Atmospheric Environment 120 (2015) 127–136

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Semi-empirical process-based models for ammonia emissions from beef, swine, and poultry operations in the United States

Alyssa M. McQuilling*, Peter J. Adams

Center for Atmospheric Particle Studies, Carnegie Mellon University, Pittsburgh, PA, USA

HIGHLIGHTS

- Developed process-based farm emissions models for NH3 emissions from livestock.
- The FEMs capture 20–70% of NH3 emissions variability for beef, swine, and poultry.
- The FEMs rely on mass balance and literature-tuned parameters to model emissions.
- Model performance is limited by lack of reported contextual data in the literature.
- NH3 emissions from open sources are more difficult to model and measure.

ARTICLE INFO

Article history:
Received 10 December 2014
Received in revised form
25 August 2015
Accepted 27 August 2015
Available online 1 September 2015

Keywords:
Ammonia emissions
Process-based model
Livestock production
Manure management

ABSTRACT

Farm-level ammonia emissions factors in the literature vary by an order of magnitude due to variations in manure management practices and meteorology, and it is essential to capture this variability in emission inventories used for atmospheric modeling. Loss of ammonia to the atmosphere is modeled here through a nitrogen mass balance with losses controlled by mass transfer resistance parameters, which vary with meteorological conditions and are tuned to match literature-reported emissions factors. Variations due to management practices are captured by having tuned parameters that are specific to each set of management practices. The resulting farm emissions models (FEMs) explain between 20% and 70% of the variability in published emissions factors and typically estimate emission factors within a factor of 2. The r^2 values are: 0.53 for swine housing (0.67 for shallow-pit houses); 0.48 for swine storage; 0.29 for broiler chickens; 0.70 for layer chickens; and 0.21 for beef feedlots (0.36 for beef feedlots with more farm-specific input data). Mean fractional error was found to be 22–44% for beef feedlots, swine housing, and layer housing; fractional errors were greater for swine lagoons (90%) and broiler housing (69%). Unexplained variability and errors result from model limitations, measurement errors in reported emissions factors, and a lack of information about measurement conditions.

1. Introduction

Ammonia is a significant air pollutant because of its impacts to land, water, and human health through eutrophication, deposition, and the fine particulate matter formation (PM). Excessive ammonia leads to the eutrophication of terrestrial ecosystems and many waterways (Draaijers et al., 1989). Deposition of nitrogen oxides and sulfur dioxide have decreased in recent years; however, ammonia emissions have not (Driscoll et al., 2001; Fenn et al., 2003). Ammonia is a key component in the formation of fine PM (Ansari and Pandis, 1998), especially nitrate PM, as gas-phase nitric acid condenses only when ammonia is available for neutralization. Ammonium nitrate formation depends on: the amount of ammonia present, temperature, relative humidity and other pollutant concentrations (West et al., 1999). Because ammonium nitrate formation is temperature-dependent, the spatiotemporal variations in ammonia emissions can have a significant impact on the formation of PM. As ammonium nitrate formation is favored at colder temperatures, emissions in winter can have a greater impact on particulate matter formation than ammonia emitted in warmer seasons. Control and predition of PM concentrations are important because fine PM has been linked to respiratory ailments, cardiac

* Corresponding author.
E-mail address: alyssamo@andrew.cmu.edu (A.M. McQuilling).

http://dx.doi.org/10.1016/j.atmosenv.2015.08.084
1352-2310/

events, and premature death (American Lung Association, 2006; Pope and Dockery, 2006).

Ammonia is emitted from many sources, but in the United States, the animal livestock sector contributes 70–90% of total national emissions (Battye et al., 1994, 2003; Bouwman et al., 1997; Pinder et al., 2006), mostly from dairy and beef cattle, swine, and poultry. Ammonia emissions from livestock are expected to increase as animal populations continue to grow and production intensifies to meet greater global demands (USEPA, 2004). Emissions of ammonia occur throughout the entire livestock production process—from animal housing, manure storage, and its application.

Early ammonia emission inventories relied on static emission factors (EF) to estimate the livestock contribution to the national ammonia emission inventory. However, it has been demonstrated that ammonia emissions are strongly dependent on meteorology, nutrition, and manure management; a single emission factor is unable to capture this variability (Ad Hoc Committee on Air Emissions from Animal Feeding Operation (National Research Council), 2003). Only recently, the 2011 NEIv2 has added a temperature dependence to the emissions profile for ammonia. More recent work has attempted to account for some of this variability by using regression to relate an important parameter, e.g. temperature or animal age, to the emission factor (Rotz and Oenema, 2006), but it is still difficult to capture all the factors that cause variability in emissions.

Process-based models offer an alternative approach to capture emissions variability resulting from meteorology and management practices, which should aid $PM_{2.5}$ modeling. Therefore, the goal of this work is to build process-based models of ammonia emissions used for building national/regional emissions inventories. While complex, first principle process-based models may be able to characterize more emissions, they are computationally intensive and require detailed input data which is unlikely to be available for all farms and practices (Zhang et al., 2005). While they may reproduce emissions behaviors at specific farms with well-characterized conditions, their utility for building emissions inventories has not yet been demonstrated.

Our model is a balance between an empirical approach and first-principles process-based model. We use a nitrogen mass balance and a process description of ammonia losses, but tune model parameters to reproduce measured emissions factors. We deliberately limit model complexity to the most important emissions processes and to inputs that are typically available. The strategy pursued here for developing process-based models is guided by the need to build emissions inventories, and the requirements and data limitations associated with this application. Previous measurement campaigns also often sampled emissions from a single part of the production process. This means that we may not have information about the emissions process from the start to end of production, making nitrogen mass balance in the system difficult. The lack of whole-farm measurements is one gap in much of the literature available and a benefit of the estimates of ammonia emissions produced by the FEM.

In this paper, we describe the adaptation and evaluation of previously developed process-based ammonia emissions models for beef cattle, swine, broiler and layer emissions based on the existing model framework called the FEM (for dairy cows) which conducts a mass balance on system nitrogen and water volume (Hutchings et al., 1996; Pinder et al., 2004a). Our model relies on input parameters to reproduce ammonia emissions for different farms, including meteorology, management practices and manure characteristics. The previous studies addressed only grazing cattle (Hutchings et al., 1996) and mature dairy cows (Pinder et al., 2004a, 2004b).

2. Model description

2.1. Model overview

Our FEM captures ammonia emissions variability (caused by differences in meteorology, practices, and manure) through the use of a semi-empirical process-based model while constraining overall emissions via mass balance on available nitrogen in the farm system. For each livestock type, the FEM is composed of a series of submodels, each of which treats a different stage of manure management: housing (or grazing), storage, and application. The manure management trains for each livestock type are shown in Fig. 1a–c, while the inputs, outputs, and time step of each submodel are shown in Fig. 1d. Submodel configuration for each livestock type and management practices is detailed in Table 2.

The model uses inputs for farm type, manure nitrogen, and meteorological conditions to predict farm-specific ammonia emissions. Meteorological data are from the National Climate Data Center (NCDC), based on the time and location of the literature studies used in tuning if not directly provided. Farming practices and nitrogen inputs were based on literature-reported values for beef, swine and poultry from ammonia emissions measurement studies and animal nutrition research (Table 1).

2.2. Animal nitrogen

Nitrogen is used by animals for weight gain and growth, bodily maintenance, and commodity production, but animals do not use all the nitrogen that they are fed. Unused nitrogen is then excreted as waste. If we better understand nitrogen use efficiency, we can better constrain the amount of total ammoniacal nitrogen (TAN) available for volatilization as ammonia. Literature studies have shown that more waste nitrogen leads to higher manure ammonia

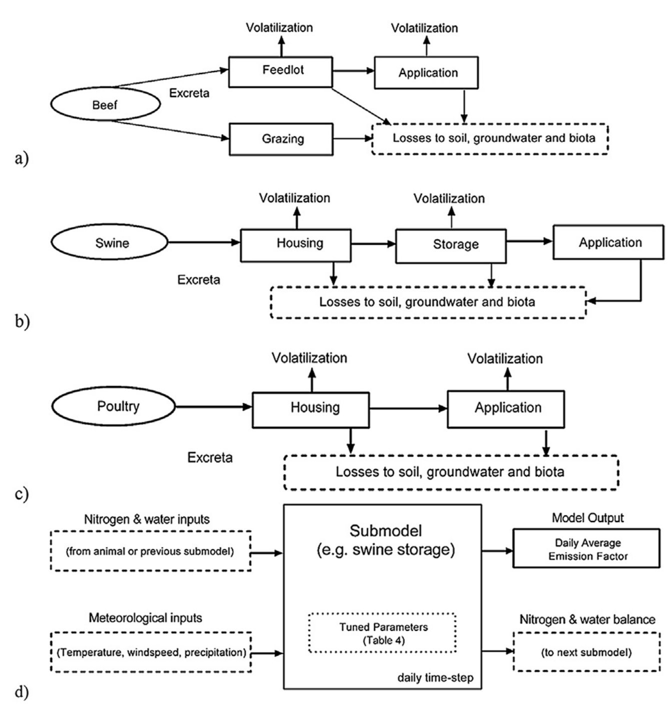

Fig. 1. Waste and nitrogen flows used in the farm emissions models (FEMs) for a) beef cattle, b) swine, and c) poultry. Fig. 1d shows how data flows through our submodels, showing how farm and meteorological input data are combined with the submodel's tuned parameters to produce emission factors and provide a mass balance which is passed along to subsequent submodels.