PREDICTING MANAGEMENT EFFECTS ON AMMONIA EMISSIONS FROM DAIRY AND BEEF FARMS

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ABSTRACT. *Relationships were developed to predict ammonia (NH_3) nitrogen losses from cattle manure in animal housing, during manure storage, following field application, and during grazing. Ammonia loss in each phase was predicted using a mechanistic model for NH_3 volatilized from the surface of an aqueous solution of ammonium where the NH_3 is transported to the free atmosphere through a pathway with finite resistance. Ammonia emission rate was a function of the ammoniacal N content in the manure, ambient temperature, manure pH, manure moisture content, and the exposed manure surface area. Model relationships were calibrated by selecting values for the resistance to NH_3 transport for the various loss pathways, which predicted daily and annual emissions similar to those reported in published studies. In further evaluation, these calibrated relationships predicted average annual losses similar to those documented in previous work over a range in climate locations. These relationships were integrated into a whole-farm simulation model to provide a tool for evaluating and comparing long-term nitrogen losses along with other performance, environmental, and economic aspects of farm production. Whole-farm simulations illustrated that the use of a free stall barn, bottom-loaded slurry storage, and direct injection of manure into the soil reduced NH_3 emissions by 33% to 50% compared to other commonly used dairy housing and manure handling systems in the northeastern U.S. The improvement in nitrogen utilization more than offset the increased cost in manure handling, providing a small increase in farm profit. The farm model provides a research and teaching tool for evaluating and comparing the economic and environmental sustainability of dairy and beef production systems.*

Keywords. *Ammonia emission, Cattle production, Farm model, Nitrogen loss, Simulation.*

The effect of farms on the environment has become a major social concern in many developed countries, particularly in regions with high concentrations of animal production. On many of our animal producing farms today, more nutrients are being brought onto the farm through feed, fertilizer, legume fixed N, and deposition than are leaving the farm in animal products or crops sold. This leads to the accumulation of nutrients in the soil and loss to the environment.

Environmental concerns include nutrient losses to the atmosphere, surface water bodies, and groundwater. Nutrients of greatest concern are nitrogen (N) and phosphorus (P). Nitrogen loss in the form of nitrate leaching to groundwater has been a major concern for agriculture. In recent years, P loss in runoff following storm events has also become an important issue. A growing concern, though, is the volatilization of gases from animal facilities. An important gaseous emission is N in the form of ammonia (NH_3). Depending on farm management, NH_3−N losses can be up to two or more times the N loss occurring through other pathways (Rotz, 2004). Ammonia emissions are of concern because NH_3 in the atmosphere contributes to the formation of fine particulate matter with potential adverse effects on human health, including premature mortality, chronic bronchitis, and asthma attacks (McCubbin et al., 2002). Atmospheric NH_3 also contributes to over-fertilization, acidification, and eutrophication of ecosystems, which may occur near or at a considerable distance from the NH_3 source (NRC, 2003).

Changes in technology and management such as low-protein diets, low-emission barns, covered manure storages, and manure application through injection into the soil can be used to reduce ammonia emissions (Rotz, 2004). However, such changes should not be made without considering interactions with other aspects of farm performance, environmental impact, and profitability. Focusing on the reduction of loss from one part of the farm is of little value if that change just leads to additional loss from another part of the farm. For example, reducing NH_3 emission in the barn can simply lead to greater emissions during manure storage and field application if all components of the farm are not managed in an integrated way to reduce loss. Reducing gaseous N loss can also lead to over-application of N on cropland, with excessive loss through nitrate leaching. Environmental benefits also must be weighed against production costs and farm profit to determine the economic impact on the producer.

Thus, a comprehensive whole-farm approach is needed to develop and evaluate animal production systems that reduce environmental concerns while maintaining profitable operations. The Integrated Farm System Model (IFSM) was developed as a research and educational tool to assist this type of evaluation (Rotz and Coiner, 2005). This farm simulation model is used to evaluate and compare the

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long-term performance, economics, and environmental impact of farm production systems. To broaden the application of this model, a more robust component was needed for predicting NH_3 emissions from manure in housing facilities, during storage, following field application, and during grazing. Addition of this component model enabled a more comprehensive assessment of the effects of changes made to reduce NH_3 emissions and their interactions with other parts of the farm.

Both empirical and mechanistic approaches have been used to model NH_3 emissions from manure. Sogaard et al. (2002) developed an empirical model of NH_3 volatilization from field-applied slurry using an experimental database collected throughout Europe. Empirical information also has been used to model NH_3 emissions from animal agriculture in the U.S. (EPA, 2004) and the impacts of farming practices on N fluxes for all of agriculture in the Netherlands (de Vries et al., 2001). Mechanistic models predict emissions by describing the physical, biological, and chemical processes involved (Ni, 1999). Monteny et al. (1998) developed a detailed mechanistic model to simulate NH_3 emissions from Dutch dairy cow houses that use slatted floors with slurry storage under the slats. Hutchings et al. (1996) used less detail in a dynamic model of NH_3 volatilization to predict all sources of emission from grazing livestock farms. This model has been adapted by others to predict NH_3 emissions from field-applied slurry (McGechan and Wu, 1998), to simulate losses in the dynamic farm model FASSET (Berntsen et al., 2003), and to map temporal and spatial variation in NH_3 emissions from dairy farms across the U.S. (Pinder et al., 2004).

Our goal was to develop and evaluate a process-based model of NH_3 emissions in cattle production for use in IFSM. Specific objectives were: (1) to adapt and expand the mechanistic model of Hutchings et al. (1996) to simulate NH_3 emissions from manure in housing facilities, during storage, following field application, and during grazing; (2) to verify emission predictions for common manure handling practices; and (3) to use the farm model to illustrate the environmental impact and economics of manure management options commonly used on U.S. dairy farms.

Model Description

Ammonia loss from manure can be predicted using a relationship for NH_3 volatilized from the surface of an aqueous solution containing ammonium where the NH_3 is transported to the free atmosphere through a pathway with a finite resistance (Hutchings et al., 1996). Assuming a very low (zero) concentration of NH_3 in the free atmosphere, volatile loss can be determined as:

$$\text{Loss} = \text{TAN} * c * \gamma / (r * M * Q) \qquad (1)$$

where

Loss = NH_3–N loss (kg N/m^2/d)
TAN = total ammoniacal N in the manure solution (kg N/m^2)
r = resistance of NH_3 transport from the manure surface to the free atmosphere (s/m)
M = manure solution mass per unit area of exposed surface (kg/m^2)
γ = manure specific density (assumed to be 1000 kg/m^3)
Q = dimensionless equilibrium coefficient for the NH_3 gas in the air for a given concentration of TAN in the solution.
c = time conversion (86400 s/d).

By Henry's law of distribution, the equilibrium coefficient can be defined as:

$$Q = K_h * K_a \qquad (2)$$

where

K_h = Henry's law coefficient
K_a = disassociation coefficient of ammonium.

These two coefficients are a function of temperature and pH (Sherlock and Goh, 1985):

$$K_h = 10^{(1478 / (T + 273) - 1.69)} \qquad (3)$$

$$K_a = 1 + 10^{(0.09018 + 2729.9 / (T + 273) - \text{pH})} \qquad (4)$$

where

T = manure solution temperature (°C)
pH = manure solution acidity.

By integrating these relationships over the time of manure exposure, NH_3 loss is predicted. As described in the following sections, this general relationship was adapted to predict losses in animal housing, during manure storage, following field application, and from grazing animals. Relationships developed for each of these specific emission sources were then calibrated to predict reported emission rates. This was done by selecting values for the resistance to NH_3 transport (r) for the various emission pathways that provided daily emission rates similar to those reported from experimental studies. Given the limited data available for developing model parameters, this calibration procedure was used to ensure that predicted daily and annual emissions adequately represented reported emissions.

Two assumptions were made that simplified this model for whole-farm simulation. First, r was set at constant values for emissions other than those in a barn. Although meteorological conditions such as temperature and wind velocity affect this resistance, these effects were not considered. Second, manure pH may vary through time due to biological and chemical processes in the manure. Because these changes would normally be small and difficult to predict, we assumed a constant pH during each of the four pathways of loss. These simplifications were justified because these variations would tend to average out over time, with little impact on whole-farm simulations over many years of weather.

Animal Housing Loss

Ammonia loss was modeled for cattle housing facilities typically found on U.S. farms. These included tie stall, free stall, and open feedlot facilities. Manure was collected from gutters in a tie stall barn, from smooth floors in a free stall barn, and from an open soil surface on a feedlot. Manure was removed from tie stall and free stall barns through periodic scraping in intervals of two days or less. Scraping of feedlots was assumed to occur at relatively long intervals of several weeks or more. Another common practice in free stall housing is manure removal through flushing with recycled liquid separated from manure solids. Since data were not available to compare scraped floors to those flushed with this TAN-containing solution, they were assumed to have the same emission rate. The option of using a slatted floor with a storage tank below the floor was not modeled. Limited data indicate that the loss with this option is greater than that from a scraped floor but likely similar to the total loss from a scraped floor and an open manure storage tank (Rotz, 2004).

Daily NH_3–N emission was determined assuming that the characteristics of the exposed manure remained relatively constant throughout each day. Although manure is typically removed at intervals within a day, scraping also tends to mix urine and feces and spread a thin surface layer that remains on the floor surface. Scraping frequency has been found to have little effect on NH_3 emission (Braam et al., 1997; Rotz, 2004).

The exposed manure surface area was set considering typical barn designs (PSU, 2006). For free stall barns, the area was defined as 80% of the alley area available to animal traffic divided by the number of stalls. This provided an area of 3.5 m^2 per cow (or finishing beef animal). For growing animals, surface areas were 2.0, 2.5, and 2.4 m^2 for dairy heifers under one year of age, heifers over one year of age, and stocker beef cattle, respectively. For tie stall barns, an area of 1.5 m^2 per cow was assumed, which was twice the open gutter surface area behind each animal. This area included the open gutter surface, gutter walls, and the surrounding floor typically fouled by each animal. The manure solution mass on the floor (M) was determined as the daily urine excreted by the housed animals divided by the exposed surface area. Urine production was obtained from the animal component of IFSM where urine excretion was a function of animal size, feed intake, protein intake, and milk production (Fox et al., 2004; Rotz and Coiner, 2005).

For NH_3 loss during enclosed animal housing, the resistance of NH_3 transport (r) was a function of the ventilation air temperature (Hutchings et al., 1996; Mannebeck and Oldenburg, 1991):

$$r = \text{HSC}\,(1 - 0.027\,(20 - T)) \qquad (5)$$

where HSC is a housing-specific constant (s/m).

A value for r was determined for each simulated day using the average ambient temperature. Manure temperature was assumed to be equal to this average daily temperature in determining the equilibrium coefficient with equations 2, 3, and 4. Manure solution pH was set at 7.7 to represent a typical value for urine excreted by lactating dairy cattle buffered in a mixture with feces (Pinder et al., 2004; Burgos et al., 2005).

A suitable housing-specific constant was established by calibrating the model to predict reported NH_3–N losses from free stall barns. Most measurements have been made in northern Europe, where typical emission rates range from 20 to 45 g N/cow/d (Monteny and Erisman, 1998; Groot Koerkamp et al., 1998). For a 25-year simulation of dairy cows in a free stall barn using Wageningen weather and a selected housing-specific constant of 260 s/m, the model predicted annual NH_3–N losses of 33 to 39 g N/cow/d with a 25-year mean of 35.7 g N/cow/d. Daily NH_3 loss increased 1% to 6% for each °C increase in ambient temperature, which was similar to that found by Groot Koerkamp et al. (1998).

The same housing model was used for open feedlots except that a constant value was assigned for r. Since ventilation was not a factor, the influence of temperature on r was not included. Surface areas covered by urine were set at 5.0 and 3.2 m^2 for mature and growing animals, respectively. These areas were estimated considering the average area covered by urine deposits per animal over 2 d (Oenema et al., 2001). The pH of feedlot manure was set at 7.7 (Eghball et al., 1997). A constant r value of 80 s/m was used. This, along with the simulated storage of manure on the lot, caused loss of nearly all available TAN.

The TAN in manure deposited on the barn floor or earthen lot was obtained from the animal component of IFSM. The daily TAN was the non-organic portion of the total N excreted, which was determined as the sum of the urine N from all animals in the housing facility. Urinary N production was a function of the age, size, and milk production level of the animals in each housing facility and the amount and type of protein in their diet (Rotz and Coiner, 2005).

With the use of equation 1, NH_3 loss was determined for each day based on the amount of manure TAN excreted and the ambient temperature for the day. By integrating over each simulated year, annual losses were determined. The proportion of N lost during animal housing each year was the annual NH_3–N loss divided by the total N excreted in the housing facility during the year.

Manure Storage Loss

On farms where manure is stored outdoors for an extended time in a pile, tank, or pond, NH_3 emission continues during this storage period. This loss was modeled considering the TAN content and pH of the stored manure, the ambient temperature, and the exposed surface area for the storage facility. Manure was stored in either liquid (5% dry matter, DM), slurry (8% DM), semisolid (13% DM), or solid (20% DM) form. Manure DM content affected the volume of manure stored and the resistance to NH_3 transfer at the manure surface. For a feedlot, manure was assumed to be stored in solid form.

The TAN in storage on a given day was the accumulated TAN removed from the housing facility plus a portion of the organic N entering storage. The TAN entering storage each day was the urinary N excreted minus the TAN lost in the housing facility. Slurry and liquid manures were assumed to spread across the exposed surface of the storage facility, where the surface area was determined by the storage dimensions set by the model user. Thus, in the early stages of loading, manure was in a relatively thin layer, with a large surface area per unit volume stored. As the storage facility filled, this surface area to volume ratio decreased, so less NH_3 was lost per unit of manure TAN in storage.

The organic N entering storage was that excreted in feces, assuming that no loss or transformation would occur prior to storage. The portion of the organic N mineralized to form TAN during long-term storage was set based on the work of Patni and Jui (1991). They found that 25% to 35% of the organic N in slurry was mineralized during long-term storage, with greater mineralization in the summer months, and most of this change occurring during the first 4 to 6 months of storage. Since average manure storage time was half of the full storage period, the amount of organic N mineralized was set at 12% for a 6-month winter storage period, 21% for a 6-month summer storage period, and 25% for a full-year storage period.

Daily NH_3 loss from storage was determined using equation 1, where TAN was the ammoniacal N and M was the mass of manure solution in storage on that day. On a given day, the amount of TAN was that coming into storage minus that lost from storage between the date loading began and the given date. The mass of manure solution was the total manure mass minus the manure DM loaded into storage. Daily changes due to precipitation and evaporation were ignored, but *M* included the long-term moisture added from wash water and rain. A daily value for the equilibrium coefficient was determined using equations 2, 3, and 4 and the average daily ambient temperature. Reported values for manure pH during storage vary between 6.5 and 8.5, with a typical value being 7.5 (Pinder et al., 2004; Sommer et al., 1993). A constant value of 7.5 was assumed throughout the storage period.

Major options modeled for manure storage included solid manure in a stack, semi-solid manure in a stack, slurry in a tank loaded from the top, slurry in a tank loaded from the bottom, and liquid manure in a lined earthen storage pond. Values for NH_3 transport resistance were assigned to predict appropriate losses from each storage type. The total resistance of the storage was the sum of the resistances within the manure to the surface and from the surface to the free atmosphere. The resistance within the manure solution was set as a function of the manure DM content, with the greatest resistance for solid manure and little resistance for liquid manure. For manure slurry with a DM content of 8% to 12%, a crust can form on the surface when manure is pumped into the bottom of the storage tank. Thus, a greater resistance value was set for bottom-loading tanks with manure of this consistency.

The first step in calibrating the manure storage component was to determine a transport resistance for liquid or slurry manure stored in an open tank. Several studies have measured NH_3 emission rates from storages in various locations, where daily emission rates were 0 to 18 g NH_3-N/m^2 of surface area with losses directly related to ambient temperature (Olesen and Sommer, 1993; De Bode, 1991; Williams and Nigro, 1997). Sommer et al. (1993) measured NH_3-N loss from slurry tanks in Denmark over several months during summer and winter periods, finding an average annual loss of 1.6 kg NH_3-N/m^2, or 12% of the total N stored. The resistance from the surface to the atmosphere was set low at 4.1 s/m, which allowed nearly all of the NH_3-N reaching the surface of the manure storage to be lost. A 25-year simulation was performed using Denmark weather data and manure and storage characteristics similar to those of the Danish study (Sommer et al., 1993). A transport resistance to the manure surface of 19 s/m was found to provide daily (2 to 14 g NH_3-N/m^2) and annual (1.6 kg NH_3-N/m^2) emissions similar to those measured. For solid and semi-solid manure stored in stacks, detailed loss data were not available. Resistance values of 10 s/m were selected for both solid and semi-solid manure stacks to provide average long-term NH_3 loss predictions similar to reported values of about 20% of the total N stored (Rotz, 2004).

When a natural crust forms on the surface of slurry manure, the resistance to NH_3 transfer is increased. A surface crust was reported to reduce the loss of NH_3-N by 40% to 80% compared to surfaces without a crust (Olesen and Sommer, 1993; Sommer et al., 1993; De Bode, 1991; Williams and Nigro, 1997). A resistance of 75 s/m was selected to represent a slurry surface with a crust, which provided a typical reduction in annual loss of about 60%. Although this assumption may appear conservative, it seemed reasonable considering the irregularity found in crusts and that some time is required to establish a crust in farm manure storages.

Daily loss of NH_3-N was determined such that the cumulative loss up to a given date could not exceed the accumulated TAN in storage. This was particularly important in the early stages of loading, when a thin layer of manure on the bottom of the storage facility created maximum exposure for the loss of TAN. By integrating equation 1 with these assumptions over the full year, an annual storage loss was determined. For storages with a 6-month capacity, the storage was emptied in early April and again in early October for use as organic fertilizer on cropland. With a 12-month capacity, the storage was emptied only in April.

On a feedlot, manure was assumed to be stored in a solid form following the initial housing phase. Loss of the TAN remaining after the housing phase continued during a user-assigned 6 or 12 month storage period. Periodic scraping of manure could occur, or the manure could remain spread across the lot. Scraped manure was stored in piles with general dimensions assigned by the model user. The same parameters were used to predict the daily rate of TAN loss as used for solid manure storage.

Field Application Loss

Manure is normally applied to crop or grassland so the nutrients can be taken up and recycled through growing plants. Manure can be applied either through daily hauling or from long-term storage. With a daily strategy, smaller amounts of manure are applied each day. When storage is used, large amounts of manure are applied over a period of several days, normally in the spring and fall. The same model was used to simulate each of these approaches. With daily hauling, the manure produced each day was applied the same day. With 6-month storage, half of the annual manure produced and stored on the farm was field applied over 10 d periods in early to mid-April and early to mid-October. For 12-month storage systems, all manure for the year was applied in a 10 d period in April.

Three manure application methods were modeled: broadcast spreading, irrigation, and direct injection into the soil. Some TAN is lost as the manure moves through the air in the actual application process. Based on a summary of relevant research (Rotz, 2004), this loss was set at 1% of the applied TAN for broadcast spreading and 10% for irrigation, with no loss during injection. Thus, the manure TAN reaching the field surface was that hauled from the barn or manure storage on a given day minus this loss. The TAN hauled to the field was either that excreted minus that lost in the barn that day for daily haul systems or that removed from storage for stored manure systems.

Loss from manure applied on a given day was determined by integrating equation 1 over the days until the manure was incorporated by a tillage operation. A maximum of 15 d was set for this period since all TAN would normally be lost after this much time on a field surface (Meisinger and Jokela, 2000). Because the emission rate is very rapid when manure is first applied, this integration was done on a 0.08 d (290 s) time step. Loss during each time step was determined using an equilibrium coefficient (eqs. 2, 3, and 4) calculated using the average ambient temperature of each day. Manure pH was set at 8.0 to account for a 0.5 increase that may occur for the first few days after manure is spread on a field surface (Sommer et al., 1991; Kirchmann and Lundvall, 1998).

The mass of manure solution on the surface (*M*) varied through time. The initial value following application was set assuming a manure application rate of 0.3 kg DM/m^2. The solution mass was this application rate divided by the manure DM content minus the manure DM. This solution mass was adjusted during each time step to account for infiltration, evaporation, and rain.

A simple relationship was used to predict evaporation in proportion to the incident solar radiation of the day. Daily evaporation (EV) varied from 0% to 60% of the available solution mass as daily solar radiation varied from 0 to a maximum level of 30 MJ/m^2. When rain occurred, the manure solution was increased assuming a uniform rate of rainfall over the daily period.

Solution infiltration was determined as a function of the manure DM content (Hutchings et al., 1996):

$$IR = e^{(6.95 - 31.9 * DMC)} \tag{6}$$

where

IR = infiltration rate (kg/m^2/d or mm/d)

DMC = manure DM content (fraction).

Daily infiltration was limited to a maximum of 70% of the available manure solution mass. This solution mass at each time step was *M* minus EV. During each time step, the manure solution mass was reduced by the infiltration and evaporation rates times the length of the time step and increased by the rainfall rate times the time step length.

Manure TAN on the soil surface also varied through time. The initial TAN was that reaching the soil following the application process. During each time step, NH_3 loss occurred to the atmosphere and TAN moved into the soil with the infiltration of moisture. The TAN moving into the soil was set in proportion to the manure solution that infiltrated into the soil, i.e., if IR was 10% of *M*, then 10% of the available TAN was removed from the surface pool and was thus unavailable to move into the atmosphere. Ammonia emission was determined for each time step using equation 1. This loss was a function of the TAN and *M* on the field surface at the given time, the value of *Q*, and an assumed resistance for NH_3 transport from the manure to the free atmosphere. At the completion of each time step, TAN and *M* were adjusted to provide initial values for the next time step.

To calibrate the model, a value for the transport resistance was selected that provided losses in TAN for different application procedures similar to those reported. In a review of volatile losses during field application, Meisinger and Jokela (2000) summarized that 35% to 70% of the TAN applied in the broadcast application of cattle slurry was lost. Between 30% and 70% of this loss occurred within the first 4 to 6 h following application, with 50% to 90% lost in the first day. With solid dairy manure, they reported greater losses of 61% to 99% of the applied TAN. Within liquid and slurry manure types (less than 12% DM), reported NH_3–N loss increased by about 5% of applied TAN for each 1% increase in DM content.

A transport resistance within the applied manure layer to the free atmosphere of 180 s/m was selected to provide TAN losses similar to those reported by Meisinger and Jokela (2000). For a 25-year simulation in southern Pennsylvania, average annual loss of TAN from slurry (8% DM) applied in the spring and fall ranged from 53% to 76% with a 25-year average of 65%. For liquid slurry (5% DM), simulated annual losses were 41% to 69% of applied TAN for an average of 56%. Between 21% and 39% of this loss occurred within 8 h of application, with 75% to 86% occurring in the first 24 h. The loss of TAN increased by 3.5% to 5.4% of TAN for each 1% increase in the manure DM content at the time of application. For semi-solid manure (13% DM), the range in annual loss was 56% to 83% of applied TAN with an average of 71%, and for solid manure (20% DM), the loss ranged from 62% to 89% with a long-term average of 79%. These predicted losses generally fell within the ranges of reported values (Meisinger and Jokela, 2000; Rotz, 2004), indicating that the model could adequately predict field application losses over a wide range of manure DM contents.

To predict loss from manure directly injected into the soil, a simpler approach was used. Ammonia N loss was set at 4% of the TAN in manure applied through deep injection into cropland and 7% of the TAN in manure applied through shallow injection to grassland. This provided relatively small losses, similar to those measured in field experiments (Rotz, 2004).

Ammonia loss was determined by integrating these relationships over the period from application until incorporation into the soil. This provided an exponential decline in the emission rate through time as influenced by changes in manure TAN content, infiltration rate, and DM content along with the effects of rainfall and ambient air temperature. When manure was incorporated the same day as applied, an average exposure time of 8 h was assumed. Losses occurring from daily applications were summed to determine an annual loss. The total loss included NH_3 volatilized during the application process plus that volatilized from the field surface. The proportion of N lost was the total annual NH_3–N loss divided by the total manure N transported to the field.

Grazing Loss

To model NH_3 loss from pastures, an approach similar to field application was used, but some simplifying assumptions were made. Grazing animals deposit urine and feces in separate spots. The N in feces is primarily organic, so NH_3 loss mostly occurs from the TAN in urine. When urine contacts plant and soil material, urease enzyme activity quickly transforms the urea to ammoniacal N that can volatilize (Sherlock and Goh, 1985). Because of the relatively low DM content, urine quickly infiltrates into the soil. Considering these relatively rapid processes, NH_3 loss was considered to be uniform throughout a daily time step. Therefore, daily losses were determined using equation 1 with daily values for available TAN, *M*, and *Q* and an assumed constant value for the resistance to NH_3 transport.

The TAN available for volatilization was the daily urine N excreted by grazing animals plus 9% of the fecal N (Rotz, 2004). The solution mass (*M*) was varied from 3 to 8 kg/m^2 (Oenema et al., 2001) as a function of the moisture-absorbing ability of the soil:

$$M = 16.5 - 0.146 * CN \tag{7}$$

where CN is a user-specified runoff curve number for the soil (dimensionless). Typical values for CN varied from 90 for a clay soil to 65 for a sandy soil (Rotz and Coiner, 2005).

Of the urine deposited, 30% was assumed to infiltrate immediately. This carried 30% of the available TAN into the soil as well. If rainfall occurred on the given day, the solution mass was diluted by the rain, i.e., *M* was increased by the daily rainfall amount. A value for *Q* was determined for each day using equations 2, 3, and 4, assuming the temperature of the deposited manure was equal to the average daily ambient temperature. The pH was set at 8.5 to reflect an increase that normally occurs in urine patches over the first few days following deposition (Sherlock and Goh, 1985).

Ammonia N loss during grazing was modeled for full-year and seasonal grazing strategies. A greater portion of the N applied during grazing should be lost with a seasonal strategy where animals are only on the pasture during warmer weather. Reported N losses from pasture normally do not specify a difference due to grazing strategy. With full-year grazing in New Zealand, Ball and Ryden (1984) reported NH_3−N losses of 66% of applied urine N under warm dry conditions, 6% under cool moist conditions, and 16% under warm moist conditions, with an average loss over the year of 28%. Our model was calibrated to their data, assuming that their loss of urine N was equivalent to the loss of TAN. A grazing dairy herd was simulated for 25 years of New Zealand weather on a silt loam soil. Using an NH_3 transport resistance of 1950 s/m, minimum and maximum daily losses throughout the year fell between 2% and 68% with average annual losses between 22% and 29% of the TAN deposited on pasture.

Daily NH_3 loss from grazing animals was determined for each day animals were on pasture. When animals were maintained on pastures throughout the winter, a daily loss was determined for each day of the year. Otherwise, losses were integrated over the grazing season set by the model user (typically mid-April through October). Calculated losses were summed over the time on pasture to obtain an annual loss. The proportion of N lost each simulated year was the NH_3−N lost from pasture divided by the total N excreted by the animals on pasture.

Model Evaluation

Model-predicted NH_3 emissions were evaluated to ensure reasonable predictions across weather years and across locations. Farms were simulated over 25 years of weather for southern Pennsylvania, the Netherlands, and central Texas to provide a wide range in weather conditions. A series of animal housing and manure management strategies were simulated that represented the major strategies used in dairy and beef production. Farm management and animal nutrition were kept as similar as possible across locations so that differences were primarily due to weather. Simulated differences in crop yield and quality, though, had a small effect on the nutrient intake and excretion of animals.

Animal Housing

Simulated and reported losses were first compared for different housing types. In a review of N loss studies, typical annual losses were 8%, 16%, and 50% of the excreted N in tie stall, free stall, and feedlot facilities, respectively (Rotz, 2004). Reported values for each housing type varied considerably around these values, which were selected as typical (table 1). Feedlot loss would include other volatile forms of N, but 90% of this loss was assumed to be NH_3−N. For a tie stall barn in Pennsylvania, simulated annual losses varied from 6% to 8% of the total N excreted, with a 25-year mean loss of 7.5%. A mean loss of 5.6% was determined for the cooler conditions of the Netherlands, and a loss of 12.1% was predicted for the hot conditions of Texas. For a free stall barn, these loss values were nearly twice those of the tie stall barn (table 1). On an open feedlot, annual emissions predicted for Pennsylvania were 38% to 44% of the N excreted. Ammonia N losses were similar across locations, with average annual losses of 40% to 47%. This loss was predicted to be a little less in Pennsylvania, where cold winter temperatures reduced emissions compared to the milder climate locations.

Table 1. Evaluation of predicted average annual ammonia emissions (percent of available N) for various components of manure handling.

	Reported Losses (%) (Rotz, 2004)		Predicted Annual Losses (%)			
			Southern Pennsylvania		Netherlands	Central Texas
	Typical	Range	Mean	Range	Mean	Mean
Animal housing						
Tie stall barn	8	2–35	7.5	6–8	5.6	12.1
Free stall barn	16	10–20	15.8	14–17	11.9	24.6
Feedlot[a]	45[b]	35–80[b]	40.6	38–44	43.8	47.1
Manure storage (with free stall barn)						
Solid manure	20	10–40	20.2	17–22	23.5	20.3
Semi−solid manure	−−	−−	19.6	17–22	22.6	20.0
Slurry, top loaded	15[c]	5–30[c]	13.4	12–15	15.6	15.2
Slurry, bottom loaded	5[c]	3–8[c]	5.2	4–6	5.3	6.9
Liquid manure	25[d]	20–50[d]	24.2	22–27	29.1	22.8
Field application (with free stall barn and bottom−loaded slurry tank)						
Irrigated	30	25–50	28.6	24–35	29.4	27.6
Broadcast	25	15–40	25.1	21–31	25.5	24.9
Broadcast/incorporated	10	6–13	9.6	7–14	9.0	14.5
Deep injection	2	1–5	2.2	2.0–2.3	2.4	1.7
Grazing						
Year−around	10	4–20	12.7	11–14	7.3	23.0
Seasonal	10	4–20	20.2	18–23	10.8	31.7

[a] Feedlot includes loss from solid manure stored on the lot.
[b] Assumes 90% of total N emission is NH_3−N.
[c] From Muck and Steenhuis, 1982; Muck et al., 1984; and Sommer et al., 1993.
[d] Estimated from single-stage lagoon assuming 50% of total N emission is NH_3−N.

Each of these predicted losses fell within the range of measured values except for a free stall barn in Texas. This predicted loss was a little greater than reported values, but no measured values were found for this type of facility in a warm climate. In another modeling study, Pinder et al. (2004) predicted ammonia emission factors in Texas that were about double those predicted for southern Pennsylvania. Overall, predicted annual NH_3–N losses during animal housing over this wide range in climates appeared very reasonable compared to reported values.

Manure Storage

Simulations were done for the same farm using solid, semi-solid, slurry, and liquid manure storage facilities, which were emptied every 6 months. Solid and semi-solid storage represented manure stacked on a pad, slurry was stored in an open tank, and liquid manure was stored in a lined earthen pond. Slurry storage was either loaded from the top, where a crust would not form, or from the bottom with crust formation.

Long-term simulations in southern Pennsylvania provided reasonable annual and 25-year mean losses for each storage type (table 1). Loss predictions for the Netherlands were sometimes greater than those for the other locations. This was due to less annual temperature variation and the resulting effect on loss during animal housing as well as storage. Since less TAN was lost in the barn under the cooler summer conditions of the Netherlands, more TAN was loaded into storage. This allowed greater loss from those storage facilities that were less efficient in conserving NH_3–N (table 1). In Texas, greater barn loss provided less TAN entering storage, which offset an increased loss from storage due to higher ambient temperatures.

Field Application

Manure application methods simulated were irrigation with delayed soil incorporation, broadcast spreading with delayed incorporation, broadcast spreading with same-day incorporation, and injection into the soil. With delayed incorporation, manure remained on the soil surface at least a week before being incorporated by tillage.

Losses predicted for the Netherlands were similar to those for southern Pennsylvania (table 1). With irrigation or broadcast spreading with delayed incorporation, essentially all TAN that did not infiltrate below the soil surface was lost to the atmosphere. Use of rapid incorporation or deep injection greatly reduced this loss. Irrigation, broadcast application, and injection gave slightly lower field losses in Texas because more TAN was lost prior to field application, and thus less was available for loss following application. With rapid incorporation in Texas, losses were greater than those in the cooler locations. This occurred because the hot and dry climate caused more rapid loss during or immediately after application.

Grazing

Year-around and seasonal grazing systems were simulated for dairy herds at the three locations (table 1). Simulated losses from grazing systems in Texas were higher than those generally reported. Since the reported data come from northern Europe and New Zealand, these higher losses in a warm climate are reasonable (Pinder et al., 2004). Without actual data for this climate, these predicted losses cannot be verified. With a sandy soil and the cooler climate of the Netherlands, predicted annual losses during seasonal grazing were 9% to 13% of the total N excreted on the pasture, with a 25-year average of 10.8%. These losses fall within the range of reported seasonal losses in this region of 3% to 14% of the excreted N deposited on pasture (Bussink, 1992, 1994). Overall, the model appeared to predict reasonable losses from grazing animals over a wide range of soil and climate conditions.

A Comparison of Management Systems

To further evaluate the NH_3-loss relationships and their use in a whole-farm simulation, four common options for animal housing and manure handling in the northeastern U.S. were simulated with the Integrated Farm Systems Model. The same representative dairy farm was used with each option. The farm included 100 Holstein cows and 85 replacement heifers on 90 ha of medium depth, clay loam soil. Crops produced included alfalfa and grass, primarily harvested as silage, corn harvested as silage and high-moisture grain, and oats harvested as high-moisture grain and straw bedding. Lactating cows were fed total mixed rations in confinement housing, while older heifers and dry cows were on pasture during the grazing season. This simulation analysis was included to demonstrate the use of the model, not to provide a comprehensive comparison of production systems. Thus, documentation of model parameters is limited to the major differences among the four options simulated.

Simulated Management Systems

The first management option was a tie stall barn where manure was removed with a gutter scraper and surface applied on a daily basis using a box spreader. Bedding material was used to provide manure in a semi-solid form. Manure storage was limited to a concrete pad for short-term storage. Field-applied manure remained on the soil surface for at least a few weeks prior to incorporation, which led to greater field loss of NH_3–N.

For the remaining three strategies, animals were housed in a free stall barn and milked in a double-six parlor. Manure slurry was stored up to 6 months in a concrete tank and applied to fields in April and October. The three strategies used surface spreading, injection, or irrigation application. For the first two strategies, manure was scraped daily using a skid-steer loader. With surface application, a tank spreader with a splash plate applicator was used, and manure remained on the surface for about 3 d prior to incorporation. With injection, the spreader included tines to insert the manure under the soil surface. The use of injection was assumed to increase implement draft and reduce field capacity of the application operation by 25%. For the irrigation strategy, manure was handled as a liquid (lower DM content). A flush system was used to remove manure from the barn, and a liquid-solid separator was used to remove some of the manure solids. This material was recycled as bedding, which reduced the need for straw by 50%. Manure was stored in a lined earthen pond and applied with irrigation equipment. Tillage operations incorporated the manure within 5 d of application.

Table 2. Economic parameters, prices, and initial costs assumed for various system inputs and outputs for the analyses of nutrient conservation technologies on representative dairy farms in Pennsylvania.

Economic parameter	Price[a] ($)
Labor wage rate	12.00/h
Diesel fuel price	0.60/L
Electricity price	0.10/kW-h
Mailbox milk price	31.50/hL
Nitrogen fertilizer price	0.95/kg N
Corn grain price	125/t DM
Soybean meal price	350/t DM
Protein mix price	380/t DM
Real interest rate	6.0% per year
Property tax rate	2.3% per year
Structure or equipment	**Initial Cost ($)**
Tie stall barn and milking equipment	360,000
Standard free stall barn	313,000
Gutter cleaner	25,000
Skid-steer loader	23,000
Flush system	25,000
Liquid-solid separator	15,000
Manure collection pad	3,000
Concrete tank storage	58,500
Lined earthen pond storage	41,000
Broadcast box spreader	12,800
Broadcast tank spreader	18,300
Injection manure spreader	25,200
Irrigation equipment	25,000

[a] Prices were set to represent long-term relative prices in current value, which were not necessarily current prices.

All prices were consistent across systems and across simulated years of weather. Important prices in the comparison of these systems are listed in table 2. Initial costs include the facilities and equipment that varied across the simulated systems. Initial costs of structures were amortized over 20 years and equipment was amortized over 10 years using a real interest or discount rate of 6% per year.

Simulation Results

A comparison of N losses, manure handling costs, and farm profit for the four management scenarios is shown in table 3. In the tie stall housing system, NH_3–N loss in the barn was 37% less than that in a free stall barn. There was no loss in storage with daily hauling of manure, but surface spreading of semi-solid manure caused high field loss of NH_3–N.

Compared to the tie stall system, a free stall barn, 6-month slurry storage, and surface spreading of manure provided a 17% increase in total NH_3–N loss from the farm (table 3, column 2 vs. column 1). Greater losses in the barn and during storage more than offset a decrease in the loss following field application. Greater volatile loss of N led to less N incorporated into the soil and thus lower leaching and denitrification losses. Less available soil N also caused a small decrease in protein levels in forage, which required a small increase in purchased supplemental feed to meet the needs of the herd. Annual manure handling costs were essentially the same with reductions in equipment, labor, and bedding costs offsetting increases in storage and fuel costs.

Direct injection of the manure greatly reduced NH_3–N loss following application, providing a 43% reduction in NH_3–N loss from the farm compared to the broadcast application system (table 3, column 3 vs. column 2). With less volatile loss, more N was available in the soil. This increased crop yields and forage protein contents, which reduced the annual purchased feed cost by $26/cow. Higher soil N levels also increased leaching and denitrification losses by about 50%. Annual manure handling costs increased by $17/cow compared to surface spreading due to small increases in equipment, fuel, and labor costs.

The largest loss of NH_3–N occurred using the liquid manure and irrigation strategy (table 3, column 4). Loss following field application was relatively low because most of the manure TAN was lost prior to application and because the liquid manure infiltrated into the soil more readily. The remaining organic N was relatively stable, with little loss prior to incorporation. With less N incorporated into the soil, crop yields and protein contents were a little lower, which again affected purchased feed requirements. Lower soil N levels also reduced nitrate leaching and denitrification losses compared to the other three systems.

Differences in manure handling costs across systems were not large (table 3). The highest cost occurred with manure injection, and the irrigation system had the lowest cost. Large differences in the costs of storage, fuel, labor and bedding material occurred across systems, but these differences tended to offset each other, giving annual manure handling costs of $192 to $231/cow.

Farm profit using the tie stall barn was $100/cow less than that using free stall housing (table 3). Most of this difference was due to added costs in animal facilities and milking labor. Although this type of barn is still commonly used throughout the northeastern U.S., a new barn of this type and size would not normally be built today. Among the remaining three strategies, differences in farm profit were small. Differences of up to $10/cow per year were primarily due to differences in manure handling and purchased feed costs.

These simulation results illustrate that changes can be made to reduce NH_3–N loss while maintaining and perhaps improving farm profit. Of the four production systems simulated, the most profitable was that using the injection of manure, and this strategy reduced NH_3–N emissions by 33% to 50% relative to the other options. Although the reduction in NH_3 emissions led to greater leaching and denitrification losses of N, this may also be corrected through improved management. By redistributing manure among farm crops or using cover crops, the increased available N may be better utilized to offset this increase in N loss of other forms. This type of refinement was not done in this series of simulations in order to maintain consistent farm characteristics across manure handling strategies.

Discussion

This model of ammonia emissions was developed specifically for use in whole-farm simulation. With this goal in mind, simplifying assumptions were made in model development. For example, the pH of urine and manure slurry is known to vary through time as influenced by management and the environment (Sommer and Sherlock, 1996; Patni and Jui, 1991; Sherlock and Goh, 1985). Because of limited available data on these changes and because these effects would not be expected to have much effect at the whole-farm

Table 3. Effect of animal housing and manure handling practices on nitrogen losses, manure handling costs, and farm net return for a simulated dairy farm in southern Pennsylvania.[a]

	Tie Stall Barn[b]	Free Stall Barn		
	Daily Haul Surface	Slurry Tank[c] Surface	Slurry Tank[d] Injected	Earthen Pond[e] Irrigated
Nitrogen losses				
Ammonia nitrogen loss (kg N/cow)	62.1	72.7	41.3	82.0
Barn	16.5	26.1	26.5	25.9
Manure storage	0.0	7.0	7.1	35.1
Field application	40.9	35.0	3.0	16.5
Grazing	4.7	4.6	4.7	4.5
Nitrogen leaching loss from fields (kg N/ha)	30.3	25.2	37.7	21.6
Denitrification loss from fields (kg N/ha)	21.6	18.2	26.2	15.6
Manure handling costs				
Manure handling cost ($/cow)	215	214	231	192
Equipment	105	97	109	125
Holding or storage facility	3	51	51	36
Fuel and electric	9	17	20	14
Labor	38	28	30	15
Purchased bedding	60	21	21	2
Farm net return				
Feed production cost ($/cow)	848	853	852	857
Purchased feed cost ($/cow)	364	377	351	389
Animal facilities cost ($/cow)	487	441	441	441
All other costs[f] ($/cow)	666	594	594	593
Total production cost ($/cow)	2580	2479	2469	2472
Milk and animal sale income ($/cow)	3101	3101	3101	3101
Net return to management ($/cow)	521	622	632	629

[a] 100 cows and 85 heifers on 90 ha in alfalfa, grass, corn, and oats with a moderate milk production simulated over 25 years of weather for Chambersburg, Pennsylvania.

[b] Animals housed and milked in a tie stall barn ($360,000). Manure collected with a gutter cleaner ($25,000), hauled and surface applied daily using a box spreader ($12,800) with delayed soil incorporation. Numbers in parentheses are assumed initial costs of equipment and structures.

[c] Animals housed in a free stall barn and milked in a parlor ($313,000). Manure scraped with a skid-steer loader ($23,000), pumped into the bottom of a storage tank ($58,500), and surface applied using a tank spreader ($18,300) with delayed soil incorporation.

[d] Animals housed in a free stall barn and milked in a parlor. Manure scraped, pumped into the bottom of a storage tank, and applied using a tank spreader with subsurface injection ($25,200).

[e] Animals housed in a free stall barn and milked in a parlor. Manure flushed into a lined earthen pond ($41,000) using a flush system ($25,000) and a solids separator ($15,000), and applied using irrigation ($25,000) with delayed soil incorporation.

[f] Includes annual costs for milking labor, livestock expenses, and property tax.

level, a constant pH was assumed in our model for manure at each stage of handling.

Considering our goal for whole-farm simulation, the model was evaluated against the limited farm-level data available. The model was shown to provide acceptable prediction of emissions over a broad range of manure management and climatic conditions. Thus, the model should provide reasonable emission predictions under the goal for which it was developed, i.e., predicting manure management effects on farms at various climate locations.

Care is needed in extrapolating the use of the model beyond the conditions for which the model parameters were developed. For example, the model is very sensitive to the manure or urine pH for each of the sources of ammonia emission. By assigning constant values for typical or average pH and then deriving values for transport resistance that provided appropriate emissions, this sensitivity was removed from our model. No attempt was made to verify the model's response to changes in manure pH, so use of the model for evaluating this effect is not recommended without further verification. Other changes, such as exposed surface area during animal housing and field application rates of manure, also should not be made without verification since the current relationships were calibrated or tuned to the specific assumptions of our model.

To further develop and evaluate this model, more basic research is needed on the physical, biological, and chemical processes involved in the formation and release of NH_3 from manure under the wide range of conditions found on farms. For example, many different relationships have been used to model the coefficients for Henry's law and the disassociation of ammonium used in equation 2 (Ni, 1999). More information is needed to determine the best of these relationships for simulating the various conditions of manure storage and handling. This includes better definition of the effects of manure characteristics and meteorological conditions on these processes. Better information is also needed to define the transport resistance of NH_3 from various manure types and surfaces and the environmental effects on this resistance.

More farm-level data on emissions are also needed for model evaluation or validation. Emissions from housing facilities, manure storage facilities, and land applications of manure need to be monitored over many months and even years, along with management and meteorological information, to develop a comprehensive data base of farm-level emissions. This type of database would be very useful, and in fact necessary, for validating emission models at the farm scale. By validating models on even a few select farms, model users would be more confident in applying these models to the wide range in farm management practices found in dairy and beef production.

For those interested in further evaluation of farming systems, the Integrated Farm System Model is available from the Pasture Systems and Watershed Management Research Unit website (http://ars.usda.gov/naa/pswmru). The program operates on computers that use any Microsoft Windows operating system. A copy of the program, including an integrated help system and reference manual, can be obtained at this website, and instructions for downloading and setting up the program are provided.

Conclusion

A process-based model was developed to predict daily NH_3–N losses in cattle production as a function of management and climatic conditions. Mathematical relationships were developed to describe NH_3 emission processes in animal housing, during manure storage, following field application, and during grazing. These loss relationships were added to the Integrated Farm System Model to form a tool for evaluating management effects on annual and long-term average NH_3–N losses and their interaction with other aspects of farm performance, environmental impact, and profit. Whole-farm simulations illustrated that the use of a free stall barn, bottom-loaded slurry storage, and direct injection of manure into the soil reduced farm-level NH_3 emissions by 33% to 50% compared to other commonly used animal housing and manure handling systems in the northeastern U.S. while at least maintaining farm profit.

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