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A MODEL OF AMMONIA VOLATILIZATION FROM A GRAZING LIVESTOCK FARM

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Abstract—A dynamic model was developed to predict the ammonia volatilization from grazing livestock farms and to allow potential control measures to be evaluated. The relationships within the model were based on the underlying physical and chemical processes but empirically based factors were used to reduce the demand for input data and where the understanding of the underlying processes was inadequate. On a daily basis, the model simulates the partitioning of dietary nitrogen into dung and urine and its subsequent fate within the pasture or the slurry handling system. The fate of dry matter and water added in dung, urine and from other sources is also predicted. The model illustrates the indirect interactions between ammonia sources, highlights the influence of slurry management on ammonia losses, stresses the need for integrated, whole farm measurements and demonstrates that assessments of the impact of control measures may be misleading unless considered at the scale of the whole farm.

Key word index: Model, ammonia volatilization, animal housing, slurry, manure, urine.

INTRODUCTION

Animal production systems are the major source of atmospheric NH_3 in Europe (Buijsman *et al.*, 1987). Deposition of this NH_3 may contribute to undesired changes in oligotrophic ecosystems (Schulze *et al.*, 1989) and volatilization reduces the nutrient value of animal manures.

Previous studies have assessed the magnitude of NH_3 losses at a large scale and the specific contribution of agriculture (e.g. Buijsman *et al.*, 1987; ApSimon *et al.*, 1987; Jarvis and Pain, 1990). Estimates of agriculture's contribution differ widely (Lee and Dollard, 1994), indicating the need for improved information. Others have considered the losses associated with specific on-farm sources such as animal housing (Janssen and Krause, 1990) or waste storage (Olesen and Sommer, 1994) or farming practices such as slurry spreading or grazing (e.g. van der Molen *et al.*, 1990; Pain *et al.*, 1989; Jarvis *et al.*, 1991; Sommer *et al.*, 1991). On-farm NH_3 sources are often linked, as, for example, where excreta are voided in animal housing, transferred to a slurry store and then eventually applied to the land. Assessing the true impact of control measures designed to limit NH_3 loss requires a whole farm approach. Earlier models capable of simulating NH_3 volatilization at the farm scale have been static (Hansen *et al.*, 1990) and often embedded within models of the whole N economy (Scholefield *et al.*, 1991; van de Ven, 1992). There is a need for a dynamic model which focuses closely on NH_3 volatilization at the farm level if detailed estimates of the NH_3 losses from livestock farms are to be obtained and the true effectiveness of control measures assessed. The first version of such a model is presented here.

MODEL STRUCTURE

The model simulates NH_3 sources on grazing livestock farms or the part of mixed enterprise farms that is used for grazing livestock. The model tracks the N input as animal feed until it is lost by volatilization or the area of land on to which it was deposited/applied ceases to be an active NH_3 source. The routes of N flow within the model are shown in Fig. 1.

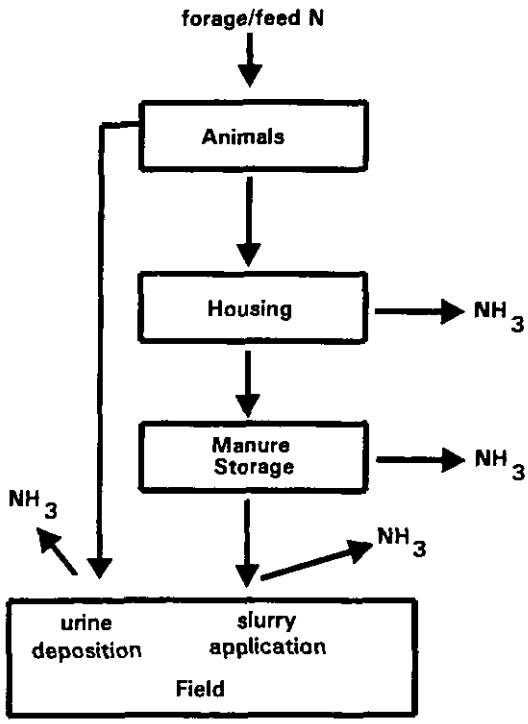

Fig. 1. The major routes for nitrogen flow in the NH_3 volatilization model.

Three general assumptions are made: (a) the livestock are managed and behave as a single flock or herd, (b) volatilization of ammonia is nowhere limited by urease activity and (c) where two sources occupy the same land area in sequence, the second source does not interact with the first.

The model operates with a daily time step or less as losses are often nonlinearly related to environmental parameters, so estimating losses using a weekly or monthly figure could lead to serious error in the estimates of NH_3 loss.

A generalized NH_3 *source*

The sources of NH_3 on a farm share a common feature. The NH_3 is volatilized from the surface of an aqueous solution of NH_4^+ and is then transported through a pathway with a finite resistance to the free atmosphere. Ignoring the concentration of NH_3 in the free atmosphere, the volatilization of NH_3 from an aqueous solution x (A_x; kg d^{-1}) can be described as

$$A_x = \frac{a_x \mathrm{TAN}_x Q_x \gamma}{r_x V_x} \tag{1}$$

where a_x is the surface area of solution exposed to the air (m^2), TAN_x is the total ammoniacal N (TAN) in solution x (kg m^{-2}), Q_x is a dimensionless equilibrium coefficient determining the NH_3 gas in the air for a given concentration of TAN in solution x, r_x is the resistance to NH_3 transport between the surface of solution x and the free atmosphere (d m^{-1}), V_x is the mass of the solution (kg m^{-2}) and γ is the density of the solution, assumed here to have the same value as water (1000 kg m^{-3}). This relationship is used as the basis for submodels of all the major sources on the farm.

Following Sherlock and Goh (1985a), Q_x can be described as

$$Q_x = K_{h,x} K_{NH_4,x} \tag{2}$$

where $K_{h,x}$ is the Henry's law coefficient and $K_{NH_4,x}$ is the dissociation coefficient of ammonium:

$$K_{h,x} = 10^{(-1.69+1477.7/\theta_x)},$$

$$K_{NH_4,x} = 1 + 10^{(0.09018+(2729.92/(\theta_x+273))-pH_x)} \tag{3}$$

where θ_x and pH_x are, respectively, the temperature (°C) and pH of the liquid. The resistance to transport (r_x) will vary between sources, as described in detail below.

The rate of NH_3 loss predicted by equation (1) is very sensitive to the pH over the range commonly encountered in urine and slurry. The pH of slurry and urine changes with time of exposure to air as NH_3, CO_2 and H_2O are lost. Also, the relationship between volatilization and initial pH varies between slurries due to variations in the buffering capacities of the liquids (Husted *et al.*, 1991). At present the changes with time and variation between slurries cannot be easily predicted. The approach adopted here is to simulate A_x as a function of the initial value of pH_x using equation (1). Although the rate of loss is allowed to vary between the types of source, it is accepted that differences in buffering capacity will lead to error in simulating volatilization within a type.

An index of symbols is shown in Appendix A.

ANIMAL SUBMODEL

The use of equation (1) requires the quantity and form of N and the volume of urine/slurry to be known for each source. The faecal dry matter production must also be calculated as the solids content of slurry influences the NH_3 lost after land application.

Faeces

The daily faecal dry matter output on the farm ($D_{f,t}$; kg DM d^{-1}) is

$$D_{f,t} = S_t F_t (1 - \alpha_t) \tag{4}$$

where α_t is the apparent digestibility of the feed (kg DM (kg DM)$^{-1}$), S_t is the number of animals on the farm and F_t is the quantity of feed eaten per animal (kg DM animal^{-1}).

Faecal N is mainly of microbial origin (SCA, 1990) so the concentration of N in faeces varies little in response to variations in that of the feed. We assume a constant N concentration in faeces (c_f; kg N (kg DM)$^{-1}$). The faecal N production

($N_{f,t}$; kg N d^{-1}) can be calculated as

$$N_{f,t} = D_{f,t}c_f. \quad (5)$$

The water contained within the faeces ($V_{f,t}$; kg d^{-1}) is

$$V_{f,t} = D_{f,t}\beta \quad (6)$$

where the faecal moisture content β (kg (kg dry weight)$^{-1}$) is assumed to be a constant.

Urine

The urinary N production ($N_{u,t}$; kg N d^{-1}) is calculated by subtracting the N partitioned to milk, new animal tissue and faeces from the total intake

$$N_{u,t} = S_t(F_t c_{h,t} - (M_t c_m + K_t c_w)) - N_{f,t} \quad (7)$$

where $c_{h,t}$ is the N concentration in the feed supply (kg N (kg DM)$^{-1}$), M_t is the milk yield (kg animal^{-1} d^{-1}), c_m is the N concentration in milk (kg kg^{-1}), K_t is the empty body weight gain (kg d^{-1}) and c_w is the N concentration in new tissue (kg N kg^{-1}).

The mass of urine produced ($V_{u,t}$; kg d^{-1}) is

$$V_{u,t} = S_t u_t u_f \quad (8)$$

where u_t is the urination rate (kg urination^{-1}) and u_f is the frequency (urinations animal^{-1} d^{-1}). Both u_t and u_f are assumed to be constants.

AMMONIA LOSSES FROM ANIMAL HOUSES

It has been shown that similar amounts of NH_3 are lost per unit area from the floor and the surface of slurry stored beneath the floor (Voorburg and Kroodsma, 1992; Oosthoek *et al.*, 1990). It is assumed here that losses occur from an area (a_1; m^2) equal to the sum of the area of flooring occupied by the animals and the surface area of any slurry storage. Scraping the floor is assumed to have no effect on losses as a thin layer of manure is assumed to be left on the floor after scraping (Oosthoek *et al.*, 1991). It is assumed that the NH_3 emitting surfaces are formed only by freshly voided urine so $TAN_{1,t} = N_{u,t}$ and $V_{1,t} = V_{u,t}$. The effect of diluting urine with any water used for washing animals or flushing is ignored, although this water ($V_{w,t}$; kg d^{-1}) is added to the slurry before it is passed to the slurry store.

Studies have shown that NH_3 loss from animal houses is related to the indoor temperature (Muck and Richards, 1983; Burton and Beauchamp, 1986). Although this would be expected from equation (3), these losses are also due to increased ventilation, as the farmers try to limit the rise in indoor temperature (Oosthoek *et al.*, 1990). There appears no simple way to separate these direct and indirect effects of temperature. The equilibrium coefficient ($Q_{1,t}$) is calculated at a temperature of 20°C; temperature effects are considered together with the resistance to NH_3 transport (below). The pH is assumed to be that of urine (a model input) unless floor washings are artificially acidified, when the target pH is used.

The air flow pattern transporting the NH_3 outside the housing is a complex function of both house design and ventilation strategy (Janssen and Krause, 1990). For simplicity, the resistance to transport ($r_{1,t}$; d m^{-1}) is simulated using a relationship found by Mannebeck and Oldenburg (1991) which relates loss to the temperature of ventilation air, which we equate to the mean daily air temperature outside (θ_t; °C). The losses reported by Mannebeck and Oldenburg (1991) are here normalized by the loss at 20°C and multiplied by a housing-specific constant (X_1) to obtain $r_{1,t}$ for both naturally and artificially ventilated housing:

$$r_{1,t} = X_1(1 - 0.027\,(20 - \theta_t)). \quad (9)$$

The housing-specific constant is used to adjust losses to match observed values. This relationship combines the effect of outside temperature on inside temperature, of ventilation rate and the effect of both inside temperature and ventilation rate on NH_3 loss. The loss from animal housing ($A_{1,t}$; kg N d^{-1}) is then

$$A_{1,t} = \frac{H_t a_1 \, TAN_{1,t} Q_{1,t} \gamma}{r_{1,t} V_{1,t}} \quad (10)$$

where H_t is the proportion of the day during which the animals are housed. This submodel assumes that there is no interaction between faeces and urine (no buffering) and that losses are confined to the proportion of the day during which the animals are housed.

AMMONIA LOSS FROM STORED SLURRY

The surface area of the source (a_2; m^2) is assumed to be that of the slurry store. The TAN is evaluated as the amount of ammoniacal N in the store ($TAN_{2,t}$; kg) and the volume by the volume of slurry present ($V_{2,t}$; kg). Mineralization of slurry organic N is ignored. The use of bulk parameters will not accurately reflect conditions at the slurry surface but pH changes and stratification within the slurry are too poorly understood to predict with accuracy (Olesen and Sommer, 1994). A compromise is made by introducing a store-specific resistance to adjust the predicted loss to match empirical data (see below).

The equilibrium coefficient ($Q_{2,t}$) is calculated equating the surface temperature to air temperature whilst the pH is assumed to be the mean for the whole store. Stratification will also introduce inaccuracies in $Q_{2,t}$ and these are also partially overcome by the store-specific resistance.

The wind speed affects the resistance to transport of NH_3 ($r_{2,t}$; d m^{-1}) through its effect on the aerodynamic resistance to transport from the slurry surface to the free atmosphere. Following Olesen and Sommer (1994), $r_{2,t}$ is made the sum of a boundary layer resistance ($r_{b,t}$; d m^{-1}), an aerodynamic resistance ($r_{a,t}$; d m^{-1}), a cover resistance ($r_{c,t}$; d m^{-1}; the

Table 1. Surface resistance for a range of coverings for slurry stores

Cover type	Cover resistance ($d\,m^{-1} \times 10^{-3}$)
None	0
Straw	0.59
Oil	2.11
Peat	2.67
PVC sheet	2.11
Expanded clay	4.42
Lid	6.71
Crust	2.13

Calculated from data in Sommer *et al.* (1993).

resistance of the *i*th slurry surface covering) and a store-specific resistance (r_T; $d\,m^{-1}$). The values of $r_{b,i}$ and $r_{a,i}$ are determined in the manner described by Olesen and Sommer (1994) and then converted to daily values. The assumptions of adequate fetch and neutral stability that underlie this approach are unlikely to be met in full within a slurry store. This inadequacy is overcome by the use of the empirically determined store-specific resistance. The value of $r_{c,i}$ for a variety of materials used for covering the slurry surface has been determined empirically (Table 1).

The rate of loss of NH_3 from stored slurry ($A_{2,t}$; $kg\,Nd^{-1}$) is

$$A_{2,t} = \frac{a_2 \mathrm{TAN}_{2,t} Q_{2,t} \gamma}{r_{2,t} V_{2,t}}. \tag{11}$$

If the store dries out ($V_{2,t}$ falls to zero), all the remaining TAN is assumed to volatilize but the dry matter remains.

Loading frequency and position

Ammonia loss rates are increased if fresh slurry is loaded on to the slurry surface as this increases the concentrations of NH_4^+ in the surface layer and disrupts any crust. Loss rates then fall over the subsequent 24–48 h as NH_4^+ in the surface layer is depleted and a crust re-forms. This effect is incorporated within the model by reducing the cover resistance to zero for the day on which slurry is added to the surface of the store.

AMMONIA VOLATILIZATION DURING APPLICATION OF SLURRY

Micrometeorological measurements have shown that losses during application using conventional spreaders, trail hose application and a cable-driven irrigator were less than 1% of the TAN applied (Pain *et al.*, 1989; Phillips *et al.*, 1991). Using broad spreading equipment, Sommer (1989) found volatilization during application to be less than 4% of the TAN applied. However, Boxberger and Gronauer (1990) found losses of up to nearly 10% of applied TAN when using an irrigation device, although the greater losses in this latter study may have been due to the measurement technique used. We assume a proportion, Ω, of the applied TAN is lost during application.

In the presence of a crop and when application is by broad spreader, a proportion of the slurry will be intercepted by the plant canopy. It is assumed that an amount η ($kg\,m^{-2}$) of the slurry applied by broad spreading methods to planted land is intercepted by the crop. We assume there will be no direct foliar absorption and that all the TAN in intercepted slurry will be lost by volatilization.

Ammonia volatilized during spreading ($A_{3,t}$; $kg\,Nd^{-1}$) is:

for spreading to land with a crop

$$A_{3,t} = (\Omega R_{2,t} + a_{3,b}\eta)\frac{\mathrm{TAN}_{2,t}}{V_{2,t}} \tag{12}$$

for spreading to bare soil

$$A_{3,t} = \Omega R_{2,t}\frac{\mathrm{TAN}_{2,t}}{V_{2,t}} \tag{13}$$

where $R_{2,t}$ is the mass of slurry applied (kg) and $a_{3,t}$ is the area covered by the slurry (m^2).

AMMONIA LOSS FROM APPLIED SLURRY

Unlike the sources in animal housing and manure storage, the source within an area to which slurry has been applied is not replenished. As a result, the rate of loss from surface-applied slurry is commonly highest shortly after application, declining rapidly thereafter (e.g. Pain *et al.*, 1989; Sommer *et al.*, 1991; Sommer and Ersbøll, 1994). The slurry NH_4^+ at risk of loss decreases with time through volatilization and through infiltration into the soil. The NH_4^+ that enters the soil becomes bound with the soil's cation exchange complex and is largely protected from volatilization. Here we identify the mass of slurry from which volatilization can take place ($V_{4,t}$, kg) to be on or very near the soil surface. This mass is reduced by infiltration and evaporation and increased by rainfall. The TAN in this mass is decreased by volatilization and infiltration. Any upward movement of NH_4^+ in the soil is ignored. The effect of rainfall on NH_3 volatilization has been included as empirical data suggest that this is important (Beauchamp *et al.*, 1982). The volatilization from slurry applications is described in Appendix B.

Effect of application and cultivation methods

Ammonia losses from slurry vary depending on the choice of application or cultivation technique. The mechanisms by which the different techniques affect loss vary. For example, rotovating the soil surface

Table 2. Adjustments made to properties of slurry applications to reflect effects of different cultivations

Treatment	Adjustment	Sources*
Pre-application harrowing	Increase I_s by 220%	Sommers and Ersbøll (1994)
Trail hose application	Reduce a_4 by 30%	Döhler (1990) and Bless *et al.* (1991)
Sod injection	Reduce V_4, TAN_4 and D_4 by 90%	Klarenbeek and Bruins (1991)
Deep injection	Reduce V_4, TAN_4 and D_4 by 99.5%	Klarenbeek and Bruins (1991)

*Representative figures were taken from a few sources for demonstration purposes; an extensive review was not undertaken.

prior to application appears to reduce loss by increasing the infiltration rate (Sommer and Ersbøll, 1994) whilst any reduction achieved by injection or post-application cultivation is due to a reduction in the volume and area of slurry exposed to the atmosphere (e.g. van der Molen *et al.*, 1990; Chardon *et al.*, 1990). The relationships used within the model to simulate the effect of application/cultivation techniques are shown in Table 2.

Where cultivation does not occur immediately after application, the potential for reducing losses is decreased (Klarenbeek and Bruins, 1991) and losses must be partitioned between the pre- and post-cultivation periods. This is achieved by separately simulating the losses for the periods before and after cultivation, using equations (B7) and (B8) (Appendix B).

Applied slurry losses submodel

Given that slurry applications can be NH_3 sources for a number of days, the total NH_3 loss from applied slurry on day t is

$$A_{4,t} = \sum_{b=1}^{t} A_{4,b,t} \tag{14}$$

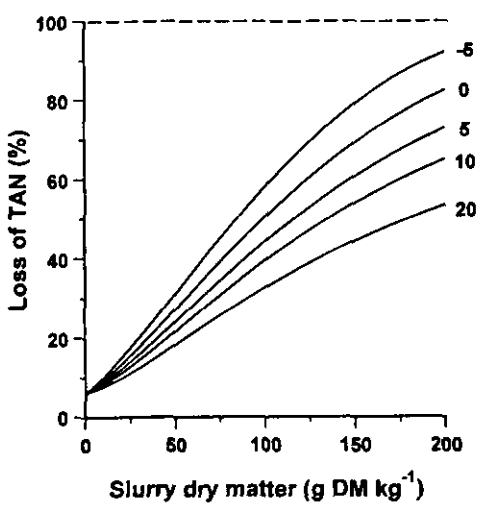

Fig. 2. The volatilization of NH_3 as affected by dry matter in the slurry for five values of excess rainfall ($g\,m^{-2}\,d^{-1} \equiv mm\,d^{-1}$). Initial values: TAN = $27\,g\,m^{-2}$, volume applied = $3\,kg\,m^{-2}$, pH = 7.7. Environment: soil infiltration = $230\,kg\,m^{-2}\,d^{-1}$, air temperature = 15°C, wind speed = $4\,m\,s^{-1}$ and no cultivation.

where $A_{4,b,t}$ is the volatilization on day t from an application made on day b. Volatilization is followed until $V_{4,b,t}$ falls to zero or the $TAN_{4,b,t} < 10^{-7}\,kg\,m^{-2}$.

Behaviour of submodel

The behaviour of the applied slurry submodel is illustrated in Fig. 2. Note that the effect of varying the difference between rainfall and evaporation rate increases with increasing solids content of the slurry. In fact, for a slurry with no solids, rainfall and evaporation rate increase and decrease, respectively, the duration of volatilization, but if all other factors remain constant, neither has an effect on the cumulative loss from a given application.

AMMONIA LOSSES FROM URINE PATCHES

Ammonia losses from grazing animals vary with the environment (Whitehead and Raistrick, 1991) and with the level of fertilizer N applied (Jarvis *et al.*, 1989; Bussink, 1990). In N. Europe, the proportion of N excreted during grazing that is volatilized is generally small (around 10% or less), but is significant in absolute terms as excretal N flows can be large (Scholefield *et al.*, 1991).

The losses from urine patches are treated in the model as though they were slurry applications with a zero solids content. No allowance is made for the time taken for urea to hydrolyse to NH_4^+. However, as with broad spread slurry, an amount η is assumed to be intercepted by the grass crop and all the NH_3 within it lost. There is good evidence that this makes an important contribution to losses from urine patches (Sherlock and Goh, 1985b; Whitehead and Raistrick, 1991). The urine contains no suspended solids so a time step of 1 d is used during the simulation.

TOTAL LOSS FROM THE FARM

The total NH_3 loss from the farm ($A_{F,t}$; $kg\,Nd^{-1}$) is

$$A_{F,t} = \sum_{i=1}^{5} A_{i,t}. \tag{15}$$

The TAN, suspended solids and mass of water were tested for continuity to ensure all material input could be accounted for at the end of the simulation.

Appropriate parameter values were either obtained from the literature or estimated by fitting submodel predictions to observed values. In each case, the data source is shown in Appendix A.

No attempt has been made to validate the model. Although estimates of farm emissions of NH_3 based on N balance models are available (Jarvis, 1993), the authors are unaware of any data set that would allow the model to be validated at the farm scale. The presence within the housing and slurry store submodels of specific house and store factors precludes validation in these cases. The slurry/urine submodel could be validated if a data set could be obtained in which both pH and infiltration rate were measured over the duration of volatilization. The submodel predicts responses to environmental factors that agree qualitatively with those in the literature. The predictions are within the range of values found in the literature, but such is the breadth of that range that it would be difficult to do otherwise. There is an urgent need for simultaneous measurement of ammonia losses from the various on-farm sources over periods of weeks or months.

EXAMPLE SIMULATIONS

Type of livestock system

The model was used to simulate the NH_3 loss from two contrasting types of livestock systems, beef cattle and dairy cows, under the same weather conditions. The quantity and quality of feed and animal growth or milk production for each system are shown in Table 3 and were based on examples given in SCA (1990). The stock number within the dairy system was chosen such that the annual N input to both systems was the same. The duration of the simulation was 1 yr, starting on 1 November and with an empty slurry store. Daily weather data were obtained for the Foulum Research Centre, Denmark, for 1991–1992; mean temperature 7.8°C, total precipitation 730 mm and mean wind speed $3\,m\,s^{-1}$. The evaporation rate was equated to the potential evapotranspiration rate (annual total 405 mm). During the grazing period (days 180 to 365 inclusive), the beef cattle were not housed whereas the dairy cows were housed for $8\,h\,d^{-1}$.

The slurry utilization strategy aimed to simulate applications to spring and autumn sown cereal crops or spring grass whilst also encompassing a range of environmental conditions. Slurry applications were made within both systems at intervals of 5 d from day 200 (17 May) at a rate of $30\,m^3\,ha^{-1}$ until the slurry store was emptied (day 240 and day 225 for the beef and dairy systems, respectively). The first three applications in the spring were made to bare soil, the remainder to fields with a crop cover. Within the dairy system, the slurry that accumulated over the grazing period was fully utilized by further applications to bare soil, beginning on day 345 (10 October) and finishing on day 364 (30 October).

The N excretion per dairy animal ($121\,kg\,N\,yr^{-1}$) was a little higher than the $108\,kg\,N\,yr^{-1}$ obtained from the regression equation of Kirchgessner *et al.* (1991). The equivalent value for the beef cattle ($40\,kg\,N\,yr^{-1}$) is intermediate between the figures for calves and young cattle found by Mandersloot (1992). The ammonia loss from the beef and dairy systems represented 10 and 21%, respectively, of the N excreted. These are lower than the 24 and 27% calculated in ECETOC (1994), reflecting the higher dietary N-concentration assumed in the latter report.

Over 6.5 times more NH_3 was lost per dairy animal than per beef animal (Table 4a), emphasizing the need to disagreggate national animal numbers into different functional classes. The differences cannot be removed by using simple scaling factors such as intake or body size because they arise from systematic variations in animal intake, feed quality and farm management.

A greater proportion of the N input to the dairy system was lost than from the beef cattle system (Table 4a). Despite a greater export of N in milk than

Table 3. Characteristics of the example beef cattle and dairy systems

		Beef	Dairy
Number		100	27.8
Feed intake	$kg\,animal^{-1}\,d^{-1}$	7.5	16.6
Digestibility of feed	%	70	75
N in feed	%	1.6	2.6
Animal growth	$kg\,animal^{-1}\,d^{-1}$	0.6	0
Milk production	$kg\,animal^{-1}\,d^{-1}$	0	18.8

Characteristics common to both systems: housing: a_1 $3.3\,m^2$ $animal^{-1}$, $pH_{1,t}$ 8.0, $V_{w,t}$ $333\,kg\,d^{-1}$, slurry transferred to store weekly; slurry store: a_2 $18.9\,m^2$, $pH_{2,t}$ 7.7, a_y $250\,m^2$, no surface covering, filling location at top; spreading: Ω 0.02, application: $pH_{4,t}$ 7.7, I_s $230\,kg\,m^{-2}$, slurry applied by broad spreading, grazing: $pH_{5,t}$ 8.0.

Values for urine pH are intermediate between those of urine and urine-treated soil (Haynes and Williams, 1992) or slurry (Sommer and Olesen, 1991). The remaining values are derived from data in SAC (1989), Sommer and Olesen (1991) and Lilly (1994).

Table 4. Predicted annual losses of NH_3–N from the two livestock farming systems described in Table 3

(a) Total annual inputs, outputs and losses for each system

System	N input per animal (kg)	Total N input (kg)	N in milk/tissue (kg)	TAN excreted (kg)	NH_3–N lost (kg)	% of N input lost	Loss per animal (kg)
Beef	44	4380	416	1869	484	11.0	4.2
Dairy	138	4379	1011	2299	710	16.2	25.5

(b) Distribution of losses

	Ammonia source (%)				
System	Grazing	House	Storage	Spreading	Applied
Beef	25	9	28	3	36
Dairy	14	7	47	3	29

Table 5. Effect of applying control measures on NH_3 losses from the beef cattle and dairy systems

	Ammonia losses (as percentage of losses without control measures)					
Control measure	Grazing	House	Storage	Spreading	Applied	Total loss
Beef						
A	100	68	102	107	101	98
B	100	100	41	114	111	84
C	100	100	33	114	162	104
D	100	100	100	0	9	64
A + C + D	100	68	33	0	15	45
Dairy						
A	100	70	101	100	101	99
B	100	100	53	113	113	83
C	100	100	55	113	189	106
D	100	100	100	0	9	70
A + C + D	100	70	56	0	19	51

Control measure: A, reduce floor and store surface area per animal from 3.3 to 2.3 m^2; B, cover slurry storage with expanded clay; C, cover slurry storage with lid; D, apply slurry by sod injection.

in animal tissue, the higher quality of feed used in the dairy system meant a greater proportion of the feed N was excreted as TAN. In addition, a greater proportion of this TAN was lost from the dairy than from the beef system (33% vs 26%). The TAN can pass to the soil via two routes: deposition as urine during grazing or through the slurry handling system. The latter offers greater opportunities for NH_3 loss owing to prolonged exposure of the slurry surface in the animal housing, storage and after application. The beef cattle were not housed during the summer so the slurry handling system was inactive, lowering its contribution to the total loss (Table 4b). In contrast, the dairy slurry handling system was active throughout a period when the environmental conditions for volatilization were most favourable.

Effectiveness of control measures

The losses from animal housing can be reduced by altering the design and management of the housing (e.g. Groenestein, 1994) whilst those from storage can be reduced by covering the slurry store (e.g. de Bode, 1991; Sommer *et al.*, 1993). The effectiveness of both methods was tested (Table 5). Effective reductions in the losses from animal housing or slurry storage were less effective in reducing losses from the whole system. In most cases, this was because the reduction in loss led to an increase in the concentration of TAN in the slurry so there was an increase in losses from subsequent sources.

The consequences of using a lid on the slurry store were more complex. In this case, in addition to retaining more TAN in the slurry, the lid prevented rainwater entering. This raised the solids concentration in the slurry and, at the time of application, reduced the rate of infiltration into the soil. The effect of this was to increase volatilization from the applied slurry so the use of a lid on the slurry store had little impact on the total loss from the whole system.

Slurry injection was the most effective single method of reducing losses; proportionately more so in the beef than the dairy system because losses after application were of greater importance. Even greater

reductions were possible when a combination of several control methods was used, although the difference between the beef and dairy systems persisted.

These interactions between NH_3 sources highlight the need to consider the fate of excreta at a farm level when assessing the effectiveness of control measures.

CONCLUSIONS

The substantially greater loss of NH_3 per animal from dairy cattle than from beef cattle emphasizes the need to distinguish between different classes of animal when calculating losses on a farm, region or national scale. The use of dynamic models such as the present one is a means by which emission factors can be amended. The model highlights the complex interactions that occur within and between the various sources of NH_3 on livestock farms. These interactions will modify the effectiveness of control measures and the model clearly demonstrates that it is important to consider the fate of excreta at a farm level when assessing such measures.

The model requires improvement, particularly to the simulation of losses from housing, of chemical transformations within the urine and slurry and of slurry infiltration. A sensitivity analysis and a review of parameter values are required. Inclusion of the losses that occur from solid manures is also a priority as many livestock farms still handle animal wastes in this form. All the control methods considered led to an increase in NH_4^+ entering the soil. This NH_4^+ will enter the soil N cycle and increase the potential for other pollution, e.g. NO_3 leaching or loss of N_2O to the atmosphere. This emphasizes the need to adopt a holistic approach to farm N management.

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APPENDIX A: NOMENCLATURE

Variables subscripted t are the values on day t. Variables subscripted x are the values for NH_3 source number x where source number 1 = animal housing, 2 = stored slurry, 3 = losses during application, 4 = applied slurry and 5 = urine patches.

$A_{x,t}$	NH_3 volatilization from source x (kg N d^{-1})
$A_{F,t}$	total loss of NH_3 from the farm (kg N d^{-1})

State variables

$TAN_{x,t}$	mass of TAN (kg m^{-2})
$TAN_{x,b,t}$	mass of TAN within slurry ($x = 4$) or urine ($x = 5$) deposited on day b (kg m^{-2})
$V_{x,t}$, $V_{x,b,t}$	as above but for the wet weight of slurry or urine (kg m^{-2})
$D_{x,t}$, $D_{x,b}$	as above but for the dry weight of slurry solids (kg m^{-2})
$pH_{x,t}$, $pH_{x,b}$	as above but for pH
$a_{x,t}$	surface area of source (m^2)

Model inputs

α_t	apparent digestibility of animal feed (kg DM (kg DM)$^{-1}$)
θ_t	outside air temperature (°C)
a_y	area of roofing and yard that contributes water to the slurry (m^2)
$c_{b,t}$	nitrogen concentration in the feed supply (kg N (kg DM)$^{-1}$)
E_t	evaporation rate (kg m^{-2} d^{-1})
F_t	quantity of feed eaten per animal (kg DM animal^{-1} d^{-1})
H_t	proportion of the day during which the animals are housed
I_s	soil infiltration rate (kg m^{-2} d^{-1})
K_t	empty body weight gain (kg d^{-1})
M_t	milk yield (kg animal^{-1} d^{-1})
p_t	precipitation rate (kg m^{-2} d^{-1})
$R_{1,t}$	mass of manure removed from the animal housing (kg)

$R_{2,t}$ mass of slurry removed from the slurry store to be applied to land (kg)
S_t number of animals on the farm

Parameters and secondary variables

β water content of faeces ($\mathrm{kg\,(kg\,DM)^{-1}}$) = 6.9*
γ specific weight of slurry ($\mathrm{kg\,m^{-3}}$) = 1000
ε volatilization rate parameter ($\mathrm{kg\,m^{-2}\,d^{-1}}$), equation (B10)
λ dry matter added in bedding and spilt feed ($\mathrm{kg\,DM\,animal^{-1}\,d^{-1}}$) = 0.96**
η interception of slurry or urine by crop ($\mathrm{kg\,m^{-2}}$) = 0.2†
Ω proportion of slurry or urine TAN lost during spreading = 0.02
ζ, μ constants determining the effect of slurry solids on infiltration
c_f concentration of nitrogen in faeces ($\mathrm{kg\,N\,(kg\,DM)^{-1}}$) = 0.025*
c_m concentration of nitrogen in milk ($\mathrm{kg\,N\,(kg\,DM)^{-1}}$) = 0.0053‡
c_w concentration of nitrogen in new animal tissue ($\mathrm{kg\,N\,(kg\,tissue)^{-1}}$) = 0.024‡
$D_{f,t}$ daily faecal dry matter output of the animals ($\mathrm{kg\,DM\,d^{-1}}$)
$I_{b,j}$ infiltration rate during the jth time step within an area that received slurry on day b ($\mathrm{kg\,m^{-2}\,d^{-1}}$)
I_m minimum infiltration rate ($\mathrm{kg\,m^{-2}\,d^{-1}}$)
I_t infiltration rate ($\mathrm{kg\,m^{-2}\,d^{-1}}$) = 0.02
$N_{f,t}$ faecal nitrogen production ($\mathrm{kg\,N\,d^{-1}}$)
$N_{u,t}$ urinary nitrogen production ($\mathrm{kg\,N\,d^{-1}}$)
$Q_{x,t}$ value of the equilibrium coefficient (equation (2))
$r_{1,t}$ resistance to NH_3 transport from the animal housing to the atmosphere ($\mathrm{d\,m^{-1}}$)
$r_{2,t}$ resistance to NH_3 transport from the slurry store to the atmosphere ($\mathrm{d\,m^{-1}}$)
$r_{a,t}$ aerodynamic resistance ($\mathrm{d\,m^{-1}}$)
$r_{b,t}$ boundary layer resistance ($\mathrm{d\,m^{-1}}$)
$r_{c,i}$ resistance of the ith slurry surface covering in the slurry store ($\mathrm{s\,m^{-1}}$)
r_T store-specific resistance ($\mathrm{d\,m^{-1}}$) = 0.000301§
u_f urination frequency (urinations animal^{-1} d^{-1}) = 12¶
u_r urination rate (kg urination^{-1}) = 1.6¶
u_a area of a single urine patch ($\mathrm{m^2}$) = 0.68¶
$V_{u,t}$ mass of urine produced ($\mathrm{kg\,d^{-1}}$)
$V_{f,t}$ mass of water in faeces ($\mathrm{kg\,d^{-1}}$)
$V_{w,t}$ water used in animal housing for washing animals or flushing (kg) = 333‖
$V_{y,t}$ roof and yard runoff ($\mathrm{kg\,d^{-1}}$)
X_1 housing-specific constant = 0.00843**

Data sources: *Dickinson and Craig (1990), †Sherlock and Goh (1985b), ‡SCA (1990), §Olesen and Sommer (1994), ¶van de Ven (1992), ‖Hansen *et al.* (1990), **Mannebeck and Oldenburg (1990).

APPENDIX B: THE TIME COURSE OF NH_3 LOSS IN SLURRY APPLICATIONS AND URINE PATCHES

The rate of change of TAN present in the slurry/urine remaining on the soil surface (TAN_x; $\mathrm{kg\,m^{-2}}$) can be described as

$$\frac{\mathrm{dTAN}_x}{\mathrm{d}t} = -\frac{Q_x\gamma}{r_x}\frac{\mathrm{TAN}_x}{V_x} - I\frac{\mathrm{TAN}_x}{V_x} \tag{B1}$$

where I = infiltration rate ($\mathrm{kg\,m^{-2}\,d^{-1}}$) and the remaining parameters are defined as in equation (1). To improve clarity, let

$$\varepsilon = \frac{Q_x\gamma}{r_x}. \tag{B2}$$

Rearranging equation (B1) gives

$$\frac{1}{\mathrm{TAN}_x}\mathrm{dTAN}_x = -\frac{(\varepsilon + I)}{V_x}\mathrm{d}t. \tag{B3}$$

The volume ($V_{x,t}$; $\mathrm{m^{-2}}$) changes due to infiltration, evaporation and rainfall and at time t

$$V_{x,t} = V_{x,0} - (I + E - p)t \tag{B4}$$

where $V_{x,0}$ is the mass at time $t = 0$, p = precipitation rate ($\mathrm{kg\,m^{-2}\,d^{-1}}$) and E = evaporation rate ($\mathrm{kg\,m^{-2}\,d^{-1}}$). Substituting for V_x in equation (B3) and integrating gives

$$\mathrm{TAN}_{x,t} = K(V_{x,0} - (I + E - p)t)^{(\varepsilon + I)/(I + E - p)} \tag{B5}$$

$$K = \mathrm{TAN}_{x,0}(V_{x,0})^{-((\varepsilon + I)/(I + E - p))} \tag{B6}$$

where $\mathrm{TAN}_{x,0}$ is the TAN present at time $t = 0$ ($\mathrm{kg\,m^{-2}}$).

Volatilization and infiltration can be rapid so the loss on each day is simulated using J small time steps of duration $\delta t = 0.01$ d. The volatilization during the jth time step of day t from slurry ($x = 4$) or urine ($x = 5$) applied on day b ($A_{x,b,t,j}$; $\mathrm{kg\,N\,d^{-1}}$) is:

when $(I_{b,t,j} + E_t - p_t) = 0$

$$A_{x,b,t,j} = a_{x,b}\frac{\varepsilon}{\varepsilon + I_{b,t,j}}\mathrm{TAN}_{x,b,t,j} \times (1 - \exp(-\varepsilon + I_{b,t,j}/V_{x,b,t,j}\delta t)) \tag{B7}$$

otherwise

$$A_{x,b,t,j} = a_{x,b}\frac{\varepsilon}{\varepsilon + I_{b,t,j}}\mathrm{TAN}_{x,b,t,j}(1 - \exp^{K_{b,t,j}} \times (V_{x,b,t,j} - (I_{b,t,j} + E_t - p_t)\delta t)^{(\varepsilon + I_{b,t,j})/(I_{b,t,j} + E_t - p_t)}) \tag{B8}$$

where $a_{x,b}$ is the area of application/deposition made on day b ($\mathrm{m^2}$), $\mathrm{TAN}_{x,b,t,j}$, $V_{x,b,t,j}$ and $I_{b,t,j}$ are, respectively, the TAN present above the soil surface ($\mathrm{kg\,m^{-2}}$), the mass of slurry/urine above the soil surface ($\mathrm{kg\,m^{-2}}$) and the infiltration rate ($\mathrm{kg\,m^{-2}\,d^{-1}}$) at the beginning of the jth time step for applications/depositions made on day b. E_t and p_t are, respectively, the evaporation and precipitation rate on day t ($\mathrm{kg\,m^{-2}\,d^{-1}}$). ε and $K_{b,t,j}$ are defined as

$$\varepsilon = \frac{Q_{x,b,t}\gamma}{I_{x,t}},$$

$$K_{b,t,j} = \ln(\mathrm{TAN}_{x,b,t,j}(V_{x,b,t,j})^{-((\varepsilon + I_{b,t,j})/(I_{b,t,j} + E_t - p_t))}). \tag{B9}$$

If $V_{b,t,j+1}$ falls to or below zero during a time step, then

$$A_{4,b,t,j+1} = \frac{\varepsilon}{\varepsilon + I_{b,t,j}}a_{4,b}\mathrm{TAN}_{4,b,t,j} \tag{B10}$$

and no further volatilization takes place.

The infiltration rate in the absence of slurry solids is determined by that of the soil (I_s; $\mathrm{kg\,m^{-2}\,d^{-1}}$). In reality, volatilization has been observed to increase with the concentration of slurry solids as increasing viscosity reduces infiltration (Sommer and Olesen, 1991; Svensson, 1994). The infiltration rate is assumed to be limited either by the soil or the slurry:

$$I_{b,t,j} = \min(I_s, I_c) \tag{B11}$$

where I_c is the infiltration rate determined by the slurry ($\mathrm{kg\,m^{-2}\,d^{-1}}$). The relationship between slurry composition and viscosity is poorly understood so I_c is related directly to

concentration of solids in V_4:

$$I_c = \exp\left(\xi - \mu \frac{D_{4,b}}{V_{4,b,t,j} + D_{4,b}}\right) \tag{B12}$$

ere ζ and μ are constants. It is assumed that the solids in slurry remain on the soil surface. Using data from Som-r and Olesen (1991), ζ and μ were evaluated as 6.950 and 9, respectively. With these parameter values, the infiltra-n rate approaches zero when the solids concentration is h, leading to excessive expenditure of time simulating the rate of loss that occurs as the slurry TAN nears exhaus-n. This was overcome by constraining I_c to be $\geq I_m$, an bitrary minimum infiltration rate.

The resistance to transport ($r_{4,t}$) is simulated in the man-outlined for losses from slurry stores, omitting the cover istance. The equilibrium coefficient is calculated with the nperature equated to air temperature whilst the pH is umed to be that of the slurry/urine at the time of applica-n.

Volatilization on day t from applications made on day $t = 0$ (kg m^{-2}; $A_{4,b,t}$; kg d^{-1}) is then

$$A_{4,b,t} = \sum_{j=1}^{J} A_{4,b,t,j}. \tag{B13}$$

itial values for slurry applications

The masses of slurry, TAN and suspended solids are fined at the time of application, when $b = t$ and $a_{4,b} = a_{3,t}$:

$$\mathrm{TAN}_{4,b,b,0} = \frac{1}{a_{4,b}}\left(\frac{R_{2,b}\mathrm{TAN}_{2,b}}{V_{2,b}} - A_{3,b}\right),$$

$$V_{4,b,b,0} = \frac{R_{2,b}}{a_{4,b}},$$

$$D_{4,b} = \frac{R_{2,b}D_{2,b}}{a_{4,b}V_{2,b}}. \tag{B14}$$

The pH of the slurry is an input to the model.

itial values for urine depositions

The initial conditions are

$$a_{5,b} = (1 - H_b)S_b u_t u_a,$$

$$\mathrm{TAN}_{5,b,b,0} = \frac{(1 - H_b)N_{u,b}}{a_{5,b}},$$

$$V_{5,b,b,0} = \frac{(1 - H_b)S_b u_t u_t}{a_{5,b}}, \quad D_{5,b} = 0 \tag{B15}$$

here u_a is the area of a single urine patch (m^2).

The pH of the urine is an input to the model. The aerodynamic resistance is calculated assuming the emitting surface has an area of u_a.

APPENDIX C: BUDGETS FOR TAN, WATER AND DRY MATTER

Budgets for the TAN ($\mathrm{TAN}_{x,t}$), water ($V_{x,t}$) and dry matter ($D_{x,t}$) are as follows.

Housing, $x = 1$

$$\mathrm{TAN}_{1,t+1} = \mathrm{TAN}_{1,t}\left(1 - \frac{R_{1,t}}{V_{1,t}}\right) + \frac{(H_t N_{u,t} - A_{1,t})}{a_1} \tag{C1}$$

$$V_{1,t+1} = V_{1,t} + \frac{1}{a_1}(H_t(V_{u,t} + V_{f,t}) + V_{w,t} - R_{1,t}) \tag{C2}$$

$$D_{1,t+1} = D_{1,t}\left(1 - \frac{R_{1,t}}{V_{1,t}}\right) + \frac{H_t D_{f,t} + \lambda S_t}{a_1} \tag{C3}$$

where $R_{1,t}$ is the volume of manure removed at time t (kg) and λ is the dry matter added in bedding and spilt feed (kg DM animal^{-1} d^{-1}).

Storage, $x = 2$

$$\mathrm{TAN}_{2,t+1} = \mathrm{TAN}_{2,t} + \frac{1}{a_2}\left(\frac{R_{1,t}\mathrm{TAN}_{1,t}}{V_{1,t}} - \left(A_{2,t} + \frac{R_{2,t}\mathrm{TAN}_{2,t}}{V_{2,t}}\right)\right) \tag{C4}$$

$$V_{2,t+1} = V_{2,t} + \frac{1}{a_2}(R_{1,t} - R_{2,t} + V_{y,t}) + p_t - E_t \tag{C5}$$

$$D_{2,t+1} = D_{2,t} + \frac{1}{a_2}\left(\frac{R_{1,t}D_{1,t}}{V_{1,t}} - \frac{R_{2,t}D_{2,t}}{V_{2,t}}\right) \tag{C6}$$

where $R_{2,t}$ is the mass of manure removed to be applied to land and $V_{y,t}$ is the mass of runoff from roofs and unroofed yards (kg d^{-1}). The roof/yard runoff is calculated as follows:

when $p_t > E_t$

$$V_{y,t} = a_y(p_t - E_t) \tag{C7}$$

and otherwise $V_{y,t} = 0$. a_y is the area of roofing + unroofed yard that discharges runoff to the slurry store (m^2).