Ammonia Emissions from Dairy Farms: Development of a Farm Model and Estimation of Emissions from the United States

Robert W. Pinder
Department of Engineering and Public Policy
and
Natalie J. Anderson, Ross Strader, Cliff I. Davidson, and Peter J. Adams
Department of Civil and Environmental Engineering
Carnegie Mellon University, 5000 Forbes Ave, Pittsburgh, PA 15213
email: rwp@andrew.cmu.edu

ABSTRACT

Previous inventories of ammonia emissions have not characterized seasonal and geographic variations in emission factors. We combine a model of manure management on a single dairy farm with a national survey of management practices to estimate the seasonal and geographic variation in ammonia emissions from dairy farms, one of the largest sources. We estimate monthly, county-level emission factors by combining a dairy farm emissions model with an estimation of the national distribution of farming practices. The annual, county-level emission factors are estimated to range between 13.1 and 55.5 kg NH_3 cow^{-1} year^{-1}, and the seasonal variation is estimated to be as high as a factor of seven in some counties. Emission factors are estimated to be lowest in the winter and highest in southern and western states.

INTRODUCTION

Ammonia is an important atmospheric pollutant that plays a key role in several air pollution problems. When combined with nitric acid, ammonia forms aerosol nitrate, which contributes significantly to total particulate matter (PM) (McNaughton and Vet, 1996). A substantial fraction of ammonium nitrate aerosol is found in particles less than 2.5 micrometers in diameter (PM2.5). Previous reductions in PM2.5 have been achieved primarily by reducing sulfate; however, in parts of the Eastern United States, further decreases in sulfate will yield only modest reductions or in some cases increases in aerosol concentrations (West et al., 1999). A potential alternative is reduction of nitrate aerosol via reduction in ammonia emissions. However, the sensitivity of aerosol nitrate concentrations to ammonia varies seasonally and geographically. At low temperatures (275 K) and high nitrate concentrations, the formation of the aerosol phase is thermodynamically preferred, and a 1 $\mu g\ m^{-3}$ decrease in ammonia can cause a 4.7 $\mu g\ m^{-3}$ reduction in PM. At high temperatures or when little nitrate is present, PM concentrations are not sensitive to ammonia (Ansari and Pandis, 1998). Concentrations of nitrate vary temporally and spatially, so a detailed inventory of the seasonal and geographical variations of ammonia emissions is needed to evaluate control strategies.

In the United States, the largest source of ammonia emissions is livestock, estimated to be between 50 and 85% of total emissions (Battye, 1994; USEPA Trends, 1998). These emissions arise from urine patches on grazed pastures, excreta voided onto the floor of housing facilities, manure held in storage, and volatilization during the application of manure onto fields (Sommer and Hutchings, 1997).

Estimates of emission factors are both highly variable and uncertain. For example, emissions from manure spread onto fields have been reported to range from 10% to 120% of the ammonia applied (Plöchl, 2001). While there is uncertainty in such measurements, real variability in experimental environments suggests that under certain conditions both extremes are possible (Sommer and Hutchings, 2001).

Variation in ammonia emissions results from the dependence of ammonia volatilization on meteorological conditions and seasonal and regional differences in farming practices. In field studies, higher temperatures and wind speeds have been shown to increase the volatilization of ammonia (Sommer et al., 1991; Demmers et al., 1998). Heavy rains cause emissions to decrease to near zero (Sommer and Olesen, 2000). Seasonal changes in farming practices also play an important role. In cooler climates, cows are often confined in housing units for the duration of winter, and the manure stored during this period is often not applied to the fields until spring. In warmer climates, the cows may graze year round. Geographic variation is also important, as larger, more intensive operations are predominant in the West and Southeast, while smaller farms are still prevalent in the Northeast and Midwest.

Previous inventories are limited in that they lack high-resolution emission factors that capture the seasonal and geographical variation in ammonia emissions, as in recent inventories of Europe (Bouwman et al., 1997; Pain et al., 1998; van der Hoek, 1998; Skybova, 2001) and the United States (Strader et al., 2001). Most inventories select a single emission factor from the range of possible estimates. However, emission factors are calculated for a particular type of farm during specific conditions. To select one such emission factor and apply it universally does not account for differences in farming practices and seasonal changes.

This research addresses these limitations by first developing emission factors for dairy cows that vary by month and county. Calculation of these emission factors considers variability in climate conditions and farming practices. Second, these factors are combined with animal activity data to form a national ammonia emission inventory for dairy cows. As an input to an air quality model, this inventory can be used to gain more accurate estimates of the impacts of ammonia emissions, and it can be used to evaluate the effectiveness of reducing ammonia emissions by changes in farming practices.

METHOD

Figure 1 illustrates the overall structure of the model. This research has two main components. The first component is the Farm Emissions Model (FEM)—a semi-empirical model of ammonia emissions from a dairy farm. The inputs to the FEM are the set of manure management practices and yearly climactic conditions at a single dairy farm. The FEM predicts monthly emission factors for a dairy cow. The second component, the National Practices Model (NPM), is a statistical model used to predict farming practices for each county in the United States. Inputs to this model include the distribution of farm sizes in a county, milk production, historical farming practices, and climate data. For every county, the NPM predicts the most common farming practices for that location, and then the FEM is executed with each of the predicted farm types.

This process is then repeated for every county in the contiguous United States to generate a national inventory.

Structure of the Farm Emissions Model

Most experiments that estimate ammonia emissions collect samples at a particular phase of the manure management process over a period of time. Such experiments generally focus on a subset of the factors that affect emissions. Due to the vast number of farm configurations, important factors, and confounding interactions, all of the experimental results to date only cover a subset of possible emissions scenarios. The FEM is designed to use these experimental results to generalize over the set of the farming practices and conditions required for a national inventory. In order to explain the variability present in emission factors, the FEM explicitly models the processes that have the highest impact on ammonia emissions. However, our understanding of some processes is not sufficient to justify a mechanistic model. These factors are represented by parameters that are tuned to match empirical data from experiments drawn from the literature.

The FEM tracks the flow of nitrogen throughout each of the stages of manure management: feeding, housing, storage, application, and grazing. This structure is modeled after Hutchings et al (1996). Figure 2 and Figure 3 show the flows of nitrogen and manure. Each stage has a separate submodel that accounts for the chemical and physical processes specific to that component. Mass of nitrogen and volume of manure are conserved throughout each stage of the model. In the first stage of the model, manure is partitioned between the housing and grazing submodels depending on the fraction of time the animal is housed. Manure deposited in housing structures is moved to storage daily. Solids may be separated from the manure and stored separately. Manure is moved from storage and applied to the fields either daily, weekly, monthly, or seasonally.

Generalized Description of Ammonia Volatilization in the FEM

While there are structural and parametric differences between each of the submodels, they share the common feature that ammonia is volatilized from the surface of a liquid solution and is then transported through a pathway of finite resistance away from the atmospheric surface layer. Following Hutchings et al. (1996), the per cow volatilization of ammonia can be described as

Equation (1) Emissions (kg NH_3 / cow day) = $A[\mathrm{TAN}]H^{*}r^{-1}$

Where

A = fouled surface area per cow (m^2 cow^{-1})
[TAN] = total ammoniacal nitrogen (kg m^{-3} as NH_3)
H^* = effective Henry's Law Constant (dimensionless)
r = the mass transfer resistance (day m^{-1})

The determination of the initial concentration of TAN begins with cow's nutrition and metabolism. The nitrogen present in a cow's diet is partitioned between tissue growth, milk, urine, and feces. Urea is the dominant source of volatilized ammonia and the only source explicitly modeled. It is assumed that 75% of the nitrogen in urine is in the form of urea. The remainder of the urinary nitrogen is bound in several different organic acids, some of which are thought to hydrolyze to ammonia (Bristow et al., 1992; Bussink and Oenema, 1998). These additional compounds are not considered by this analysis. For solid manure, a constant emission factor of 5 kg cow^{-1} year^{-1} (Amon et al., 2001) is assumed, because the seasonal variation in emissions from solid manure is poorly understood.

Urea nitrogen is hydrolyzed to form ammonium by the urease enzyme, which has been found to be abundant in housing areas (Jongbreur and Monteny, 2001). Ammonium then dissociates into aqueous phase ammonia and hydrogen ion, according to a temperature-dependent equilibrium constant. Temperature inputs are derived from monthly climate normals that specify the mean and variance for the distribution of temperatures for each of the 345 climate divisions in the United States (NCDC Clim81, 2002). Ammonia is partitioned between the aqueous and gas phase according to the Henry's Law constant, which depends on temperature and pH. Higher temperatures and an alkaline pH favor the formation of gas phase ammonia.

Finally, mass transfer of gas phase ammonia to the free atmosphere is inhibited by the transport resistance, *r*. This resistance is the sum of three components: the aerodynamic, quasi-laminar, and surface resistances (Seinfeld and Pandis, 1998). The aerodynamic and quasi-laminar resistances are dependent of wind speed. A complete description of the calculations for these resistances can be found in Olsen and Sommer (1994). This model uses regional and monthly averaged wind speed data from the National Climate Data Center (NCDC, 1998). The surface resistance arises from diffusion through the top layer of soil or the surface crust formed on the top of manure storage tank. It is meant to capture poorly understood processes that are specific to the stage of the model. This parameter is tuned to match empirical data.

The concentration of total ammoniacal nitrogen is dependent on the solution volume, which is affected by precipitation, evaporation, and infiltration. Climate normals are also used for precipitation data (NCDC Clim82, 2002). The model is not sensitive to the evaporation rate, so it is assumed to be constant (25 g hr^{-1} m^{-2}) (Pollet et al., 1998). Infiltration is the rate at which liquid manure exits the region of soil that is sufficiently shallow to allow volatilization. The county average infiltration rate is calculated from a national soils database (MUIR, 1997) as a weighted average over county lands used for agriculture.

Variations for each submodel

<u>Housing</u>

The housing submodel tracks the transformation of urea nitrogen, TAN, and solution volume. The housing submodel differs from other stages in that it the resistance parameter is not the sum of three separate resistance calculations, but instead a single resistance is tuned as a function of temperature. As in Mannebeck and Oldenburg (1991), the resistance can be modeled as a two parameter function of the following form:

Equation (2) $r = p_1(1 - p_2(298 - T))$

where

p_1, p_2 = tuned parameters

T = temperature (Kelvin)

Three types of housing structures are present in the model: freestall, tiestall, and no housing. Freestall and tiestall are barn configurations and use the resistance model described above. They differ in that cows in tiestall barns are confined to their stalls and foul a smaller surface area. No housing is when the animals are confined on open-air, concrete lots. This case does not use the two parameter resistance model, but instead uses a surface resistance as in the general description above.

Storage

In the storage model, the surface resistance represents the potential formation of a viscous layer or crust on the surface of the slurry. A separate parameter is tuned for storage tanks with and without surface crust. A constant fraction (0.8) of storage units is assumed to have a crust. Three different types of storage are considered by this model: lagoon, slurry tank, and earthen basin. Each has a different surface area per cow, which is calculated from recommendations found in dairying manuals (MWPS-18, 1993).

Application

The application model tracks the nitrogen and total volume after it has been applied to a field. It differs from the previously discussed submodels in that the manure infiltrates deep into the soil where the ammonia is not susceptible to volatilization. Also, during irrigation and broadcast application, a fraction of the manure is intercepted by the crop canopy, where all of the ammonia is volatilized.

Three parameters are tuned in the application model: a surface resistance and a two-parameter function that approximates the effects of dry matter content on volatilization. Four different application techniques are included, irrigation, trailing hose, broadcast, and injection. These techniques differ in the dry matter content, since irrigation and injection must have a low fraction of solids. Trailing hose has a lower fraction of the volume intercepted by the crop canopy and injection deposits the slurry beneath the surface, decreasing the fraction of the applied volume that is susceptible to volatilization.

Grazing

Manure deposited in the grazing model is treated similarily to manure applied onto the fields, except that the transformation of urea nitrogen to TAN must be modeled. The grazing model has one tuned parameter to represent surface resistance. Grazing cows are either on drylots or pasture, each with its own surface resistance.

Parameter Tuning

To estimate the tuned parameters, this research uses Bayesian parameter estimation with Monte Carlo simulation (Sohn et al., 2000). This technique was selected because it can be used with sparse data and it provides probabilistic distributions for the resulting parameters, which can be used to characterize uncertainty. To find the distribution of a parameter, first a prior distribution is assumed. This prior is sampled iteratively, and the likelihood of the iteration is calculated using the FEM to predict the results of published experiments. The FEM inputs are assigned to the values reported in experiment design, and the likelihood of the each parameter iteration is computed by calculating the probability of the model result given the experimental error. If a range is reported for an input value, the range is also sampled. If no value is reported for a required input parameter, a range is estimated from the literature. Table 1 lists the experiments used for tuning.

When sufficient data are available, some datasets are reserved from the parameter estimation routines for testing. The model is used to predict the results of a published experiment that was not used to tune the model. Table 2 includes the root mean squared error for each of the submodels when compared with independent data. While the housing and storage models have reasonably small error, the application and grazing submodels have the largest error, possibly due to insufficient detail in the modeling of soil interactions. Also, the application and grazing submodels have the largest variance in their parameter posterior distributions, which is a reflection of the uncertainty of these calculations.

National Practices Model

The National Practices Model is a set of regression models used to predict the distribution of farming practices in each county. These are estimated based on survey data from the National Animal Health Monitoring System. The survey includes data from farms in 20 top dairying states that account for 82% of the national milk production. Not all of the counties in these states are represented, so a statistical model is necessary to predict under-sampled areas. Each type of farming practice is predicted by stepwise logistic regression as in Equation 3,

Equation (3) $$\ln\left(\frac{\mathrm{P}(y)}{1-\mathrm{P}(y)}\right) = \alpha + \beta \bullet x$$

Where

$\mathrm{P}(y)$ = probability of the farming practice y
α = vector of estimated intercept parameters
β = vector of estimated coefficients
x = vector of input values

All of the modeled values are dichotomous, except for frequency of application in summer and winter, which are multinomial and correspond to daily, weekly, monthly, and seasonal manure application. The inputs to the models are climate data, geographic region, historical patterns of dairying, cow population, milk yield, and the set of other manure management practices used on the farm. The set of other practices are included because the farming practices are correlated. For example, manure stored in lagoons is usually applied to fields via irrigation. Table 3 lists the r^2 values for each estimated model. The criteria for retaining a variable in the stepwise procedure is $p < 0.25$, so all of the coefficients are significant at least to that level.

Not all of the farming practice variables are predicted with regression model, because their r^2 values are low and the inaccuracy is high. For these practices, the mean value for each survey state is used, and for states not in the survey, the geographical region average is used. Practices estimated in this way include whether animals that are unconfined are on pasture or drylots, and whether manure is handled in liquid, solid, or both liquid and solid forms.

The second stage of the National Practices Model is to apply the resulting regression models to derive a county-level distribution of farming practices. For each county, the regression models predict the probability that a given farm has a set of farming practices. From these probabilities, the top one hundred most likely farm configurations and their probabilities are calculated. Each of these farm types are executed by the FEM, and the county-level monthly emission factor is the average of the one hundred results, weighted by farm size and probability of occurrence.

RESULTS

The national inventory predicts annual emission factors that range from 13.1 to 55.5, with an average of 23.9 kg NH_3 cow^{-1} $year^{-1}$. The geographical distribution is shown in Figure 4. The highest emission factors are found in Southern and Western states such as Arizona, Texas, and California. This can be attributed to warmer temperatures and more intensive practices.

Figure 5 shows the ratio of the January to July emission factors. As expected, there is a strong seasonal trend by which emissions in the summer are greater than those of the winter, by as much as a factor of seven. Farms in the Northeast and Northern Midwest have the greatest seasonal variation, resulting from a combined effect of greater seasonal variation in climate and manure management practices, such as higher levels of confinement in the winter and seasonally delayed manure application.

Figure 6 displays the total dairy emissions per km^2. This map highlights the traditional dairying areas of Wisconsin, Pennsylvania, and New York, and also new dairy regions in California, Washington, Arizona, New Mexico, and Southeastern Idaho.

CONCLUSIONS

This research has developed a seasonally and geographically resolved inventory for ammonia emissions from dairy cows. Nationally, the annual emission factors differ by a factor of four between the highest and lowest counties, and the seasonal variation from summer to winter is as large as factor of seven for some counties.

Future work will use this inventory as an input to an air quality model to examine the sensitivity of PM with respect to the seasonal variation in ammonia. Future work will also examine the potential for this model to be used to estimate the impacts of changes in manure management practices on ammonia emissions. After building and tuning alternative submodels, the Farm Emissions Model can be used to test emission-reducing strategies and their application across the United States.

DISCLAIMER

Data included in some parts of this analysis were provided by the U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Veterinary Services, National Animal Health Monitoring System (NAHMS). However, the analysis and conclusions described in this article are independent of Veterinary Services and NAHMS.

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Table 1. Emission measurements used to tune parameters in FEM

Submodel	Sources	Observations
Housing	Elzing and Monteny (1997)	5
	Monteny et al (1998)	6
	Misselbrook et al (1998)	6
	Misselbrook et al (2001)	5
Storage	Xue et al (1999)	5
	Sommer et al (1993)	2
	de Bode, et al (1991)	2
Application	Sommer, Olsen, and Christensen (1991)	42
	Sommer and Chistensen (1991)	15
	Menzi, et al (1998)	16
	Gordon, et al (2001)	8
Grazing	Jarvis, Hatch, and Lockyer (1989)	7
	Jarvis, Hatch, and Roberts (1989)	4

Table 2. Sources of independent data used for testing of tuned parameters and root mean squared error expressed as a fraction of ammonia volatilized

Submodel	RMSE	Comparison Source
Housing	0.0206	Compared with tuning set
Storage	0.0154	Sommer (1997)
Application	0.160	Sommer and Olsen (1991)
Grazing	0.102	Sherlock and Goh (1983)

Table 3. R^2 values for each farming practice regression in NPM

	Modeled Variable	R^2
Housing Type	Tiestall	0.68
	Freestall	0.41
	No Housing	0.63
Storage Type	Lagoon	0.65
	Earthen Basin	0.53
	Slurry Tank	0.47
Application Type	Irrigation	0.52
	Broadcast	0.33
	Injection	0.34
	Trailing Hose	0.54
Confined	Summer	0.43
	Winter	0.36
Frequency of Application	Summer	0.34
	Winter	0.47

Figure 1. Overview of research strategy used to calculate seasonally and geographic variability in emission factors

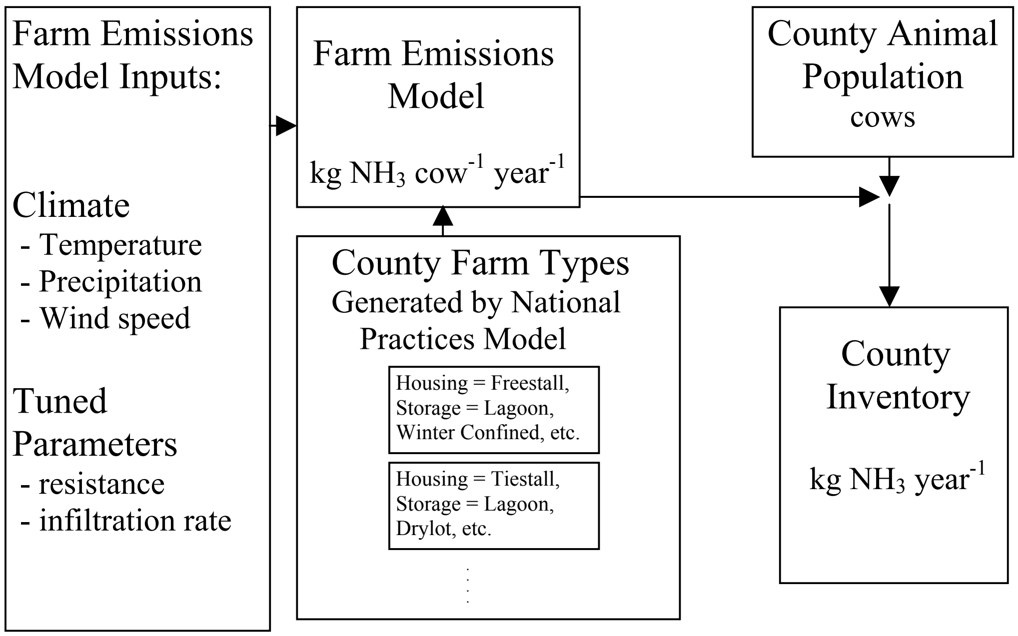


Figure 2. Flows of nitrogen in FEM

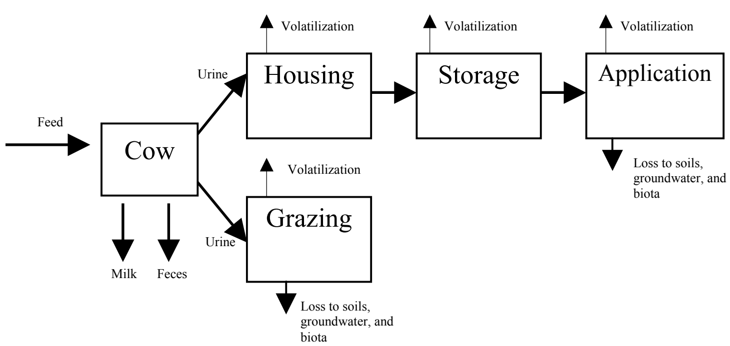


Figure 3. Manure volume flows in FEM

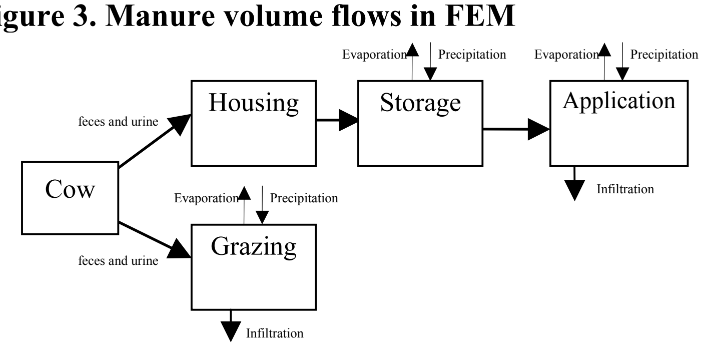


Figure 4. Annual-average county level emission factors, kg NH_3 cow^{-1} $year^{-1}$

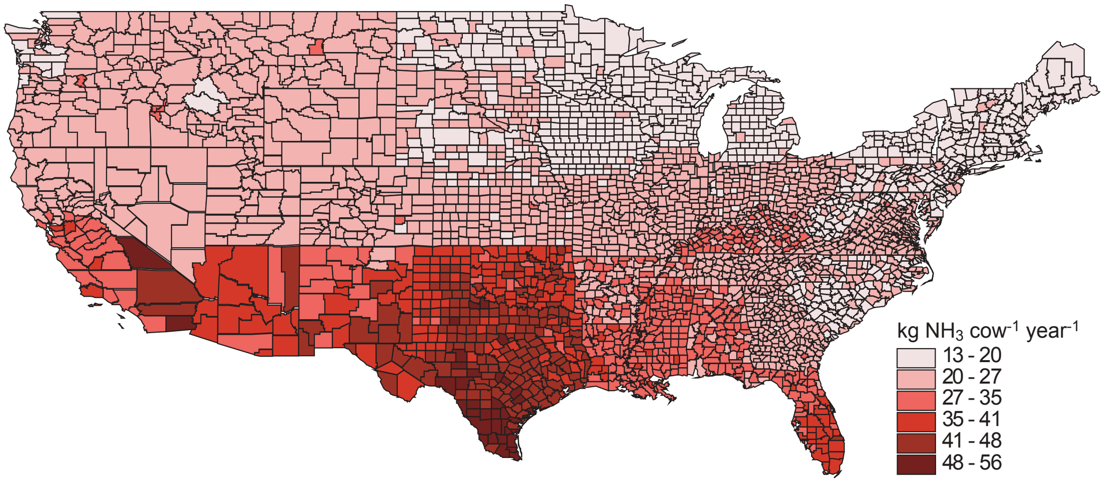


Figure 5. Ratio of July to January emission factors

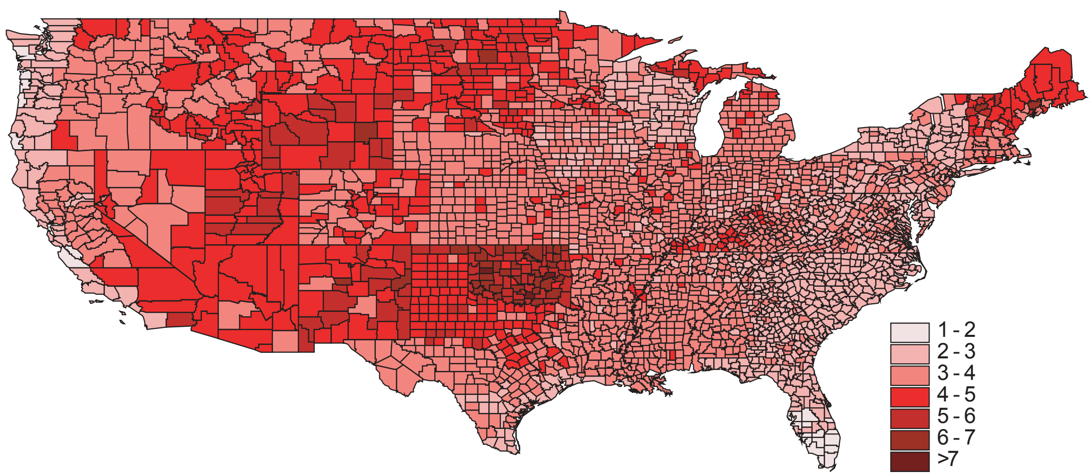
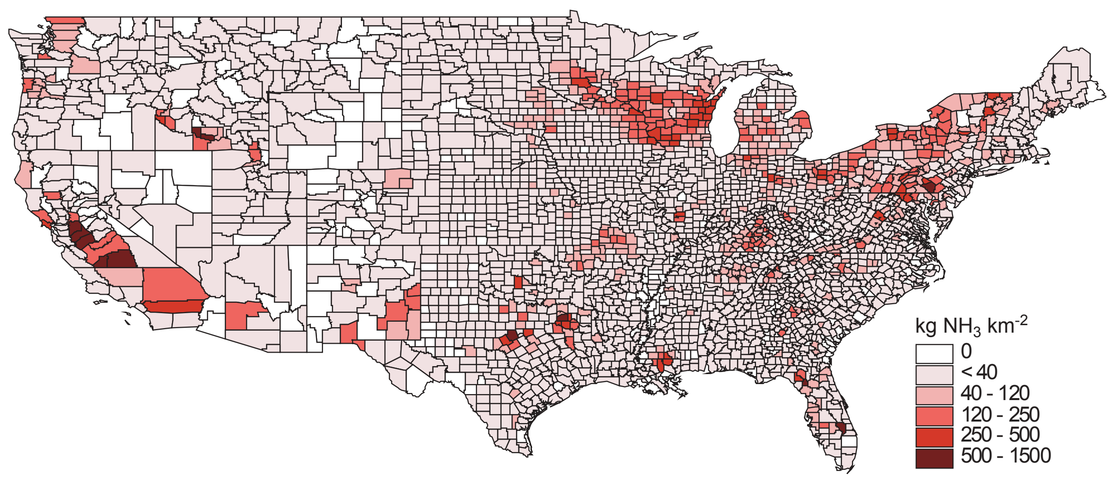


Figure 6. Annual-average ammonia emission fluxes (kg NH_3 km^{-2}) by county



KEYWORDS

Ammonia
Emission inventories
Area sources
Agriculture