manure as a resource that contains valuable nutrients. This encouragement is supported by the authorities, both via education and by regulation. The EU legislation that has the greatest impact on manure management is the Nitrates Directive. This is particularly true within areas that

are designated to be nitrate sensitive, since member states are obliged to enforce restrictions on the annual rate of application of N in manure and on the timing of manure applications, to reduce nitrate leaching. The former restriction will normally increase the area to which manure is applied whilst the latter will often prevent the application of manure during wintertime. It seems likely that the EU Water Framework Directive will increase the area of Europe for which restrictions on manure application will apply. The EU Habitat and National Emissions Ceilings Directives also impact on manure management, via restrictions on the emissions of ammonia from this source. However, restrictions related to ammonia emission will mainly relate to the application technique and not directly to the timing or rate of application. Finally, national or regional legislation may place additional restrictions on manure use, e.g. to provide additional environmental protection or as part of disease control measures.

In summary, the situation regarding manure management in the field is complex and, in the absence of an overview of the spatial variation in regulation, largely unpredictable. The solution adopted here is to describe two types of manure management in the field; with or without constraints imposed by the need or desire to utilise the nutrients in the manure.

Cropping systems

The unconstrained management is only unconstrained with respect to the utilisation of nutrients, it is still potentially constrained by the accessibility of the land and the availability of labour. The accessibility of the land can be restricted either by the trafficability of the soil or by the presence of crops that are sufficiently mature that manure application is not possible without causing a reduction in yield. The constrained management is obtained by applying further restrictions on the window(s) of opportunity for manure applications that are experienced by the unconstrained management.

For simplicity, two very general cropping systems are considered in this model; arable and grassland/roughage. The arable cropping is typified by periods of intense activity in the spring and autumn, associated with cultivation and sowing, and a period in late spring/summer when the crop is too mature for manure to be applied. These constraints are assumed to be absent from grassland/roughage cropping systems. Grassland/roughage cropping systems are, by and large, only found on farms with ruminant live-

stock. Arable cropping may also be practiced on such farms but since the grassland is always assumed to be accessible (subject to trafficability), this is ignored. Non-ruminant livestock farms will normally only cultivate arable crops. In practice, some non-ruminant manure may be applied to grassland, if such crops are within transportable distance of the manure storage. Ideally, the manure should be partitioned between the two cropping systems by using a knowledge of the location of the farm and of the two cropping systems. In the absence of such a system, it is assumed here that ruminant manure is applied only to grassland and non-ruminant manure only to arable land.

The model allows two application periods to be defined. The starting and finishing dates for the first period are defined as $D_{1,c}$ and $D_{2,c}$ respectively (d), where c is the number of the cropping system (1=arable, 2=grassland). $D_{3,1}$ and $D_{4,1}$ (d) are the equivalent dates for the second period. These dates define the periods during which manure may be applied. It is assumed that farmers do not spread manure during the hours of darkness or if the soil is too wet to be trafficked by heavy machinery. Manure is therefore only applied if:

- $D_{1,c} < d < D_{2,c}$ or $D_{3,c} < d < D_{4,c}$, where t_d is the time in days.
- h is during the hours of daylight i.e. $(12 - h_D/2) > h < (24 - h_D/2)$, where h_D is the number of daylight hours.
- The soil moisture is below an upper limit, χ_u (kg water (kg soil)⁻¹).
- There is manure available in the manure storage ($W_{2,t} > 0$).

The procedure for calculating h_D is given in Appendix A. The value of χ_u is calculated according to Koenigs (1976):

$$\chi_u = 34c_{clay} + 155c_{org}$$

where c_{clay} and c_{org} are the contents of clay and organic matter respectively in the soil (kg kg⁻¹).

Unconstrained management

For the arable cropping, it is assumed that the development of the crop canopy prevents the application of manure from late spring until harvesting. The extent to which crop development limits the period for manure applications varies between application methods, so the limit, expressed in terms of a critical leaf area index (LAI) (L_c) is made dependent on the method used. The development of the crop LAI (L) and the harvesting date are either obtained from an independent crop growth model or from the simple model de-

scribed in Appendix B. $D_{1,1}$ is then identified with the start of the year and $D_{2,1}$ with the time when $L=L_c$, whilst $D_{3,1}$ is identified with the date of harvesting and $D_{4,1}$ with the end of the year.

For grassland, it is assumed that manure can be applied year round, so $D_{1,2}$ is the start of the year and $D_{2,2}$ the end of the year. $D_{3,2}$ and $D_{4,2}$ are not identified.

Constrained management

The constraints imposed on both the arable and grassland cropping systems are that manure applications are limited to times of the year when the crop can utilise the nutrients. For spring-sown arable, $D_{1,1}$ is therefore identified with approximately two weeks prior to sowing. If the simple crop model is used, this is identified as $0.9 S_1$, the temperature sum necessary for growth to start. Manure application post-harvesting is not permitted, so $D_{3,2}$ and $D_{4,2}$ are not identified. For autumn-sown arable, the spring application period is the same as for spring-sown arable but manure may also be applied for two weeks prior to sowing ($D_{4,2} = \text{sowing date}$ and $D_{3,2} = D_{4,2} - 14$). For grassland, $D_{1,2} = D_{1,1}$ whilst $D_{2,2}$ is equated with the first date on which the air temperature falls below 0C.

Application capacity

The application capacity at the farm scale is determined by the working capacity of the machinery available but the capacity will be lower than this at larger scales, since other activities will compete for the farmers' time. It is assumed that the application capacity at the grid scale (Z , kg hr^{-1}) is dimensioned to the manure production rate, so Z is calculated as follows:

$$Z = \varepsilon S (k_{w,1} + k_{B,1}) \quad (1.28)$$

where ε is a parameter constant, specific to an application technique.

On those days when manure applications are permitted, the rate of application of manure water and DM ($k_{w,2}$ and $k_{B,2}$) is calculated at the start of the first hour at which applications can be made. If there is sufficient manure in the storage at this time ($W_3 \geq h_3 Z$), then:

$$k_{W,2} = \frac{ZW_3}{W_3 + B_3}, \quad k_{B,2} = \frac{ZB_3}{W_3 + B_3}$$

otherwise

$$k_{W,2} = \frac{W_3}{h_D}, \quad k_{B,2} = \frac{B_3}{h_D}$$

6. *Example simulations*

The ammonia emission model was used to generate example simulations for emissions from pig farming within an area for two scenarios. The first two of these scenarios resembled the unconstrained and constrained cases described in the Management Model above, where the constraints are designed to reduce nitrate leaching. The manure application periods used are typical for Denmark. In the unconstrained scenario, the manure storage capacity was 5 months production, the application rate was equivalent to 340 kg N ha⁻¹ and there was no restriction on the application of manure in winter. In the constrained scenario, the manure storage capacity was 9 months production, the application rate was equivalent to 170 kg N ha⁻¹ and the application of manure in winter was not permitted. The third scenario used the same management as in the second (constrained) scenario but with the additional imposition of measures to abate ammonia emission. The abatement measures were to reduce the dirtied floor area in the animal housing from 85 to 50%, the use of a cover on the slurry tank and the use of injection for slurry application to the field.

Synthetic meteorological data were used, with an average annual temperature of 8C, on which was imposed sinusoidal variations in seasonal and diurnal of 12C and 5C respectively. Precipitation and wind speed were constant at 2mm per day and 2 ms⁻¹ respectively. The excretion rate was 450 Mg N yr⁻¹, the manure was managed as slurry, an arable cropping system was used and there no abatement strategies were applied.

The seasonal distribution of ammonia emissions predicted by the model are shown in Fig 2 a-c.

a)

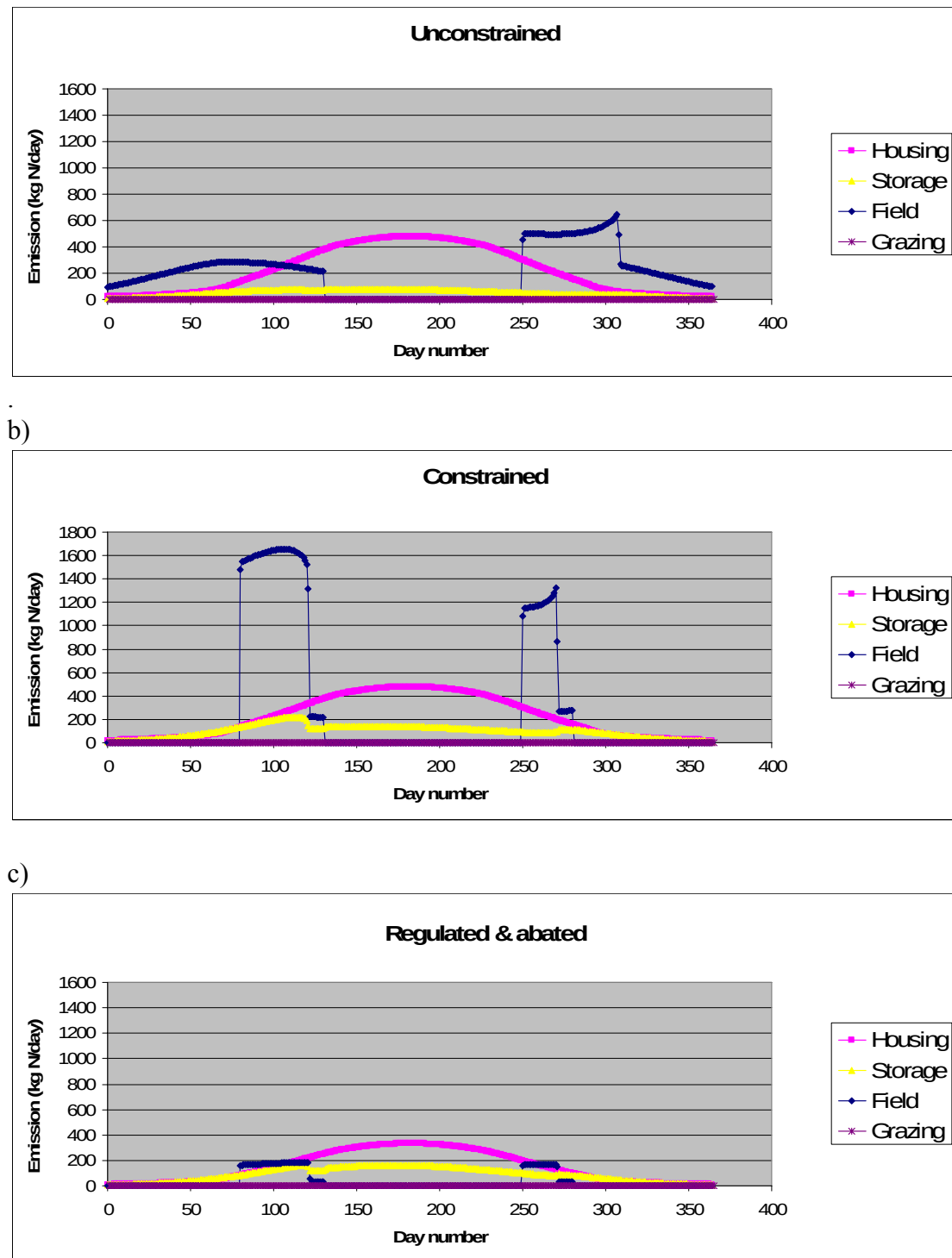


Fig 2 Seasonal ammonia emissions.

In the unconstrained situation, the emission from animal housing and manure storage peaks in the summer, due to the higher temperatures at that time. The presence of the arable crops prevents

field applications of manure between late spring and mid summer and the emission in spring and autumn is higher than in winter, due to the higher temperatures at these times. In the constrained situation, the winter emissions are absent but there are marked peaks in spring and autumn, since manure applications are now concentrated in these periods. In the constrained and abated scenario, the pattern of emission is the same as in the constrained scenario but with a much reduced level.

The fate of the nitrogen input into the farming system is shown in Fig 3.

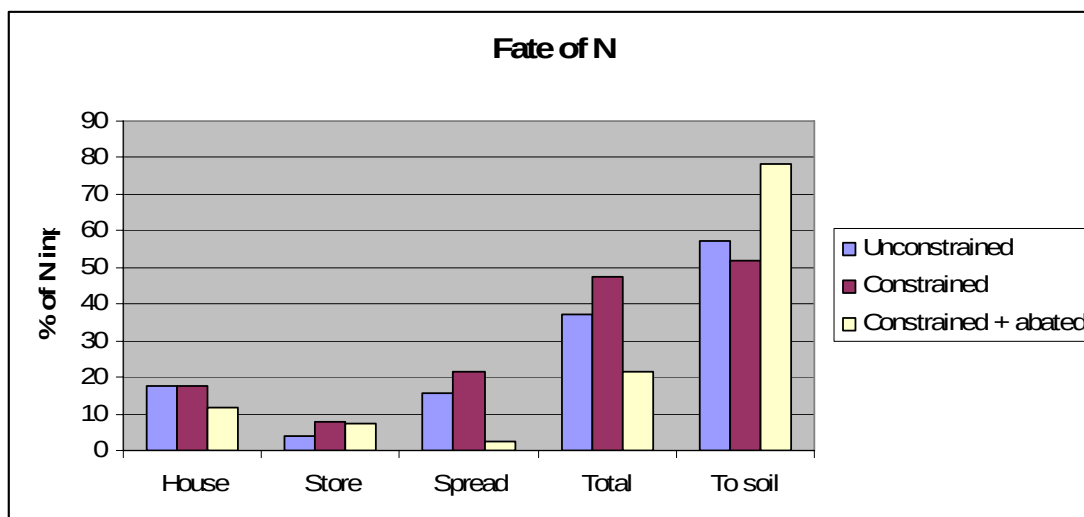


Fig 3 The fate of nitrogen input into the pig farming system

The emission of ammonia from the manure storage and manure spreading to land is greater for the constrained scenario than the unconstrained scenario. This is because the demand for greater manure storage means that a larger surface area of manure is exposed to the atmosphere and because the temperature at the time of field applications is now higher than for the unconstrained scenario. The imposition of abatement measures effectively reduces the emissions from the three sources and leads to an increase in the amount of nitrogen entering the soil. This extra nitrogen could increase crop yield but might also increase nitrate leaching, which was the objective of imposing the management constraints.

7. Conclusion and Perspectives

The aim of this project was to produce a prototype for a process-based model of emission of ammonia from animal manures that could predict emissions with a high temporal resolution. It was

appreciated at the start of the project that only a subset of the knowledge of the processes controlling the ammonia emission could be included, since the objective was an operational model and not a synthesis of all the available knowledge. Nevertheless, in comparison with emission factor type models, the number of parameters is large and presents a challenge to researchers.

An aspect not fully appreciated at the start of the project was the difficulty in obtaining input data for the ammonia emission model when used at large geographic scales. The data on existing and past manure management vary in detail between countries but in only a few cases can be considered adequate (Sweden being one such case). Furthermore, the implementation of ammonia abatement measures can sometimes affect the manure management practices. For example, emissions from manure storage can be reduced by covering the store. This cover may reduce the evaporation of water from the store and may, depending upon its design, exclude precipitation. The cover will therefore affect the volume of manure that must be applied to the land. Whether the net effect of the cover is to increase or decrease the volume of manure to be applied will depend on the local climate; in high rainfall areas, the cover will reduce the amount whilst in dry areas, it will increase it. Finally, as illustrated by the example simulations shown in this report, measures taken to control other environmental emissions from animal manures may have an effect on the manure management. This emphasizes that when considering scenarios for reducing the emission of ammonia or other compounds that may harm the environment, a dynamic manure management model of the type outlined in this report should be used.

The status at the end of the project is that the ammonia emission model has been coded into both C++ and FORTRAN but will remain a prototype until adequately parameterised and tested. The prospects for making the model operational are quite good, given the current policy focus at the EU scale on the role of ammonia in secondary particle formation. The management model has been partially programmed in C++ and work on this model is continuing within the scope of the EU NitroEurope integrated research project.

Finally, it is useful to look forward to the time if/when the ammonia and manure management models are fully operational and consider how they might be used, given the regulative framework for limiting ammonia emissions. Within both the CLRTD and NEC, the parties/member states are responsible for submitting emission data and it is these data that must be used when assessing compliance and the environmental consequences of emissions. Although both

CL RTP and NEC will be revised within the next few years, it appears unlikely that this situation will change. The legislation sets certain minimum requirements for the methodology used for construction of the emission inventories but otherwise, compilers within each country are free to choose the methodology that they deem most appropriate. When modelling the consequences of current ammonia emissions, the dynamic ammonia model could therefore be used in three ways:

- Individual countries could choose to use the model, using a parameterisation tailored to the local circumstances.
- EMEP could normalise the emissions predicted by the model to those submitted by the individual countries i.e. using the dynamic model only to predict the temporal pattern of emissions. This is the method used by Gyldenkaerne et al. (2005).
- The dynamic model could be used in reviewing country emissions. For example, if there are differences in the apparent emission factors for countries with similar agricultural systems, the model could be used to investigate whether the differences can be explained by differences in manure management practices.

Perhaps the greatest potential for the emission and manure management models is in simulating the likely effectiveness of potential abatement measures. In this situation, the choice of model normally lies exclusively with the organisation undertaking the study.

8. References

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Appendix A

Ammonia chemistry

If the total ammoniacal nitrogen (TAN) is defined as the sum of the ammonia and ammonium in solution then the concentration of ammonia in solution ($[\text{NH}_3]_{\text{aq}}$; mol kg⁻¹):

$$[\text{NH}_3]_{\text{aq}} = \frac{[\text{TAN}]}{1 + [\text{H}_3\text{O}^+]/K_{\text{N}}}$$

or

$$[\text{NH}_3]_{\text{aq}} = \frac{[\text{TAN}]}{1 + 10^{-\text{pH}}/K_{\text{N}}}$$

(1.29)

Where the dissociation constant (K_{N}) is given by:

$$\ln K_{\text{N}} = 191.97 - \frac{8451.61}{T} - 31.4335 \ln T - 0.0152123T$$

(1.30)

where T is the temperature in Kelvin.

This formulation comes from Beutier and Renon (1978).

Henry's Law states:

$$P_{\text{NH}_3} = K_{\text{H}} [\text{NH}_3]_{\text{aq}}$$

(1.31)

Where P_{NH_3} is the partial pressure of NH_3 (atm) and K_{H} is the Henry constant (atm kg mol⁻¹). The concentration of NH_3 in the air in the layer immediately above the manure (C_{NH_3} ; mol litre⁻¹) is then:

$$C_{\text{NH}_3} = \frac{K_{\text{H}} [\text{NH}_3]_{\text{aq}}}{RT}$$

(1.32)

Where T is the temperature at the manure surface (Kelvin) and R is the universal gas constant (0.082057 atm litre Kelvin⁻¹ mol⁻¹).

K_H is given by Beutier and Renon (1978) as:

$$\ln K_H = 160.559 - \frac{8621.06}{T} - 25.6767 \ln T + 0.035388T \quad (1.33)$$

If the resistance to the atmospheric transport of NH_3 is r (s m^{-1}) then the instantaneous emission of NH_3 (E ; $\text{mol m}^{-2} \text{s}^{-1}$) is:

$$E = \frac{[\text{TAN}]_{\text{aq}} \varepsilon K_H}{RT r \left(1 + \frac{10^{-\text{pH}}}{K_N} \right)} \quad (1.34)$$

Where ψ converts the concentration from litres^{-1} to m^{-3} . Since 1 mol NH_3 is nearly the same as 1 mol TAN, the concentration of TAN can be expressed in g kg^{-1} and then the emission will be in $\text{g m}^{-2} \text{s}^{-1}$. The Henry factor used in calculating the emission from animal housing, manure storage and field-applied manure is therefore:

$$H = \frac{\psi K_H}{RT \left(1 + \frac{10^{-\text{pH}}}{K_N} \right)} \quad (1.35)$$

The appropriate values of T and pH must be used in each case for the evaluation of (1.35), (1.33) and (1.30).

Appendix B

The DM concentration is:

$$\frac{D_3}{\gamma V_3 + D_3}$$

If $\frac{D_3}{\gamma V_3 + D_3} < \xi$ then it is assumed that part of the emitting area

dries. In doing so, it removes DM and the DM concentration is assumed to remain constant at ξ . The dynamics of DM in this situation are:

$$\frac{D_3}{\gamma V_3 + D_3} = \xi$$

$$D_3 = \xi (\gamma V_3 + D_3)$$

$$D_3 = \xi \gamma V_3 + \xi D_3$$

$$D_3 - \xi D_3 = \xi \gamma V_3$$

$$D_3 (1 - \xi) = \xi \gamma V_3$$

$$D_3 = \frac{\xi \gamma V_3}{(1 - \xi)}$$

And so:

$$\frac{dD_3}{dt} = \frac{\xi \gamma}{(1 - \xi)} \frac{dV_3}{dt}$$