A Process-Based Ammonia Emission Model for Confinement Animal Feeding Operations – Model Development

Ruihong Zhang[1], Thomas R. Rumsey[1], James G. Fadel[2]
[1]Biological and Agricultural Engineering Department
[2]Animal Science Department
University of California, Davis, CA, 95616
rhzhang@ucdavis.edu

Jactone Arogo
Biological Systems Engineering Department
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061
arogo@vt.edu

Zion Wang
Center for Environmental Research and Technology
University of California, Riverside, CA 92507
zsw@mail.cert.ucr.edu

Gerard E. Mansell
ENVIRON International Corporation
101 Rowland Way, Suite 220
Novato, CA 94945-5010
gmansell@environcorp.com

Hongwei Xin
Agricultural and Biosystems Engineering Department
Iowa State University
Ames, Iowa 50011-3310
hxin@iastate.edu

ABSTRACT

A process-based modeling approach was used to develop a comprehensive and predictive ammonia emission model for estimating ammonia emission rates from animal feeding operations. The ammonia emission model consists of farm emission model (FEM) and animal allocation processor (AAP) and can be used to calculate ammonia emission rates both from an individual AFO and from a group of AFOs and also allows predictions of different time scale resolutions. The Farm Emission Model (FEM) covers five animal species, including dairy, beef cattle, swine, layers, broilers, and turkeys. For each species, the FEM reflects different farm practices with regards to animal feeding, animal housing, manure collection and storage, and land application. The overall structure and selected model components of FEM are described in this paper. Some computer simulation results for a finishing swine farm are presented. The predicted ammonia emission rates are variable during the day and over the period of the year.

INTRODUCTION

Ammonia is one of the major gases produced and emitted from animal feeding operations (AFO) due to excretion of nitrogenous compounds from animals and subsequent decomposition in manure. On an AFO, ammonia can impose harms to the health of farm workers and animals at high concentrations. Off an AFO, ammonia can have local and regional air quality impact by contributing to the formation of particular matter and acid rain and nutrient enrichment of surface water. Production and emission of ammonia on an AFO involve complex, dynamic biological, physical and chemical processes and the emission rate of ammonia is influenced by many factors related to animal diet composition and conversion efficiencies, manure handling practices and environmental conditions. Animal diet composition and conversion efficiency affect the quantity and composition of manure excreted by animals and manure handling practices affect the chemical and physical properties of manure, including chemical composition, biodegradability, microbial populations, oxygen content, moisture content, and pH. Environmental conditions include temperature, wind speed, and relative humidity.

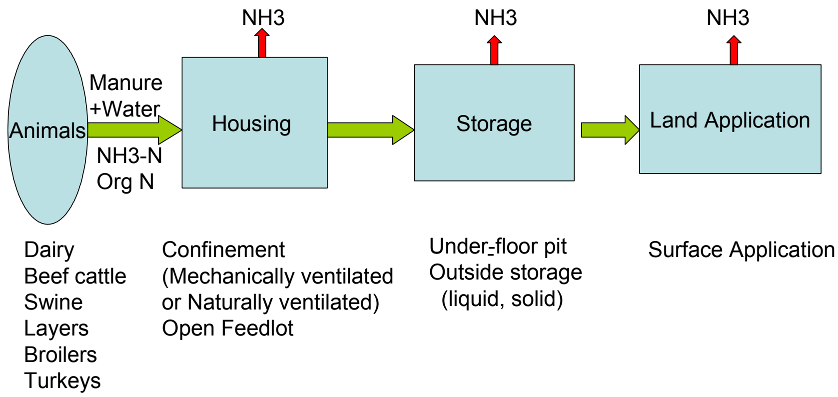
Accurate estimation of ammonia emission rate from animal feeding operations is important for both regulatory agencies and animal producers. Hourly or daily emission rates of these gases from the dairies are needed to assess their contributions to the dynamics of air quality that occurs in different areas and different times of the year so that specific emission control strategies can be effectively developed. Because of this need, a report from National Research Council (NRC, 2003[1]) highlighted the need for emission studies with focus on individual operations or sources within the animal feeding operation and recommended for development of process-based emission models. The major sources of ammonia emission on an AFO include animal housing, manure collection, treatment and storage structures, and land application.

This paper describes the development of a comprehensive process-based ammonia emission model for estimating ammonia emission rates from AFOs. As shown in Figure 1, the ammonia emission model consists of farm emission model (FEM) and animal allocation processor (AAP) and can be used to calculate ammonia emission rates both from an individual AFO and from a group of AFOs and also allows predictions of different time scale resolutions, such as hourly, daily, monthly and yearly. The FEM is designed to calculate ammonia emission rate from different sources on an AFO, including animal housing, manure storage, and land application. The AAP is designed to categorize the numbers and types of AFOs, animal feeding and manure management practices in a county, state, or region, provide input to the FEM and then sum the emission rates from individual AFOs. The ammonia emission model is still under development and validation. The development of FEM is presented in this paper and the development of AAP is presented in a separate paper. Due to the space limit in this paper, an overall structure of the FEM and selected components that are used to calculate ammonia emission rate from finishing swine feeding operations are presented.

Overall Structure of Farm Emission Model (FEM)

The FEM employs both existing models published in the literature and new models developed from this study. For each source of ammonia emission, the physical, chemical, and biochemical processes and reactions that take place and influence ammonia generation and emission are considered. Mass balances are performed on manure and nitrogen, both in ammoniacal and organic forms, as they travel through each of four components in an animal waste management system (Figure 1). The model covers five animal species, including dairy, beef cattle, swine, layers, broilers, and turkeys. For each species, the FEM reflects different farm practices with regards to animal feeding, animal housing, manure collection and storage, and land application. For a given animal species, different growth stages of the animals are considered.

Figure 1. Overall structure of Farm Emission Model.



Animal Excretion Sub-Model

Animal excretion sub-model calculates the manure and nitrogen excretion of animals in response to type and growth stage of animals, feed rations, animal productivity and animal management practices. The new ASAE Standard (ASAE D384[2]) for animal manure production and characteristics is used as the basis for developing the manure and N excretion model. Four categories of swine are considered, including weaning (5-20 kg), finishing (20-120 kg), gestating, and lactating sows. Equations are for days on feed so the equations used for swine must be divided by days on feed to convert to daily excretion. The equations used for calculating the dry matter and nitrogen excretion for finishing pigs are provided below and the definitions of variables are given in Table 1.

Nitrogen Excretion equations for finishing pigs:

Equation (1) $N_{E-T} = N_{I-T} - N_{R-T}$

Equation (2) $N_{I-T} = \dfrac{ADFI_G \times C_{CP} \times DOF_G}{625}$

Equation (3)

$$N_{R-T} = \frac{BW_F \times DP_F \times FFLP_F}{159.4} - \frac{BW_I \times (DP_F - 0.05 \times (BW_F - BW_I)) \times (FFLG_F + 0.07 \times (BW_F - BW_I))}{159.4}$$

Dry manure excretion equations for finishing pigs:

Equation (4) $DM_{E-T} = \dfrac{C_{DM} \times FI_G \times (100 - DMD)}{10000}$

Table 1. Definition of variables used for finishing pigs.

Variable	Description	Units
N_{E-T}	Total nitrogen excretion per finished pig	g/finished pig
N_{I-T}	Nitrogen intake per finished pig	g/finished pig
N_{R-T}	Nitrogen intake per finished pig	g/finished pig
DM_{E-T}	Total dry matter excretion per finished pig	g/finished pig
BW_I	initial body weight	kg
BW_F	final body weight	kg
DOF_G	days on feed to finish pig	days
DP_F	average dressing percent	%

Variable	Description	Units
$FFLP_F$	average fat free lean gain at final weight	%
$ADFI_G$	average daily feed intake over finishing period (as fed)	g/day
FI_G	feed intake per finished pig (as fed)	g/finished pig
C_{CP}	concentration of crude protein in total wet ration	%
C_{DM}	dry matter concentration of diet	%
DMD	dry matter digestibility of total ration	%
Ave BW	average body weight	kg

Animal Housing Emission Sub-Model

Animal housing emission sub-model calculates the ammonia emission rate from confinement animal houses in response to animal numbers and types, building structures, ventilation types (mechanical vs. natural), animal management practices, and manure collection practices. Material balances are used to derive differential equations to predict the concentrations of the following substances in the housing: a) ammonia in the house air and b) ammoniacal nitrogen in the manure, and c) urea within the manure. Energy balances were used to predict indoor air temperature and ventilation rate, which are incorporated into the ammonia emission rate calculations. Mathematical equations and input variables for a mechanically ventilated finishing swine house are provided as follows.

Ammonia Nitrogen emission rate is calculated using the following equation,

Equation (5) $\dot{M}_{house} = q_v \left([NH_3 - N]_{air,house} - [NH_3 - N]_{air,\,out} \right)$

where

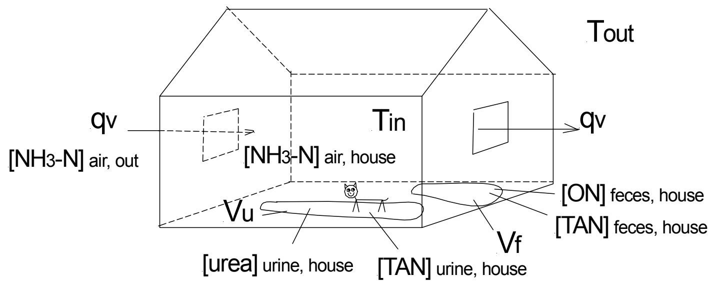
$\dot{M}_{house}$ = ammoniacal nitrogen emission rate from housing (kg N/s)
$[NH_3\text{-}N]_{air,\,house}$ – ammoniacal nitrogen concentration in the housing air (kg N/m^3)
$[NH_3\text{-}N]_{air,\,out}$ – ammoniacal nitrogen concentration in the outside ambient air (kg N/m^3)
q_V = ventilation rate (m^3 s^{-1})

A mass balance model is used to calculate the ammoniacal nitrogen concentration in the housing air. A mechanical ventilation model is used to calculate ventilation rate.

Calculating concentrations of ammoniacal nitrogen in air and urea and TAN in urine

Mass balance equations are used to derive differential equations to predict the concentration of ammoniacal nitrogen in the house air and urea and TAN components in the urine within the house (Figure 2).

Figure 2. Swine housing model for ammonia emission calculations.



The model is based in part on several ammonia emission models that have appeared in the recent literature (Pinder et al., 2004a[3]; Monteny et al. 1998[4]; Vranken, et al., 2003[5]). A schematic of the housing is shown in the sketch below. The air within the house is assumed to be well mixed, and ammonia is assumed to evolve from a single area covered by manure. It is assumed that manure is removed from the house on daily basis and therefore, within the 24 h period, only ammonia generation from urea hydrolysis in the urine is considered.

__Ammoniacal concentration in urine on housing floor__

The ammoniacal nitrogen (TAN) concentration in the urine is calculated using the following mass balance equation,

Equation (6)

$$\frac{d\left(V_u[TAN]_{urine,\ house}\right)}{dt} = V_u K_T \frac{\mu_{max}[urea]_{urine,\ house}}{K + [urea]_{urine,\ house}} - k_{fl} A_u \frac{1}{H}\left(f[TAN]_{urine,\ house} - [NH_3 - N]_{air,\ house}\right)$$

where

A_u = surface area of urine on housing floor (m^2)
f = un-ionized ammonia fraction in solution (dimensionless)
H = Henry's constant (dimensionless)
k_{fl} = mass transfer coefficient at floor (m s^{-1})
K = Michaelis constant (kg urea m^{-3})
K_T = stoichiometric unit conversion factor, 0.467
t = time (sec)
$[TAN]_{urine,\ house}$ = concentration of TAN in the urinein the house (kg urea m^{-3})
$[urea]_{urine,\ house}$ = concentration of urea in the urine in the house (kg urea m^{-3})
Vu = volume of urine, m^3
$\square_{max}$ = Maximum conversion rate at high urea concentrations (kg urea m^{-3} s^{-1})

__Urea concentration in urine on housing floor__

The urea concentration is calculated from the following mass balance for urea in the urine. It is assumed that the urine within the house is well mixed and is essentially one large puddle (Stephanopoulos, 1984[6]; Elzing and Monteny, 1997b[7]).

Equation (7) $$\frac{d\left(V_u\left[\text{urea}\right]_{\text{urine, house}}\right)}{dt} = F_u\left[\text{urea}\right]_{\text{urine, animal}} - V_u\frac{\mu_{max}\left[\text{urea}\right]_{\text{urine, house}}}{K+\left[\text{urea}\right]_{\text{urine, house}}}$$

where

$[\text{urea}]_{\text{urine, animal}}$ = concentration of urea in the urine excreted by the animals (kg urea m^{-3})

F_u = volumetric excretion rate of urine from animals ($m^3\ s^{-1}$)

Ammonia nitrogen concentration in the air in house

The concentration of ammonia nitrogen in the house air is calculated using a component mass balance.

Equation (8)

$$\frac{d\left(V_B[NH_3\text{-}N]_{\text{air,house}}\right)}{dt} = q_v[NH_3\text{-}N]_{\text{air,out}} - q_v[NH_3\text{-}N]_{\text{air,house}} + k_{fl}A_u\frac{1}{H}\left(f[TAN]_{\text{urine, house}} - [NH_3 - N]_{\text{air, house}}\right)$$

where

V_B = interior volume of housing (m^3)

Volume of urine and feces in housing

The urine is assumed to be confined to a single large area (some fraction of the total housing floor area) that is continuous and well mixed. Based on the assumption that the urine density is constant, the volume change of urine in the house (Stephanopoulos, 1984[6]) is

Equation (9) $$\frac{dV_u}{dt} = \frac{N_{\text{animals}}(t)\times L_w\times E_u}{1000\times 24\times 3600\times \rho_u}$$

Where

E_u = urination rate (kg urine/1000 kg live animal weight/day)

L_W = Average live weight (kg/animal)

$N_{\text{animals}}(t)$ = number of animals in housing as function of time

ρ_u = density of urine (kg m^{-3})

V_u = volume of urine in house (m^3)

T = time (s)

Similarly, volume change of feces in the house is,

Equation (10)
$$\frac{dV_f}{dt} = \frac{N_{\text{animals}}(t)\times L_w\times E_f}{1000\times 24\times 3600\times \rho_f}$$

where

E_f = defecation rate (kg urine/1000 kg live animal weight/day)

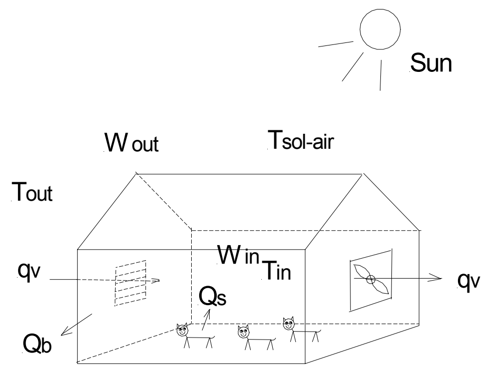
ρ_f = density of feces (kg m^{-3})

These equations are valid in between the times when the house is flushed or scraped for manure removal. It does not account for the water used for flushing, nor the release of flushed water, urine and feces.

Calculating ventilation rate and air temperature in the animal house

Thermal energy and moisture models are used for calculating the ventilation rate, indoor temperature and humidity. Figure 3 shows a model swine house.

Figure 3. Swine housing model for ventilation rate and indoor temperature calculations.



A transient thermal energy balance model similar to that given in Panagakis and Axaopoulos (2004[8]) is developed,

Equation (11) $$\sum(M_a C_a)\frac{dT_{in}}{dt} = \dot{Q}_s + \dot{Q}_b + \dot{Q}_v$$

where

$\sum(M_a C_a)$ = lumped effective building capacitance (J/°C)

T_{in} = inside air temperature (C)

t = time (s)

$\dot{Q}_s$ = animal sensible heat production (W)

$\dot{Q}_b$ = heat flow through the walls, the door and the roof (W)

$\dot{Q}_v$ = heat losses due to ventilation (W)

The equations for calculating animal heat production are taken from Pedersen and Sallvik (2002[9]), and will not be repeated here. They are primarily a number of empirical equations that were obtained by regressions on experimental data from the literature.

The structural heat losses are calculated using standard steady state heat transfer analyses (Panagakis and Axaopoulos, 2004; MWPS, 1982).

Equation (12) $\dot{Q}_b = \sum_i U_{bi} A_{bi} \left(T_i - T_{sa,i} \right)$

where

U_{bi} = overall heat transfer coefficient of each surface (W/m^2 °C)

A_{bi} = surface area (m^2)

$T_{sa,i}$ = sol-air temperature (°C)

Our model assumes heat losses through the floor are small compared to the other heat flows. The sol-air temperature (Albright, 1990[10]; Cooper et al.,1998[11]) was calculated from hourly temperature and solar radiation data for each wall and roof surface.

The heat loss due to ventilation involves the ventilation rate and the difference between the outside and inside air temperatures.

Equation (13) $\dot{Q}_v = \rho q_v c_p \left(T_{out} - T_{in} \right)$

where

q_v = ventilation rate (m^3 s^{-1})

c_p = specific heat of air (J kg^{-1} °C^{-1})

ρ = density of air (kgm^{-3})

T_{out} = outside temperature (°C)

T_{in} = indoor air temperature (°C)

An idealized linear control law is used to determine the ventilation rate (Schauber, et al.. 2000[12]).

Equation (14) $q_v = \begin{cases} V_{min}; \ T_{in} \le T_{set} \\ V_{min} + \left(T_{in} - T_{set} \right) \times \left(V_{max} - V_{min} \right) / \Delta T_c \\ V_{max}; \ T_{in} > T_{set} + \Delta T_c \end{cases}$

where

Tset = set point temperature (°C)

ΔTc = band width (°C)

Vmin = minimum ventilation rate (m^3/s)

Vmax = maximum ventilation rate (m^3/s)

The absolute humidity of the air in the house is calculated using an equation given by Panagakis and Axaopoulos (2004[8]).

Equation (15) $\rho_a V_b \frac{dW_i}{dt} = m_a \left(W_{out} - W_{in} \right) + \dot{W}_L$

where

m_a = ventilation air mass flow rate (kg s^{-1})

V_b = volume of the inside air space (m^3)

W_{in} = inside air humidity ratio (kg (H_2O) kg^{-1} (dry air))
W_{out} = outside air humidity ratio (kg (H_2O) kg^{-1} (dry air))
$\dot{W}_L$ = animal water vapor production (kg s^{-1})

The water vapor production is given by empirical equations in Pedersen and Sallvik (2002[9]).

Animal Manure Storage Sub-Model

The rate of total ammoniacal nitrogen (TAN) volatilized from the storage surface is modeled by (Arogo, et al., 2003[13]):

Equation (16) $\dot{M}_{TAN\ volatilized} = K_L\ A\left(F\,[TAN]_{TAN} - [TAN]_{air}\right)$

where

A = surface area of storage (m^2)
F = fraction of TAN present as free ammoniacal N.
K_L = mass transfer coefficient (m/s)
$\dot{M}_{TAN\ volatilized}$ = rate TAN volatilized from storage surface (kg/s)
[TAN] = concentration of TAN in the storage liquid (kg /m^3)
$[TAN]_{air}$ = concentration of TAN in the ambient air (kg /m^3)

The concentration of TAN in the storage is calculated by solving mass balance equations for total manure, total ammoniacal nitrogen and organic nitrogen with assumptions that the loss of mass due to emissions of gases and seepage through the storage are negligible. All of the mass balances were done between clean outs of the housing. The transfers from the housing to storage and from storage to field were assumed to be instantaneous, and were handled in the initial conditions for differential equations. A new set of initial conditions was used when the store was emptied and the manure removed for field application.

Total mass balance is given as,

Equation (17) $\dfrac{d(\rho V_T)}{dt} = \dot{M}_{rain} - \dot{M}_{evap}$

Component balance on TAN is,

Equation (18) $\dfrac{d(V_T[TAN])}{dt} = k_{ON}[ON]V_T - K_L\ A\left(F\,[TAN] - [TAN]_{air}\right)$

Component balance on organic nitrogen

Equation (19) $\dfrac{d(V_T[ON])}{dt} = -k_{ON}[ON]V_T$

where

V_T = volume of manure in storage (m^3)

$\dot{M}_{rain}$ = rate of rain into top surface of storage (kg s^{-1})

$\dot{M}_{evap}$ = rate of evaporation water from top surface of storage (kg $^{s-1}$)

t = time (s)

K_{ON} = rate constant for organic nitrogen mineralization (s^{-1})

[ON] = organic nitrogen concentration in storage, kgm^{-3}

The water evaporation rate is calculated using semi-empirical equations (Ham, 1999[14]), and the rain fall rate is determined from hourly weather data. The relation between pond volume, depth and surface area were determined using equations given in MWPS (1982[15]).

RESULTS AND DISCUSSIONS

Simulation results on ammonia emission rate from housing and storage of a fictitious finishing swine facility located in Davis, CA are presented. The experimental hourly weather data for Davis are available from the California Irrigation Management Information System (CIMIS) web site (http://wwwcimis.water.ca.gov/cimis/welcome.jsp). Weather data for the year 2002 were used in these preliminary tests.

Primary input data are given in the Tables 2-4. The manure parameters for these initial runs were taken from ASAE Standard D384.1 and from several papers in the literature. They were not generated using the model equations given in the first part of the model (animal excretion).

Table 2. Inputs for the swine farm.

Total number of pigs on farm	812
Number of housing units	7
Number of pigs in each house	116
Weight of single pig (kg)	148
Urine production rate (kg /1000 kg live animal wt/day)	39
Fresh manure production rate (kg /1000 kg live animal wt/day)	84

The physical data for the housing was taken from a handbook of building plans (MWPS, 1984). The plan used is for a mechanically ventilated swine house (MWPS 72601). Ventilation system parameters were estimated from Schauberger, et al. (2000[12]) and MWPS (1983). Fresh water usage was estimated from MWPS (1983).

Table 3. Inputs for housing emission sub-model.

Length (m)	28	U roof (W/m^2 °C)	0.27
Width (m)	10.1	F perimeter (W/m °C)	1.50
Eave height (m)	2.5	Set point temperature (°C)	20
Roof slope (dec)	1/4	Band width (°C)	4
Building orientation (deg from north)	90	Minimum ventilation rate (m^3/s)	0.66
Fraction of total area for urination (dec)	0.80	Maximum ventilation rate (m^3/s)	14.7
U side walls (W/m2 °C)	0.43	Time between flushing (hr)	8
U end walls (W/m2 °C)	0.43	Fresh water for flushing (gal/day/head)	15

Outdoor storage parameters were estimated from handbooks dealing with animal manure facilities (MWPS, 1983 and USDA, 1996). The basic dimensions were determined using an equation for rectangular storage volume given in the USDA (1996) handbook.

Table 4. Inputs for storage emission sub-model.

Bottom length (m)	80
Bottom width (m)	40
Side slope	3
Initial volume material in storage (m^3)	100
pH	7.0
Initial [TAN] (kg/m^3)	0.5
Initial [ON] (kg/m^3)	0.1
Time interval between removal of manure solution from storage (days)	180
Fraction of manure solution removed from storage	0.5

The model equations were solved using Matlab; an ordinary differential equation solver (ode15s) was used to solve the simultaneous differential equations. Predicted results are discussed in the sections below.

Ammonia emissions from a single house

Predicted ammonia emissions for the first two days in February (day of year = 31 through 32) and the first two days in August are shown in Figures 4 and 5, respectively. The units for emission are grams of nitrogen per day per animal unit, where an animal unit is defined as 500 kg live mass (Arogo et al., 2003[13]). The emission rates predicted by the model are on the order of 50 (g/d-AU), which is higher than the range of 6 to 35 (g/d-AU) reported for a daily flushed system reported by Arogo et al. (2003[13]) in their review.

Sharpe spikes occur at the times the manure is flushed from the house. We are not aware of published experimental data that would confirm these spikes. Predicted emissions for the first two days in August are even higher than those for the February predictions.

These emissions were averaged over each month of the year by numerically integrating the instantaneous rates (Figure 6). The emissions peak in the summer months and are approximately twice those for the winter. Harper, et al. (2004[17]) measured daily emissions rate from a swine housing; their summer time emission rates were approximately twice those for the winter. The monthly average emissions follow the monthly average temperature inside the house.

Figure 4. Predicted ammonia emission rate for two days in February.

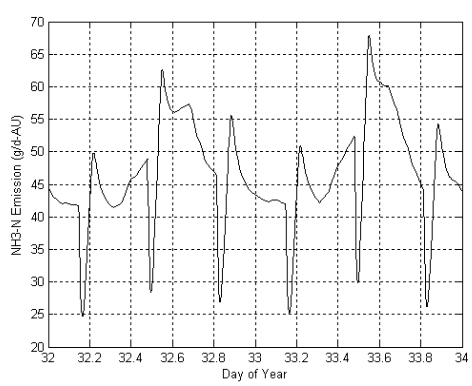


Figure 5. Predicted ammonia emission rate for the first two days in August.

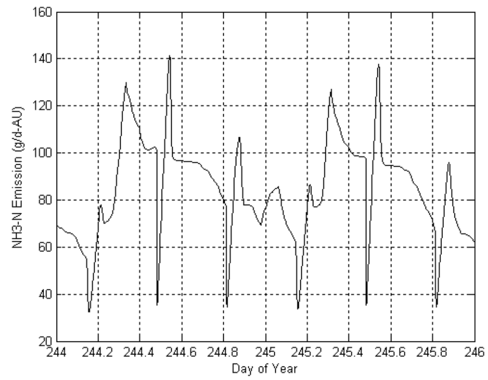
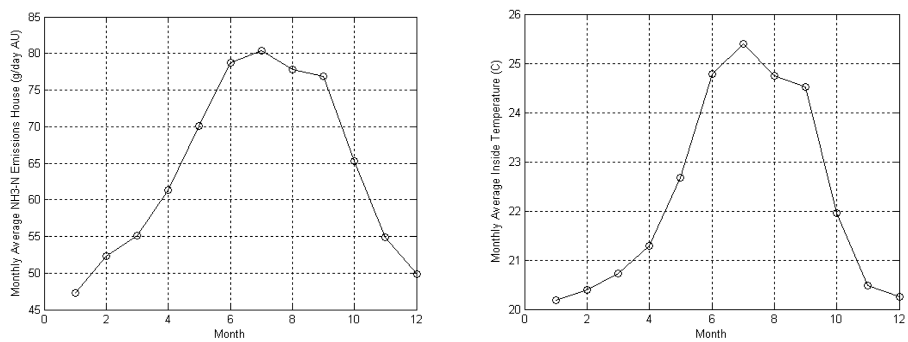


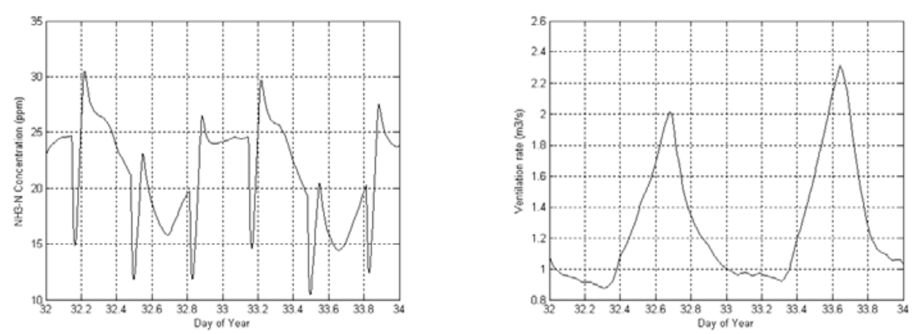
Figure 6. Predicted ammonia emission rate as monthly averages (a) in comparison with monthly average temperature inside the house (b).



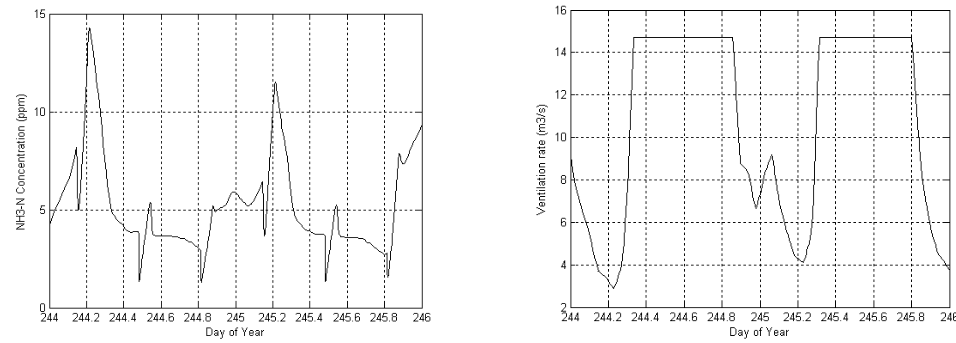
(a) (b)

The emissions are calculated from the product of the ventilation rate and the concentration of ammonia nitrogen in the house (equation (5). Plots of the ammonia nitrogen concentration (in ppm) and ventilation rate for the first two days of February and August are shown in Figure 7. Both ammonia concentration and ventilation rate contribute to the variations in emissions. The spikes that are seen in the emissions show up in the ammonia nitrogen concentrations and not in the ventilation rates.

Figure 7. Predicted ammonia concentration in the swine house for the first two days of February (a) and August (c) and ventilation rate for the same time (b) and (d).



(a) (b)

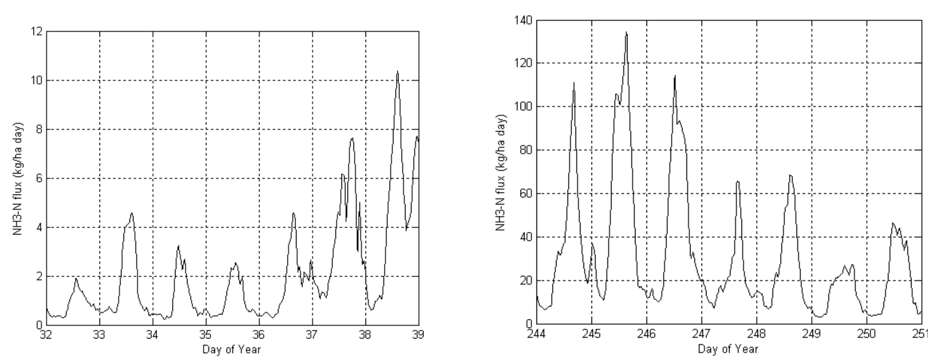


(c) (d)

Ammonia nitrogen emissions from storage

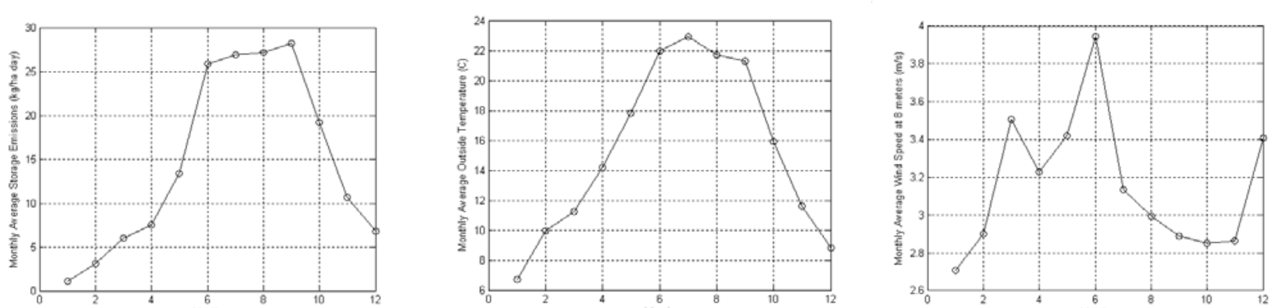
Emission from storage also varied during the day and over the period of the year. A plot of ammonia emissions for the first weeks in February and August of 2002 are shown in Figure 8. The predicted emission rates are consistent with the emissions given in the review paper by Arogo et al. (2003[3]). The rates are lower in the winter (on the order of 1 to 2 kg ha^{-1} d^{-1})) and reach 50 to 100 (kg$ha^{-1}$$d^{-1}$) during summer months. The emissions were integrated over each month of the year and shown in Figure 10 together with the temperature and wind speed. Monthly average values show a pattern similar to that found for the housing emissions (Figure 9). They track the monthly average outside air temperature. They also seem to follow monthly wind speed, although, the relationship does not seem as strong as that for temperature.

Figure 8. Predicted ammonia emission rate from manure storage for the first two weeks of February (a) and August (b).



(a) (b)

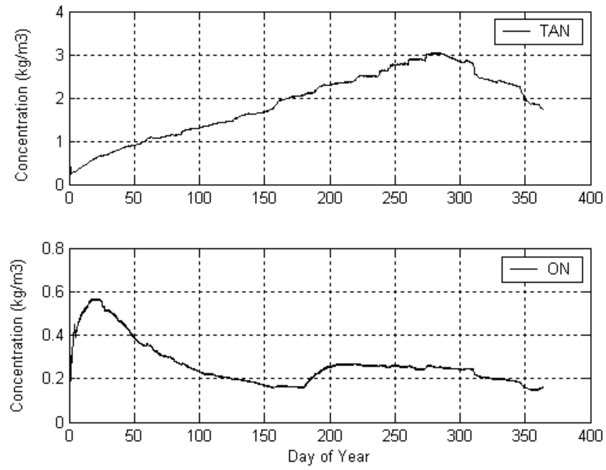
Figure 9. Predicted ammonia emission rate from storage as monthly averages (a) in comparison with monthly average temperature (b) and wind speed (c).



(a) (b) (c)

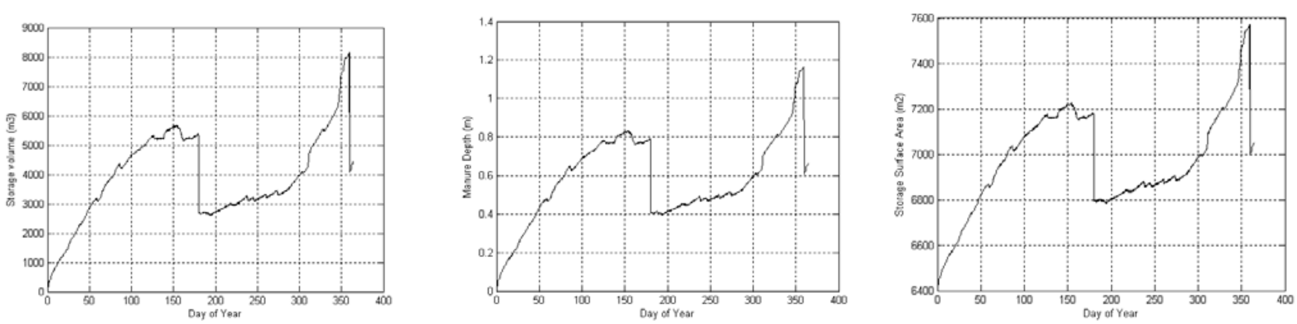
Concentrations of TAN and organic nitrogen are plotted for the entire year in Figure 10. The decline of TAN and ON concentrations is mainly caused by the dilution from increased rainfall. It is apparent that steady state concentrations are not achieved during the year.

Figure 10. Predicted ammoniacal nitrogen (TAN) and organic nitrogen (ON) concentrations in storage over one-year period.



Plots of storage volume, depth and surface area increase with time and all show the same pattern (Figure 11). The times for partial emptying (day 180 and 360) are obvious. Periods of rain are apparent when there is a sharp increase in the storage features – see for instance storage responses around days 310 and 360. There are also several periods of high evaporation loss, especially around day 160.

Figure 11. Predicted manure volume (a), depth (b), and surface area (c) in storage over one year period.



(a) (b) (c)

CONCLUSIONS

A process-based, predictive ammonia emission model was developed for estimating ammonia emission rates from animal feeding operations. Some simulation results for a hypothetical finishing swine farm located in Davis, California, are presented. The predicted ammonia emission rates are variable during the day and over the period of the year. The emission rates predicted for a flushed swine house are on the order of 50 (g N $d^{-1}AU^{-1}$), which are higher than the range of 6 to 35 (g N $d^{-1}AU^{-1}$) reported in the literature. They are highly correlated to the temperature inside the house, higher in summer months and lower in winter months. The predicted emission rates from storage are consistent with the emissions given in the literature. The emission rates are lower in the winter (on the order of 1 to 2 kg N ha^{-1} d^{-1})) and reach 50 to 100 (kg N $ha^{-1}d^{-1}$) during summer months. They are highly correlated with outside temperature and wind speed. Other conditions that affect the emission rates, such as storage configurations, are under investigation. More research is needed to complete the FEM and perform sensitivity analyses of various variables and computer simulations for different animal feeding and manure management practices, animal housing designs, and environmental conditions.

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KEY WORDS

Ammonia emission, modeling, animal manure, animal waste, animal housing, land application

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