An Improved Process Based Ammonia Emission Model for Agricultural Sources – Emission Estimates

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ABSTRACT

Ammonia is an important atmospheric pollutant that combines with sulfuric acid and nitric acid to form aerosol sulfates and nitrate, respectively. These aerosol species are major components of fine particulate matter (PM) and contribute significantly to visibility impairment. Estimates of ammonia emission factors are both highly variable and uncertain. Emissions factors vary depending on meteorological conditions and seasonal and regional differences in farming practices. Previous ammonia emissions inventories have not adequately characterized seasonal and geographical variations in emissions factors. Recent chemical transport modeling suggests that daily and hourly variability in ammonia emissions is required to model accurately the formation of ammonium nitrate and ammonium sulfates.

In a companion paper, the development of a process-based model for predicting or estimating ammonia emission rates and factors from individual or a group of animal feeding operations at local, regional and national levels was presented. This paper discusses the data requirements and implementation of the process-based ammonia emission model. Preliminary emission estimates developed from the process-based ammonia emission model are also presented. Detailed description of databases used as input values for the process-developed model and recommendations for future

improvement on the farm-based data regarding the animal feeding and manure management practices are documented. Where available, comparisons of the new ammonia emission estimates with existing ammonia emission inventories for livestock farms at a local, regional and national level are presented.

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INTRODUCTION

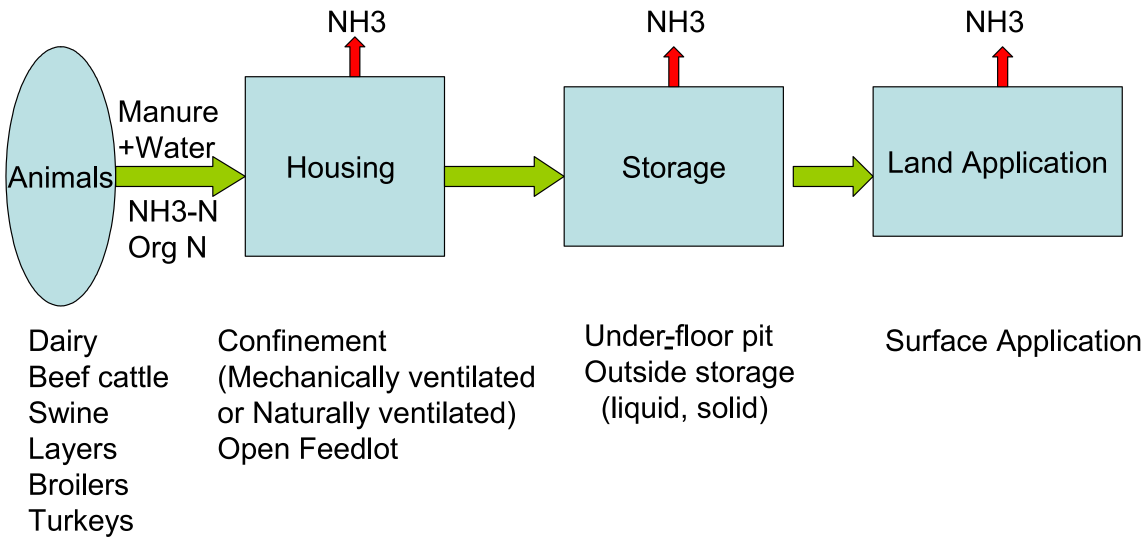
Ammonia is an important atmospheric pollutant that combines with sulfuric acid and nitric acid to form aerosol sulfates and nitrate, respectively. These aerosol species are major components of fine particulate matter (PM) and contribute significantly to visibility impairment. Estimates of ammonia emission factors are both highly variable and uncertain. Emissions factors vary depending on meteorological conditions and seasonal and regional differences in farming practices. Previous ammonia emissions inventories have not adequately characterized seasonal and geographical variations in emissions factors. Recent chemical transport modeling suggests that daily and hourly variability in ammonia emissions is required to model accurately the formation of ammonium nitrate and ammonium sulfates.

The overall objective of the study is to advance the state of science with respect to estimation of ammonia emissions from agricultural sources, specifically livestock operations, utilizing a process-based modeling approach. The emission estimates developed from this study are to be used in air quality modeling. It is therefore necessary to generate gridded, hourly resolved emission estimates for a specific grid-based modeling domain. The ammonia model is integrated within the overall emissions modeling framework of the CONsolidated Community Emissions Processing Tool (CONCEPT), an open source, public domain emission modeling system.
Integration with CONCEPT allows access to the general processors necessary for spatial allocation, specification of meteorological parameters and formatting of output for use in regional air quality modeling systems. The process-based model is developed as a suite of sub-modules, one for each of the ammonia emission source processes. Data requirements and sources, and model implementation are discussed. Preliminary ammonia emission estimates are presented and, where available, comparisons with other ammonia emission inventories are presented.

MODEL DEVELOPMENT AND IMPLEMENTATION

The process-based ammonia emissions model developed for this study was discussed in a companion paper (Zhang, et al., 2005)[1] and described in a series of project documents (Zhang, et al., 2004[2];Wang, et al., 2005[3]). In summary, the model considers each of the processes occurring on a typical livestock farm, and calculates the resulting ammonia emissions from each. By tracking the amount of manure through each stage at the farm and using mass conservation, the total ammonia emissions for each process and for the farm as a whole is estimated. The main processes treated in the model include the nitrogen excretion from the animals, animal housing, manure storage and land application of manure. Figure 1 provides a general schematic diagram of the processes currently implemented in the model. The animal species considered by the model include beef and dairy cattle, poultry and swine. A brief summary of each of the sub-modules is provided below.

Figure 1. Schematic diagram of the process-based ammonia emissions model.



The primary module of the modeling system estimates the ammonia emissions from each of the various processes occurring on the farm and consists of the following five sub-modules: pre-excretion, housing , feedlot , storage/treatment, and land application or utilization.

The pre-excretion module calculates the manure and N excretion of animals in response to type and growth stage of animals, feed rations, animal productivity and animal management practices. The new ASAE Standard for animal manure production and characteristics is used as the basis for developing the manure and N excretion model.

The housing module calculates the ammonia emission rate from confinement animal houses in response to animal numbers and types, building structures, ventilation types (mechanical vs. natural), animal management practices, and manure collection practices. Material balances were used to derive differential equations to predict the concentrations of the following substances in the housing: a) ammonia in the house air and b) ammoniacal nitrogen in the manure, and c) urea within the manure. The model equations are similar to those derived by others that have been used to analyze ammonia emissions from dairy and swine housing. The emission rate from housing depends on the ventilation rate and indoor air temperature. Mathematical models were derived using energy balances to predict housing air temperature and ventilation rates for both mechanical and natural ventilation schemes. These models also compare with well-mixed models from the literature.

The feedlot emission module calculates the ammonia emission rate from open feedlot in response to manure properties (pH and ammonia concentration) and environmental conditions (temperature and air velocity).

The liquid storage/treatment emission module calculates the ammonia emission rate from manure storage structures in response to manure properties (pH, temperature, ammonia concentration, and organic N concentration), structural and storage parameters (surface area, retention time) and environmental conditions (temperature and air velocity). It is a mechanistic model that simulates the biological, chemical and physical processes that occur with the ammonia in the manure storage, such as ammonia generation from mineralization of organic nitrogen in the storage and ammonia volatilization from the manure surface. The model includes two sub-models, under-floor pit storage model and outside storage model to account for the differences in the environmental conditions over the manure.

The land application emission module calculates the ammonia emission rate from agricultural fields where manure is applied or irrigated in response to manure properties (pH, ammonia concentration, and organic N concentration), crop type and management practices, and environmental conditions (temperature and air velocity). It is a mechanistic model that simulates the biological, chemical and physical processes that occur with the ammonia in the manure storage, such as ammonia generation from mineralization of organic nitrogen in the storage and ammonia volatilization from the manure surface.

In order to estimate ammonia emissions associated with each of these processes, the farm's configuration or manure management practices must be specified. Ideally, the required information for each particular farm is needed in order to apply the model at the farm level. Unfortunately, this information is not likely to be available for every livestock operation for a region encompassing the entire U.S. Therefore, the model has been developed to consider animal populations and typical manure management practices on a more broad scale, such as state- or county-level. Using an approach similar to the treatment of general area source emissions processing, county and/or state-level data are spatially allocated to modeling grid cells and prior to estimating emissions using the process-based approach at the farm level. These 'synthetic' farms are based on information developed by the EPA that provides data at a county-level describing the various livestock management practices.

The EPA recently developed an ammonia emission model using a similar process-based approach (EPA, 2004)[4]. The data used to drive the EPA model includes a set number of manure management trains (MMT). An MMT is defined by the specific processes occurring on a livestock farm, as well as their configuration and includes the specification of the housing, or confinement area, manure storage and land application. The MMTs defined and treated by the EPA are based on a statistical analysis of the most common livestock farm configurations and practices. State-level animal populations and county-level population distributions are combined with state-level distributions of these MMTs to account for the variation of livestock farming practices across the entire country. The MMTs defined by the EPA are presented in Table 1. The ammonia developed for the present study makes use of these data to account for the lack of specific information at the farm level. Currently the model is configured only for these specific MMTs, but can be updated to treat virtually any specific MMT comprised of the five processes described above.

Using the distribution data developed by the EPA, animal populations and MMTs are spatially allocated to specific modeling grid cells using spatial surrogates to define the 'synthetic' farms. Ammonia emissions are estimated for each of these 'synthetic' farms using a set of default parameters required for each of the specific processes as if they were actual real farms. Any data associated with real farms that may be available are also incorporated in the modeling system. Animal populations from actual farms are reconciled with the county-level data prior to the application of the model to avoid double-counting of emissions. The primary differences between the treatment of 'synthetic' and real farms are that for real farms, actual animal populations are used and the physical locations are known. In contrast, for 'synthetic' farms animal populations are based on the state/county distribution data and locations are determined through the application of spatial surrogates.

Table 1. EPA defined Manure Management Trains (MMTs)

AnimalType	MMTID	MMT Description	Animal
Beef	1+2+3	Beef Feedlot	
Beef	1	Beef Feedlot with Storage Pond, no Settling Basin	Beef
Beef	2	Beef Feedlot with Storage Pond and Settling Basin	Beef
Beef	3	Beef Feedlot with no Storage Pond or SettlingBasin	Beef
Beef	4	Beef Operations on Pastures	Beef
Poultry	1	Poultry- dry layers	Layers
Poultry	2	Poultry- wet layers	Layers
Poultry	1	Broiler house	Broilers
Poultry	2	Broiler outdoor confinement area	Broilers
Poultry	1	Turkey house	Turkeys
Poultry	2	Turkey Outdoor Confinement Area	Turkeys
Dairy	1	Flush Dairy with Solids Separation w lagoon	Milking
Dairy	2	Flush Dairy without Solids Separation w lagoon	Milking
Dairy	3	Scrape Dairy without Soilds Separation w lagoon	Milking
Dairy	4	Scrape Dairy with Soilds Separation w lagoon	Milking
Dairy	6	Scrape Dairy- Daily Spread	Milking
Dairy	7	Dairy Barn with Deep Pit	Milking
Dairy	9	Scrape Dairy- Slurry tank/basin	Milking
Dairy	8	Scrape Dairy- Solid Storage	Milking
Dairy	5	Dairy Outdoor Confinement Area	Milking
Swine	1	Swine House w/ Lagoon Systems & no Solids Separation	Swine
Swine	2	Swine House with Deep Pit System	Swine
Swine	3	Swine Outdoor Confinement	Swine
Swine	4	Swine House w/ Lagoon Systems & Solids Separation	Swine

While the EPA datasets include animal populations for the same species as considered in the present model, they are defined in a slightly different manner with respect to the animal sub-category groupings. A mapping between the EPA data and those required by the model developed for the present study was required. Table 2 presents the animal sub-categories considered by each of the models and provides the mapping scheme used to relate the two different datasets.

Table 2. Animal sub-categories defined by the model.

Animal Species	EPA Animal Subcategory	FEM Animal Subcategory	EPA.FEM Animal Sub-category Mapping
Dairy	Lactating	Lactating	n/a
	Dry	Dry	n/a
	Heifer	Heifer	n/a
Beef	Not on feed heifers	Finishing	= On feed heifers + On feed steers
	On feed heifers	Cow-calf pair	= 0.8*(205/365)*Beef cow
	Not on feed steers	Maintenance	= (1-0.8)*(205/365)*Bee cow + (160/365)*Beef cow + Bulls |+ Not on feed heifer + Not on feed steer
	On feed steers		
	Bulls		
	Calves		
	Beef cows		
Poultry & Layers	Broilers	Broilers	n/a
	Turkeys	Male turkey	= 0.5 * Turkeys
	Hens	Female turkeys	= 0.5 * Turkeys
	Pullets	Layers	= Hens + Chickens + Pullets
	Chickens		
Swine	Swine60	Finishing	= (2/3)*(Swine60+Swine60_119+Swine120_179+Swine180)
	Swine60_119	Weaning	= (1/3)*(Swine60+Swine60_119+Swine120_179+Swine180)
	Swine120_179	Lactating	= (1/6)* Swine Breeding
	Swine180	Gestating	= (5/6)* Swine Breeding
	Swine Breeding		

The process-based ammonia model was developed in a modular fashion as an open source model using PostGreSQL. The code is integrated within the overall framework of the CONCEPT emissions processing system. The model consists of two main processors: the Animal Allocation Processor (AAP) and the Farm Emission Model (FEM). The AAP serves to process the raw data and format these inputs for the FEM. The FEM performs the ammonia emission calculations for each of the processes considered at the farm level using a mass conservation approach to track the flow of manure for a specific farm configuration, or MMT, as described by Zhang et al. (2005)[1].

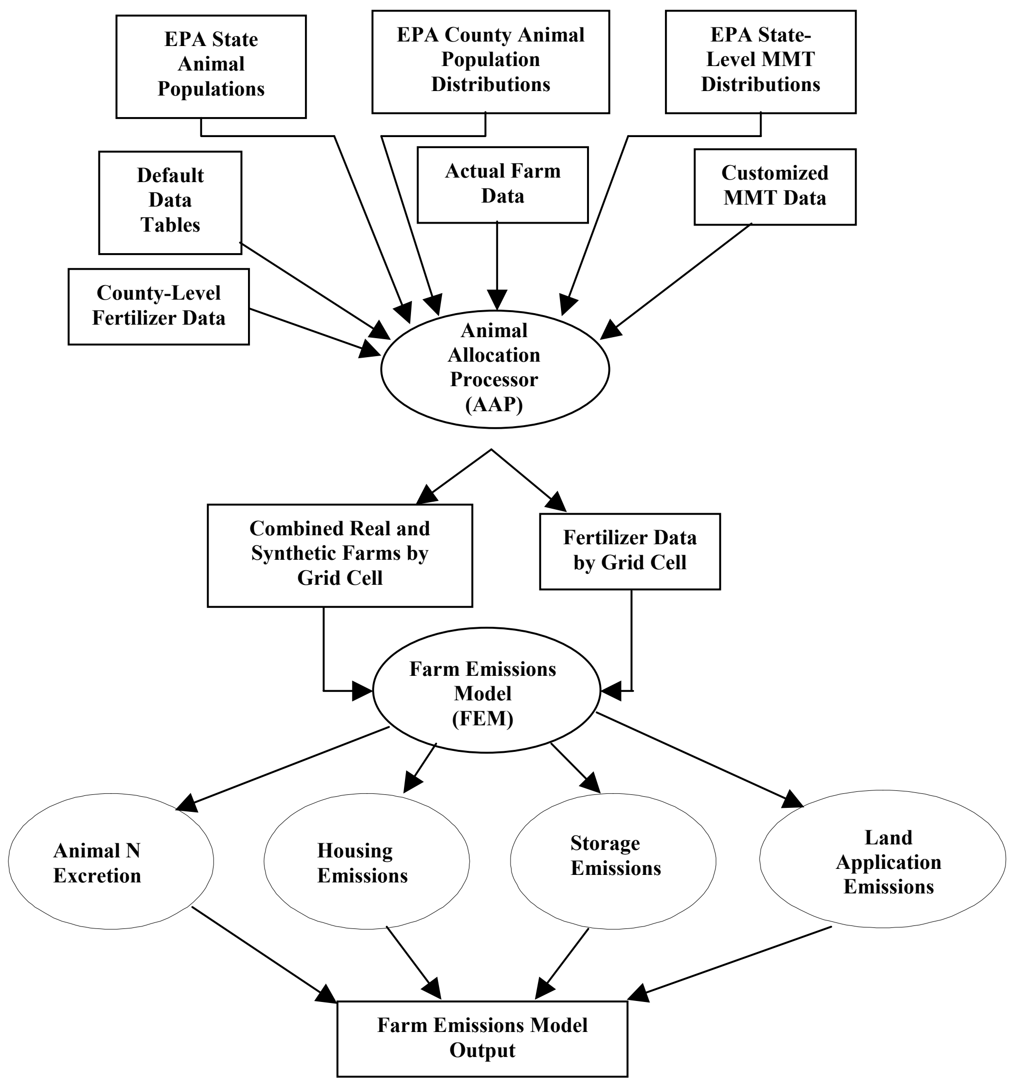
In addition to estimating ammonia emission from livestock operations, the model also includes the estimation of emission from commercial fertilizer application. Currently, the treatment of fertilizers within the process-based model serves as a place-holder approach. It is recognized that ammonia emissions from the application of commercial fertilizers will depend on various environmental parameters (i.e., temperatures, wind speeds, soil characteristics). However, at the time the model was developed these dependencies were nit yet fully developed. The model therefore uses the AAP to spatially allocate county-level fertilizer application rates to agricultural lands and passes these gridded results to the FEM for further processing and emissions estimation. Fertilizer ammonia emissions are calculated using emissions factors and activity data.

The AAP is required for developing inputs to the FEM modules of the modeling system. Based EPA animal populations and MMT distributions, the AAP generate 'synthetic' farms. The generation of these farms requires the spatial allocation processors within the CONCEPT model to allocate the county-level data to modeling grid cells. The AAP is also responsible for reconciling the county-based animal population data with any real farm data. Default parameters required for the application of the process-based emission calculations are set in the AAP. The AAP outputs ASCII datasets, appropriately formatted for input to the FEM. The county-level fertilizer data is similarly processed (spatially allocated to grid cells) and formatted for input the FEM module.

The FEM uses the results of the AAP to estimate ammonia emissions for each farm, real or 'synthetic'. The calculations within the FEM are determined by the specific MMT and animal populations specified on the input files. Required meteorological data is obtained through the CONCEPT interface as needed by the FEM module. The FEM calculate ammonia emission from each process at the farm level process on an hourly basis and, using the appropriate modules of the CONCEPT modeling system, outputs the gridded, hourly resolved ammonia emission inventory.

Figure 2 presents a schematic flow diagram of the process-based ammonia emissions model illustrating the various inputs and interaction between the AAP and the FEM.

Figure 2. Schematic flowchart for the process-based ammonia emission model.



DATA SOURCES

The processed-based ammonia model requires a variety of data obtained from numerous sources. The farm emission sub-modules treat ammonia emissions from five processes: animal excretion, animal housing, liquid and solid manure storage emissions and land application. Each of the five sub-modules takes into account the different farm practices due to the variability among livestock species and regions. Thus, each sub-module requires specific data associated with the process being modeled.

Animal excretion sub-module: Nitrogen excretion from animals is influenced by the age, species, and diet of animals. Data required to accurately model these processes include information concerning animal populations, including age, and feed ratios, among others.

Animal housing sub-module: Ammonia emissions from animal housing depend on the specific housing design and practices for each farm. In addition, the collection and storage of manure from housing operations varies by indoor and outdoor storage. The housing emission sub-module calculates the emissions from a combination of housing and manure collection methods that are commonly used for a given animal farm. Information concerning housing design and operation for each specific farm treated by the module is required. As the design and operation of animal housing varies by species, age and climate, animal populations by age and climatic conditions for each farm location are required.

Storage sub-module: Ammonia emissions associated with manure storage will vary by the type of manure. Dry manure storage is typical of beef cattle feedlot, dairy corrals, high-rise layer facility, broiler and turkey facilities. Wet manure storage is commonly used for manure collected in swine and layer facilities. The storage emission sub-modules include both dry storage and wet storage. Emissions are based on the type of storage facilities and manure. For each farm, data concerning the type and number of storage facilities is required, in addition to environmental data.

Land application module: Ammonia emission rates from different land application practices vary by type of animal manure, crop management practices and climatic conditions. Data regarding the nutrient content of manure by animal type, specific application and crop management practices for each farm and environmental conditions are required.

The required data for each of the sub-module, as summarized above, are not typically available with the type of detail required for a region encompassing the entire U.S. Therefore, a set of default values for each was assembled. These default data were developed based on information Midwest and are therefore most representative of this region. Because these required data can vary considerably across the US, a set of ranges for these parameters are provided and can be used if desired.

The process-based ammonia emissions model makes use of the MMT and animal population distributions developed by the US EPA in their ammonia emissions model as described above. This data processed through the AAP module to estimate the number of animals in each MMT, and their physical locations, to be processed by the FEM.

The county level population distribution data in the EPA model was generated from the 1997 Census of Agriculture data (USDA, 1999)[5], and the MMT apportionment was generated using a combination of data from the USDA, Census of Agriculture, and EPA's Office of Water[4]. In the AAP, the MMT data is categorized as data of type "MMT."

The populations categorized under each stage of each MMT are translated into the categories required by the FEM as noted above. In addition, the AAP must reconcile these county-level animal populations with those associated with real farms. The AAP also assigns defaults for any missing parameters associated with each of the emissions processes with each defined MMT considered by the modeling system. Finally, the AAP uses spatial surrogate data associated with agricultural lands, as defined within the CONCEPT spatial processors, to allocate the 'synthetic' farms to modeling grid cells. Actual real farms are specified by their geographic coordinates, and converted to grid cells within the AAAP prior to being processed through the FEM.

An important component of this study was the identification and incorporation of the various parameters required to estimate ammonia emissions for livestock operations using a process-based approach. These data were to be representative of the specific practices throughout the Midwest U.S. In addition to incorporating Midwest specific default parameters, the county-level animal population and MMT distributions were revised to better reflect the livestock farming practices in this region of the country. Table 3 presents a summary of the EPA distribution data for the Midwest, as well as adjusted distribution data derived from more recent information collected for these states.

Activity data and emission factors for the treatment of commercial fertilizer usage were obtained fro the Carnegie Mellon University (CMU) ammonia model developed by Strader, et al., (2004)[6]. The CMU model incorporated monthly fertilizer application rates for all counties in the US, as well as emission factors for each of the commercial fertilizer types considered. Diurnal profiles for fertilizer ammonia emission were developed from recent EPA research efforts for ammonia emission modeling techniques documented by Battye and Barrows (2004)[7] . These data were included in the current application of the model.

Table 3. EPA MMT distributions for the Midwest.

Animal Type	MMTID	MMT Description	Animal	IA		IL		IN		KS		MI		MN		MO		NE		OH		SD		WI	
				EPA	**adj**	EPA	**adj**	EPA	**adj**	EPA	**adj**	EPA	**adj**	EPA		EPA	**adj**	EPA	**adj**	EPA	**adj**	EPA	**adj**	EPA	**adj**
Beef	1+2+3	Beef Feedlot		27.4	**35**	14.2	14.2	15	**18**	37.3	**50**	28.9	**28.9**	13.2	20	1.5	**2.4**	36.2	**40**	17.5	17.5	8.7	**13**	9.4	**7.4**
Beef	1	Beef Feedlot with Storage Pond, no Settling Basin	Beef								**10**						**1**								
Beef	2	Beef Feedlot with Storage Pond and Settling Basin	Beef								**35**						**1**								
Beef	3	Beef Feedlot with no Storage Pond or Settling Basin	Beef								**5**						**0.4**								
Beef	4	Beef Operations on Pastures	Beef	72.6	**65**	85.8	85.8	85	**82**	62.7	**50**	71.1	**71.1**	86.8	80	98.5	**97.6**	63.8	**60**	82.5	82.5	91.3	**87**	90.6	**92.6**
Poultry	1a	Poultry- dry layers - high-rise	Layers	100	90	98	**90**	100	**95**	98	**98**	98	**98**	100	100	100		100	100	100	100	98	98	98	98
Poultry	1b	Poultry- dry layers - belt	Layers		10		**10**		**5**								**45**								
Poultry	2	Poultry- wet layers (lagoon)	Layers	0	0	2	**0**	0	**0**	2	**2**	2	**2**	0	0	0	**55**	0	0	0	0	2	2	2	2
Poultry	1	Broiler house	Broilers	99	99	99	Almost	99	**99**	99	**99**	99	**99**	99	99	99	**100**	99	99	99	99	99	99	99	99
Poultry	2	Broiler outdoor confinement area	Broilers	1	1	1	none	1	**1**	1	**1**	1	**1**	1	1	1	**0**	1	1	1	1	1	1	1	1
Poultry	1	Turkey house	Turkeys	99	99	99	99	99	**99**	99	**99**	99	**99**	99	99	99	**99**	99	99	99	99	99	99	99	99
Poultry	2	Turkey Outdoor Confinement Area	Turkeys	1	1	1	1	1	**1**	1	**1**	1	**1**	1	1	1	**1**	1	1	1	1	1	1	1	1
Dairy	1	Flush Dairy with Solids Separation w lagoon	Milking	0	**3**	0	**5**	0	**4**	0	**70**	2	**2**	1	**7**	0	**32**	0	**12**	1	**1**	0	0	1	**2**
Dairy	2	Flush Dairy without Solids Separation w lagoon	Milking	2	**1**	1	**10**	1	**1**	1	**0**	5	**2**	3	**3**	2	**16**	2	**12**	2	**2**	1	1	4	**1**
Dairy	3	Scrape Dairy without Solids Separation w lagoon	Milking	7	**52**	8		6	**6**	6	**5**	15	**1**	5	**20**	5	**5**	5	**24**	6	**6**	6	6	6	**34**
Dairy	4	Scrape Dairy with Solids Separation w lagoon	Milking	1	**0**	1		1	**1**	1	**10**	3	**39**	1	**1**	0	**10**	0	**24**	1	**1**	1	1	1	**10**
Dairy	6	Scrape Dairy- Daily Spread	Milking	17	**33**	12	**20**	18	**15**	14	**5**	10	**50**	19	**30**	16	**3**	16	**11**	17	**18**	17	17	17	**40**
Dairy	7	Dairy Barn with Deep Pit	Milking	4	**3**	5	**5**	4	**3**	5	**0**	5	**1**	4	**4**	5	**0**	5	**0**	5	**4**	4	4	4	**1**
Dairy	9	Scrape Dairy- Slurry tank/basin	Milking	12	**0**	14	**20**	13	**30**	14	**5**	14	**0**	12	**15**	14	**10**	14	**11**	13	**28**	13	13	12	**5**
Dairy	8	Scrape Dairy- Solid Storage	Milking	47	**0**	51	**40**	45	**30**	51	**5**	41	**0**	45	**15**	48	**2**	48	**2**	46	**30**	47	47	46	**2**
Dairy	5	Dairy Outdoor Confinement Area	Milking	10	**8**	7		11	**10**	8	**0**	6	**5**	11	**5**	9	**22**	9	**4**	10	**10**	10	10	10	**5**
Swine	Added ISU	Swine House with Earthen and Formed Manure Storage	Swine																						
Swine	1	Swine House w/ Lagoon Systems & no Solids Separation	Swine	25	**19**	25	**35**	25	**25**	62	**80**	20	**20**	19	**15**	83	83	23	**79**	22	**22**	19	19	16	16
Swine	2	Swine House with Deep Pit System	Swine	70	**80**	70	**60**	70	**70**	30	**16**	79	**79**	79	**83**	16	16	71	**16**	73	**75**	79	79	81	81
Swine	3	Swine Outdoor Confinement	Swine	1	**1**	1	**1**	1	**1**	1	**1**	0	**0**	0	**1**	1	1	1	**1**	1	**1**	0	0	1	1
Swine	4	Swine House w/ Lagoon Systems & Solids Separation	Swine	4	**0**	4	**4**	4	**4**	3	**3**	1	**1**	1	**1**	0	0	4	**4**	2	**2**	2	2	2	2

RESULTS

The process-based ammonia emissions model was implemented using the data sources described above to develop a gridded ammonia emission inventory for 2002 for the entire United States at a resolution of 36-km. Although the development of a national ammonia emission inventory for calendar year 2002 still under way and the results are undergoing review, some preliminary model results are presented here. A comparison with estimates obtained from a GIS-based ammonia emission model, developed for the Western Regional Air Partnership (Mansell, 2005)[8] are also presented.

Figure 3 presents the results of the process-based model for the state of KY for July 6, 2002. Displayed are the hourly ammonia emission estimates for beef, dairy and swine. Note that these results include only the housing and storage processes. Note also, that all hourly emission estimates presented here are in Greenwich Mean Tim (GMT). The hourly variation appears consistent with expectations with higher emission during the afternoon hours and lower emission during nighttime hours.

Figure 3. Hourly livestock NH3 emissions for Kentucky on July 6, 2002 (kg/hr).

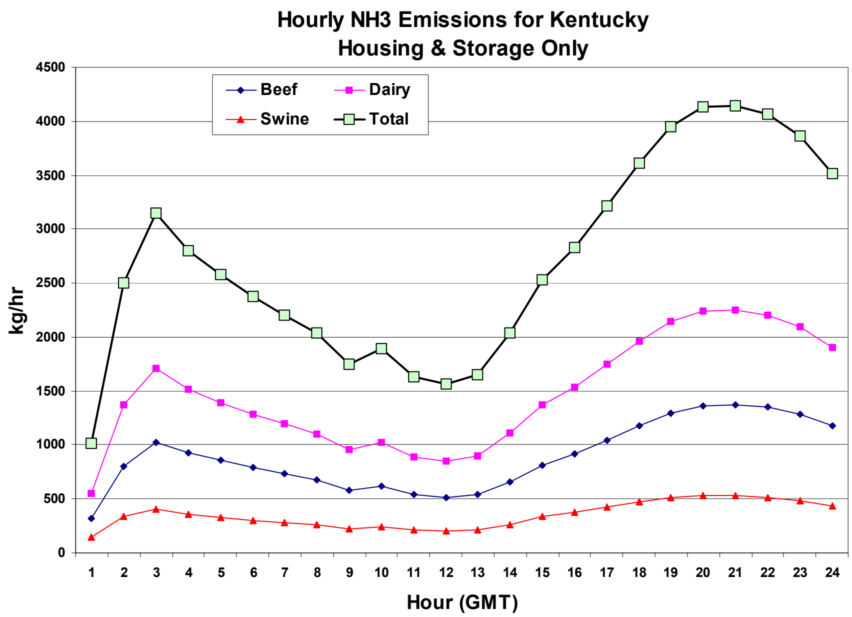


Figure 4 presents model results for hourly dairy ammonia emissions by MMT. Similar displays of estimated ammonia emissions by MMT are displayed in Figures 5 and 6 for Beef and swine, respectively. The results presented in these figure provide an indication of the effects of the various livestock farm configuration on the estimated ammonia emissions.

Figure 4. Hourly dairy NH3 emissions for Kentucky by MMT (kg/hr).

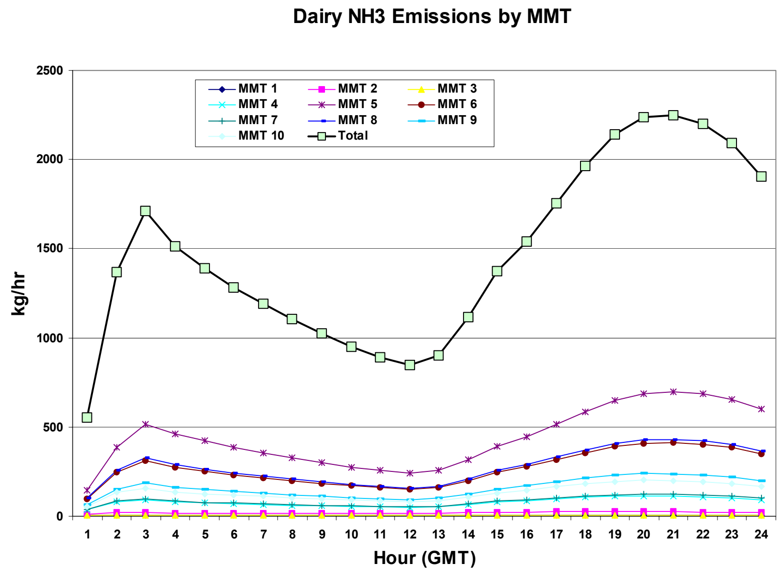


Figure 5. Hourly beef NH3 emissions for Kentucky by MMT (kg/hr).

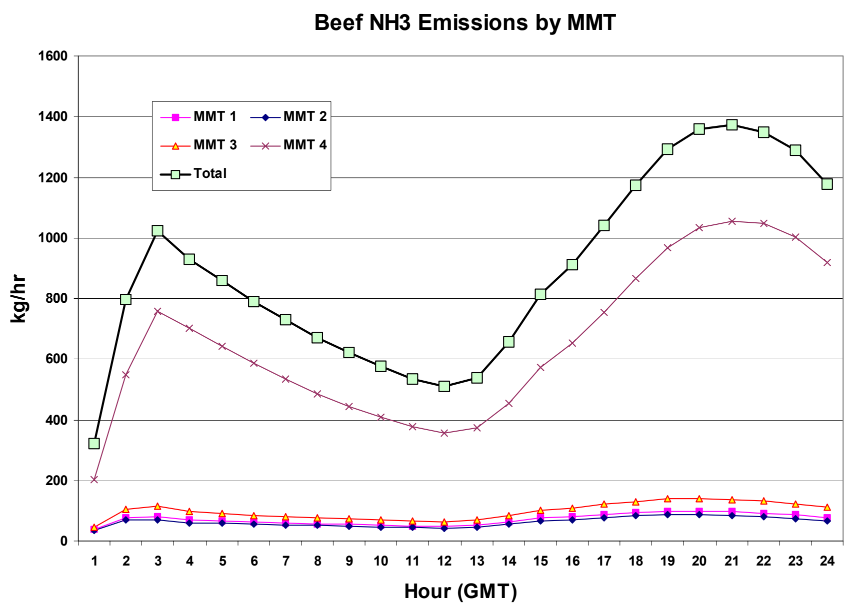
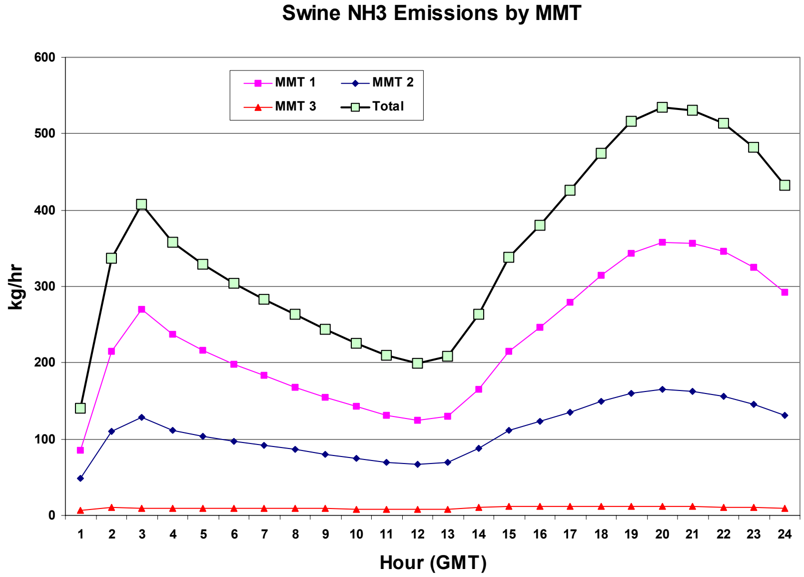


Figure 6. Hourly swine NH3 emissions for Kentucky by MMT (kg/hr).



A comparison of the ammonia emissions obtained using the process-based model developed for this study and those estimated using the WRAP ammonia model are presented in Figure 6 through Figure 9 for beef, dairy and swine, respectively. A primary difference between these two models is that the WRAP model uses a single emission factor to estimate ammonia emission fro each animal species, while the model described in this paper uses a full process-based approach. An evaluation of these results reveal significant differences in overall magnitudes, although the diurnal variations appear to be quite consistent.

Figure 7. Comparison of hourly beef ammonia emissions between LADCO and WRAP models.

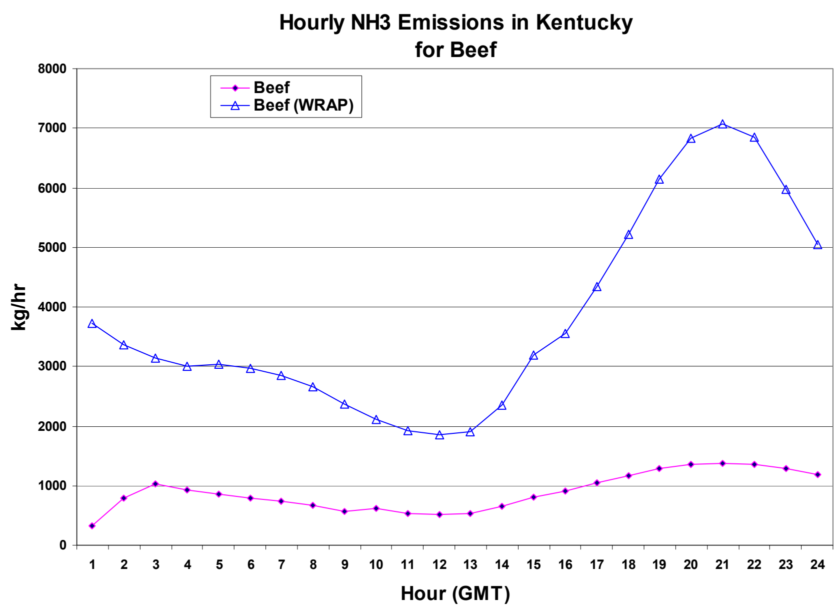


Figure 8. Comparison of hourly dairy ammonia emissions between LADCO and WRAP models.

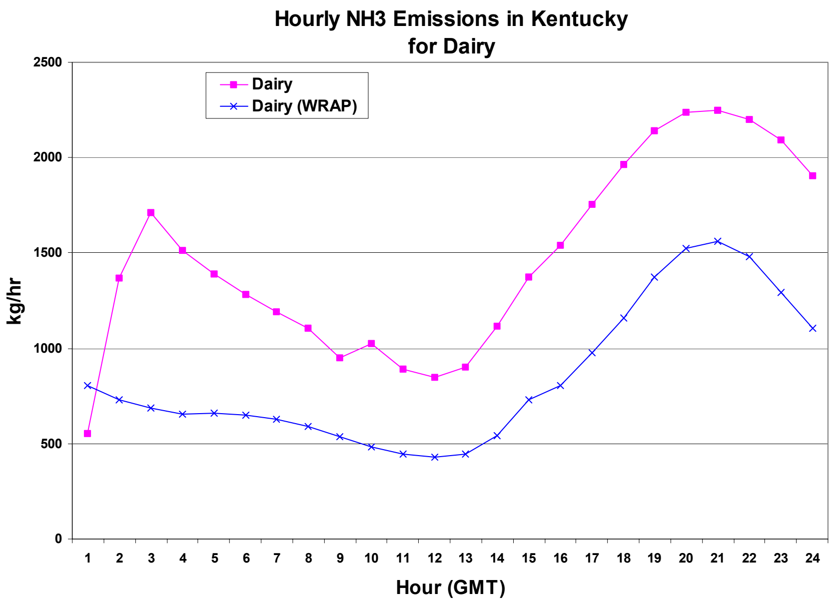
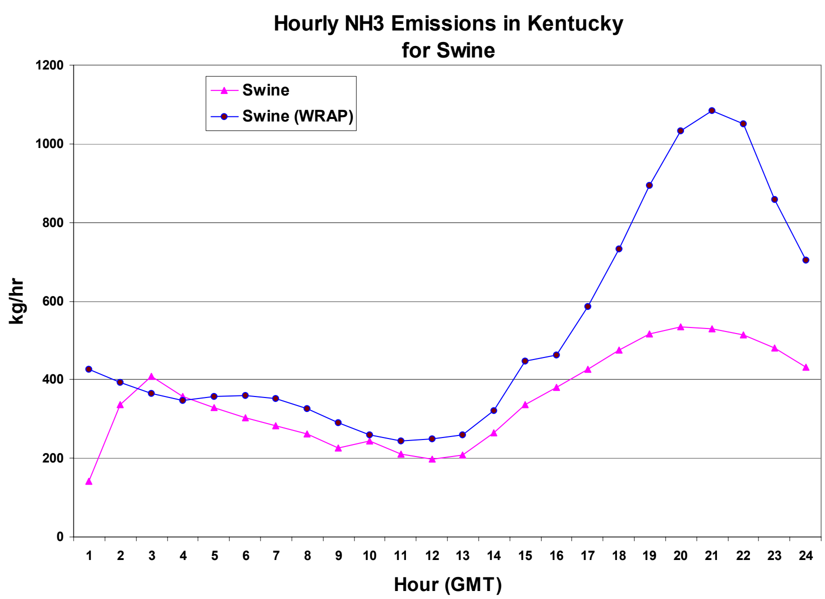


Figure 9. Comparison of hourly swine ammonia emissions between LADCO and WRAP models.



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KEYWORDS

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