Extended Abstract: Modeling livestock ammonia emissions in the United States: From farms to emissions to particulate matter

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INTRODUCTION

Ammonia is an important air pollutant because of its role in fine particulate matter formation and its contribution to the eutrophication of terrestrial and aquatic ecosystems [1–7]. Ammonia emissions, particularly from livestock, have been increasing as the demand for animal products across the globe has grown and the livestock industry has been intensified. It is estimated that ammonia emissions may increase by approximately 15% by 2030, which contrasts emissions trends for sulfur dioxide and nitrogen oxides (the other major precursors to inorganic fine PM) whose emissions have decreased by 80% and 60% respectively in the past 30 years [8–11]. Previous studies have shown that the largest source of ammonia emissions in the United States is animal husbandry, and that these emissions come largely from beef and dairy cattle, swine, and poultry As described in previous work [12–17]. In our work, we modified a farm emissions model (FEM) based on data reported in the literature for beef, swine and poultry production[18–20] developed previously for dairy production; we then evaluated this data using emissions factors from literature and those from the National Air Emissions Monitoring Study (NAEMS). Emissions from livestock sources are difficult to estimate because they vary based on meteorological conditions, farm management practices, and manure characteristics. Because of the numerous sources of variability in emissions, it is impossible to measure emissions for all potential combinations and so a model that can characterize these emissions is important. Thus, the farm emission model (FEM) developed is a process-based model that tracks the flow of total ammoniacal nitrogen and manure volume through the farm system by conducting a mass or volume balance through the whole system, ensuring mass is conserved. Model details and results from this work are described in the following sections.

METHODS

The FEM was developed to capture the seasonal variability in ammonia and the differences in emission patterns for different farm and animal types. Data sources used to evaluate our model include the literature and the observations from the NAEMS that took place from 2007-2010. For each livestock type, the farm emission model (FEM) is composed of a series of submodels, each of which treats a different stage of manure management: housing, storage, and application. Configuration of the sub-models differs for each of the livestock types and management practices used. A schematic of the general farm emission can be found in Figure 1.

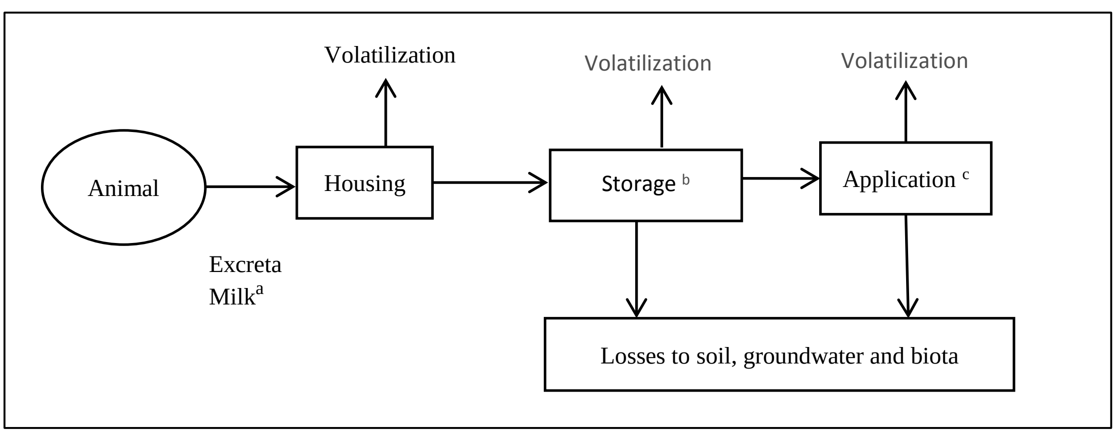

Figure 1: Schematic of farm emission model (FEM)[18,19]. ([a]Only for dairy cows; [b] Included in swine and dairy portions of this work; [c] Not included in this work since NAEMS only measured housing and storage emissions)

The emissions process in the model is described by the volatilization of ammonia from the manure liquid surface. Then, the volatilized ammonia is transported to the atmosphere above the wastes. The following equations (1-2) are used as the basis for calculating emissions in each of the individual submodels of the dairy, swine, and poultry farm emission models, and was previously used in the dairy FEM [19,21]; the third equation incorporates tuned parameters to calculate surface resistance that are used to ensure model results agree reasonably well with literature and NAEMS reported emission factors. The final equation (4) describes the total ammoniacal nitrogen mass balance that must be preserved as nitrogen travels through the manure management system.

$$EF = A * [TAN] * H^* * r^{-1} \tag{1}$$

Where EF is the emissions factor (kg day^{-1} animal^{-1} or kg day^{-1} animal unit (AU) $^{-1}$), A is the area fouled by excretion (m^2 animal^{-1}), *[TAN]*, the total ammoniacal nitrogen concentration in the waste (kg m^{-3}), H^* is the effective Henry's law constant (dimensionless), and r is the mass transfer resistance (day m^{-1})

$$r = r_a + r_b + r_s \tag{2}$$

Where the r_a is the aerodynamic resistance, r_b is the quasi-laminar resistance, and r_s is the surface resistance[22]

$$r_s = P_1 + P_2 T \tag{3}$$

Where r_s is the surface resistance, P_1 and P_2 are tuned parameters (based on literature emissions factors) to ensure model results agree with published values, and T is temperature (some submodels include slight variations on this basic equation, but role of the tuned parameters remains the same)

$$\frac{d[TAN]}{dt} = k_{urea} C_T [urea] - A[TAN]H^* r^{-1} - A[TAN]k_i V^{-1} \tag{4}$$

Where $\frac{d[TAN]}{dt}$ describes how *[TAN]* changes with respect to time, t; $k_{urea} C_T [urea]$ describes the initial amount of urea present while $A[TAN]H^* r^{-1}$ describes the loss of *[TAN]* via volatilization and $A[TAN]k_i V^{-1}$ describes the loss of *[TAN]* via infiltration.

Initially, key input data were taken from the literature to better constrain the model to actual reported farm conditions. The values used are typical for a number of input parameters, selected because they fell in the middle of the range reported throughout literature. One key exception to the use of single values for these parameters is our treatment of the manure urea content for beef cattle. Where available, we use the reported manure or feed nitrogen values to run and tune the submodels rather than the generic value assumed to be typical of farms. In order to ensure that our farm emission models produce reasonable and realistic simulated ammonia emission factors for beef cattle, swine and poultry, we used literature data to tune parameters related to the surface resistance, r_s, in the mass transfer equations (Equations 2-4). By tuning the parameters described below we are able to create our semi-empirical ammonia emissions estimates.

After tuning the FEM to literature data, we determined that there were some differences in the seasonal patterns at the NAEMS farms when compared to the results from literature. For this reason, we decided to re-tune the model resistance parameters to better capture the emissions observed on the NAEMS farms. The same parameters were used for all farms of a particular animal type and stage in manure management to avoid over-tuning the model to the data. We evaluated the performance of the model in its ability to estimate ammonia emissions on the NAEMS farms in its correlation between model and measurement, mean fractional error, and mean fractional bias.

RESULTS

Initial FEM performance was evaluated using the r^2 value between measured (literature) emission factors and modeled emission factors. The r^2 values show that the FEMs capture 20%-70% of the variability that is seen in the emissions factors reported in the literature. For swine, the housing r^2 value was 0.53 and 0.49 for lagoon storage; the r^2 was 0.29 for broilers and 0.68 for layers; the r^2 values for beef feedlots were 0.21 for all feedlots and 0.36 for feedlots where we had more information about the nitrogen content of feed or excrement of the cattle. The FEM performance for literature emissions factors was better for enclosed emission sources, such as swine barns or layer houses, as compared to open sources such as beef feedlots or swine manure storage lagoons.

After the FEM was tuned to literature, we compared model results to observations from NAEMS. After this comparison, we found that there were substantial differences between some of the literature patterns and the NAEMS observations. We found that the r^2 values between measurement and model was, on average, 0.47 and 0.21 for dairy and swine housing, respectively, 0.65 for both dairy and swine storage, 0.35 for layer housing and 0.25 or broiler housing. Daily model performance was also investigated for dairy and swine; results for these were far more mixed and the correlation coefficient between measurement and model in these cases spanned a much broader range of values, from -0.76 to 0.89. Sample model results for seasonal performance of a swine barn and swine lagoon are shown in Figure 2 below. While individual farms may show a bias high or low relative to the observations, the average results show a much smaller bias.

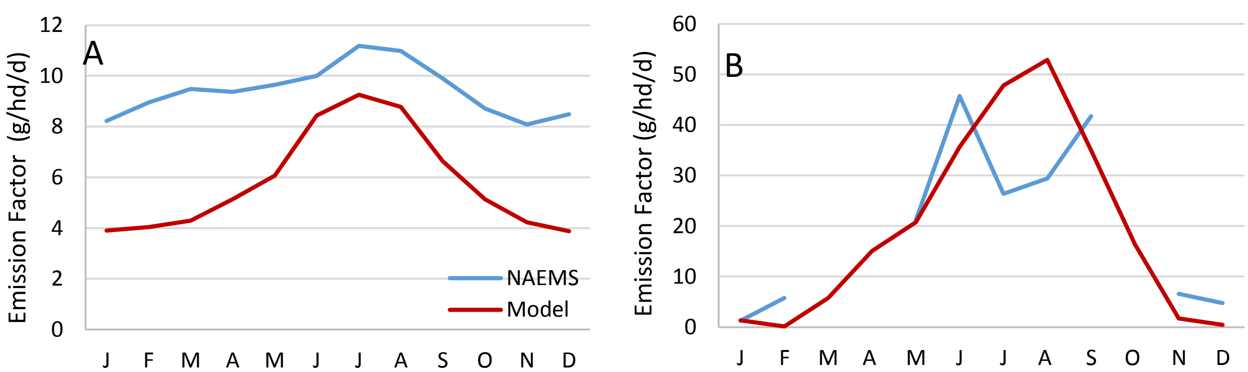

Figure 2: Sample seasonal model performance data from NAEMS. Animal types and stages are as follows: a) shallow pit swine housing in NC and b) swine storage lagoon in OK.

DISCUSSION

Ammonia emissions from livestock operations are highly variable and depend on manure characteristics, management practices and meteorological conditions. Representing this variability in emissions inventories is challenging but essential and process-based modeling offers one promising approach. Here, we have used the FEMs to estimate emissions factors for common livestock production practices for beef cattle, swine, and broiler and layer chickens. Building on previous work for dairy cows[19,21], the FEMs are based on mass balances of the nitrogen and water flowing through the farm system by using a combination of model inputs from literature and tuned model parameters for livestock in the United States. Our method of using literature-based inputs and tuned parameters means our model is semi-empirical and harnesses the ability to capture some of the variability lacking from emissions estimates that rely on static emission factors while still being broadly applicable and simple to run, allowing its use in building national emissions inventories. Model performance was evaluated using a number of metrics, including the r^2 value between measured (literature) emission factors and modeled emission factors show that the FEMs capture 20%-70% of the variability that is seen in the emissions factors reported in the literature. When comparing to literature, the FEM performance was better for enclosed emission sources, such as swine barns or layer houses, as compared to open sources such as beef feedlots or swine manure storage lagoons. Model performance was limited by the lack of data in the literature for certain common management practices for livestock production.

The National Air Emissions Monitoring Study (NAEMS) offered a new source of data for us to use to evaluate and improve our Farm Emissions Model (FEM) that had been tuned using existing literature data. Using the data from NAEMS we were able to improve our understanding of the factors that drive ammonia emissions from livestock. Using our process-based model is one approach for predicting seasonal cycles in ammonia emissions from the farms. With a previously developed framework [19,21] for dairy cows, we evaluated the FEM against data from NAEMS for dairy housing and lagoons, swine housing and lagoons, and layer and broiler housing for capturing both the seasonal and even the daily variability in emissions from livestock.

PUBLICATION INFORMATION

McQuilling, A.M., Adams, P.J., "Development of a process-based model to estimate ammonia emissions from livestock operations in the United States." Under review for publication in *Atmospheric Environment*.

McQuilling, A.M., Adams, P.J., "Using the National Air Emissions Monitoring Study (NAEMS): Improving a process-based model for the estimation of ammonia emissions from livestock in the United States." In preparation.

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DISCLAIMER

This farm-level model has been developed and evaluated to better capture the major drivers of seasonal and regional variability in ammonia emissions from livestock production. However, the emissions of any given farm may differ significantly from these predicted due to farm-specific practices not represented here. Therefore, the FEMs developed here are not recommended for estimating emissions from specific, individual farms except for the farms that were monitored as a part of NAEMS.

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