

Agricultural Air Quality Modeling



Cumulative Dispersion and Deposition Modeling of Many CAFOs: RTI's Methodology for Ammonia Gas and PM Fine as Applied to the Smithfield Settlement Agreement

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Abstract

As part of the Smithfield Settlement Agreement, RTI developed and performed a modeling approach to predict the influence of ammonia emissions from multiple Concentrated Animal Feeding Operations (CAFOs) on watersheds and human health. RTI applied this modeling approach, using more than 2,000 swine operations in the eastern North Carolina covering five river basins. This paper presents the approach and results from that modeling effort and estimates gaseous ammonia emissions and fine particulate generation under baseline conditions and with simulated reductions. Emission factors were derived from the literature, and a variety of model units (e.g., lagoons) were used to accommodate differing capacities and types of swine operations. A U.S. EPA dispersion model was used to estimate ammonia concentrations and deposition rates from 12 model operations. A geographic information system (GIS) matched each of the 2,000 CAFOs to a model operation and mapped overlapping CAFO deposition zones of up to 50 km in radius each. The total nitrogen loads from swine facilities to the designated study area of five river basins were then calculated. The estimated concentration of ammonium salt fine particulates was estimated to assess the role of swine operations contributions to ambient fine particulate matter in the study area. Estimated impacts from swine operations of both gaseous ammonia and particulate ammonium are reported.

Introduction

The July 2000 agreement between the North Carolina Attorney General's Office and Smithfield Foods, Premium Standard Farms (subsequent), and their North Carolina subsidiaries called for the development of environmentally superior alternatives to lagoon and sprayfield swine waste management. The agreement called for an economic feasibility study of candidate technologies. The study included an evaluation of both the costs to the industry and consumers and the benefits to society of the environmental improvements associated with adopting candidate technologies. The environmental benefits assessment consisted of a multimedia environmental analysis of releases from 2,295 swine operations' housing, lagoon, and sprayfield waste management systems (RTI, 2003; see Figure 1). The release of gaseous ammonia was studied for its transport, deposition, and impact as a gas but also its conversion to ammonium salt fine particulates, transport, and human health impact from inhalation exposure.

To attain the goals of the multimedia environmental analysis, RTI designed an integrated modeling framework, combining North Carolina's swine concentrated animal feeding operation (CAFO) inventory, growth-stage-specific emission factors, and air and surface water quality modeling.

This paper describes the modeling framework developed by RTI to predict the dispersion and deposition of ammonia air emissions from more than 2,000 swine CAFOs in the Smithfield Settlement Agreement (SSA) study area. The methodology uses emission factors derived from peer-reviewed literature; employs a variety of model facilities to accommodate different capacities and types of swine CAFOs; uses an existing, proven dispersion-deposition model; and processes and interprets the outcome spatially using a geographic information system (GIS). The modeling framework is part of RTI's larger *Integrated Benefits Assessment Tool* (RTI, 2003). This tool evaluates the economic, environmental, and human health benefits of alternative CAFO waste management techniques.

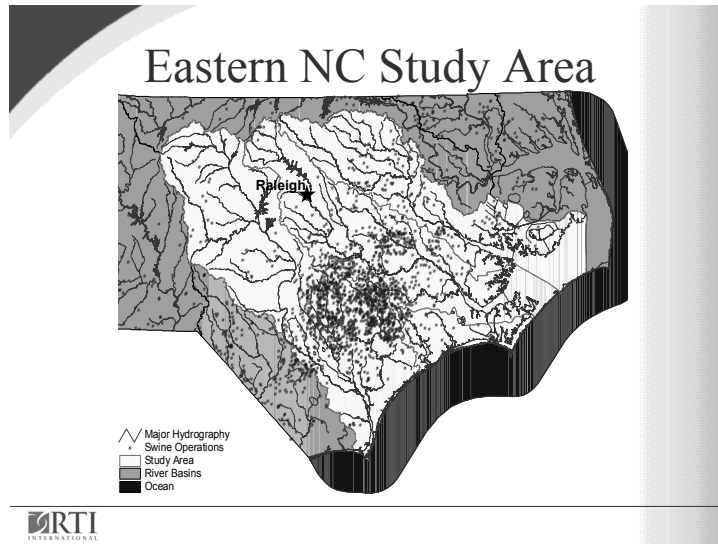


Figure 1. RTI studied the impacts of swine CAFO ammonia emissions on five major North Carolina river basins.

Method

RTI’s approach required a number of data collection, modeling, and processing activities. Figure 2 depicts this multimedia approach as it was designed to estimate the environmental impact on watersheds of air emissions from multiple CAFOs. The following technical approach focuses on the air components.

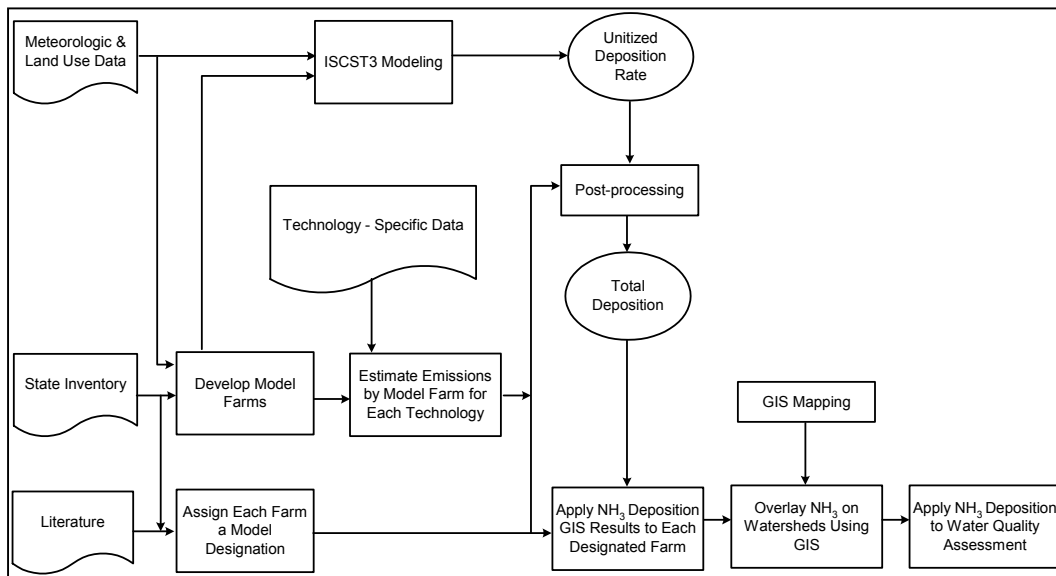


Figure 2. Ammonia atmospheric dispersion and deposition modeling approach

Data Collection and Model CAFO Development

RTI collected data from a variety of resources, including research studies, the literature, and other sources, to model ammonia emissions from swine CAFOs. We began with 2,295 swine CAFOs in five North Carolina river basins (Tar-Pamlico, Neuse, Cape Fear, White Oak, and New River). The State of North Carolina compiled a survey database that profiles these and other swine operations (N.C. DENR, 2002). This database served as the starting point for profiling the 2,295 CAFOs.

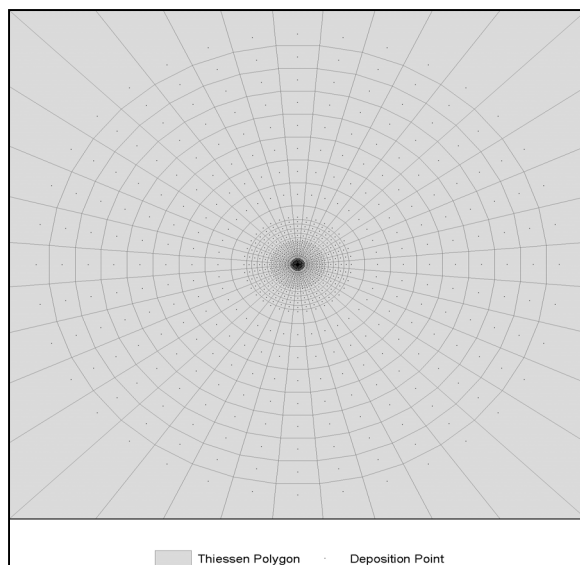


Figure 3. Deposition grid applied to each CAFO to model ammonia dispersion and deposition in a 50 km radius

RTI used each CAFO's geographic coordinates to assign these operations to one of three meteorological regions in the state. Each region possessed its own historical data on parameters such as wind speed, temperature, and land use. North Carolina's CAFO survey database also enabled RTI to assign each CAFO to one of four acreage categories (based on the swine population's steady-state live weight). This combination of three meteorological regions and four acreage categories yielded 12 model CAFOs. RTI next assigned each recorded CAFO in the study area to one of five growth stages (e.g., wean to feed) or span of growth stages (where multiple stages were raised on one CAFO). This assignment, in tandem with the 12 model CAFOs, resulted in each CAFO being characterized as one of 60 operating scenarios. RTI assumed that a model swine facility contains three ammonia-emitting sources: confinement houses with their waste collection systems, waste lagoon(s), and sprayfields. Given the variability in facility dimensions and layout, we chose to treat each model facility as a single-area emission source. The emission factor for the area source was a "composite" of the house, lagoon, and sprayfield emission factors. This composite approach was designed to allow emission factors of each source to be adjusted as source-specific control techniques are examined.

Emission factors were not available for each emission source in combination with each of the five growth stage categories. Therefore, RTI was required to use what emissions research was available from the literature (RTI, 2003) in order to derive emission factors based on steady-state live weight and the distribution of swine per CAFO by growth stage category. However, recent RTI advances to support EPA's development of WATER9 for AFOs could enable better, mass-balanced estimates of emissions. (Refer to "WATER9 – An Air Emission Model for Animal Feeding Operations – Software for Both Field Agents and Comprehensive Scientific Research" (Deerhake, Allen, and Nizich) in these proceedings.)

Unitized Deposition Modeling by Model CAFO

It is understood that gaseous ammonia deposits faster (nearer field) than other ammonia species such as fine particulate ammonium sulfate that may form following ammonia's release to the atmosphere. The dispersion/deposition of ammonia is characterized using a number of runs for model CAFOs where the emission rate is 1 mg per second per square meter (a unitized emission rate) and the chemical composition is 100% ammonia. As Figure 3 shows, this unitized ammonia emission was modeled to predict its dispersion and deposition in a 50 km radius.

RTI used the Industrial Source Complex Short-Term Model, Version 3 (ISCST3), version 02035, to model the dispersion as well as wet and dry deposition of ammonia (U.S. EPA, 1995). This model is an EPA-approved model that predicts atmospheric dispersion and deposition of specific chemical species up to

about 50 km from the source. RTI performed “unitized” dispersion and deposition ISC modeling for the 12 model CAFOs (3 locations’ meteorology x 4 CAFO sizes) which resulted in the dry and wet ammonia deposition estimates presented in Table 1. These loading rates were then applied to appropriate swine operations from the state inventory.

Table 1. ISCST3 Unitized Ammonia Deposition Results for Model CAFOs

12 Model CAFOs		Total Deposition (Mg/yr)	Dry Deposition (Mg/yr)	Wet Deposition (Mg/yr)
NWS Station (represents met. Region)	CAFO Acreage			
Norfolk, VA	500	33,522	33,177	345
Raleigh	500	39,956	39,566	390
Wilmington	500	36,846	36,360	486
Norfolk, VA	260	17,531	17,390	142
Raleigh	260	20,916	20,756	161
Wilmington	260	19,286	19,083	202
Norfolk, VA	100	6,823	6,784	39
Raleigh	100	8,155	8,110	44
Wilmington	100	7,517	7,460	57
Norfolk, VA	50	3,457	3,441	16
Raleigh	50	4,138	4,120	18
Wilmington	50	3,813	3,790	23

NWS = National Weather Service

Post-Processing of Unitized Dispersion and Deposition Modeling Results

Following unitized ammonia dispersion and deposition modeling, a post-processing system was run that portrays each CAFO in the study area as one of 12 model CAFOs with one of five operating scenarios. This approach predicted how much ammonia is emitted, dispersed, and deposited on and around each swine operation (up to 50 km). To develop a site-specific ammonia emission rate, annual average emission factors for each source (e.g., lagoon) were gleaned from the literature (RTI, 2003), accounting for animal type, growth stage, and technology when feasible.

RTI’s modeling framework matched each of the CAFOs (2,295 CAFOs in the North Carolina study) to a model operation’s predicted deposition loading field, in combination with the steady-state live weight reported by each CAFO operator in the North Carolina database. Once each CAFO was mapped, we then mapped overlapping CAFOs’ ammonia deposition zones. Each CAFO’s deposition loading field was predicted by creating Thiessen polygons around each of 1,087 modeled deposition points in the 50 km radius.

Since each CAFO in the study area had geographic coordinates, RTI placed the appropriate deposition pattern on the ground (georeferenced) for each CAFO, creating a coverage of almost 2.5 million points. RTI then overlaid this large point coverage with the hydrologic unit (a.k.a. HUC) boundaries for those 14-digit HUCs in the study area. RTI calculated summary statistics for total, dry, and wet deposition on a HUC-by-HUC basis. As shown in Figure 4, deposited ammonia emissions can play an important role in nitrogen loading to surface waters from individual CAFOs and especially from multiple CAFOs. Note the contrast of modeled deposition receptor points from a single CAFO versus the cumulative effect of a cluster of CAFOs. Figure 4’s first illustration represents the field of deposition for a single HUC from one CAFO. RTI modeling predicts a 3,000-head, southeastern U.S. CAFO can deposit approximately 58% of its estimated annual average ammonia emissions within 50 km. Warmer summer climates can increase emissions and, in turn, increase local deposition loading. Figure 4’s second illustration represents the fields of deposition for multiple CAFOs located across at least eight contiguous HUCs yet whose 50 km radii overlap. Assuming that 58% of the total estimated ammonia emitted from one 3,000-head CAFO deposits within 50 km of its center, the deposition and subsequent stream loading impacts of multiple CAFOs can be significant both within their base HUC and in adjoining HUCs.

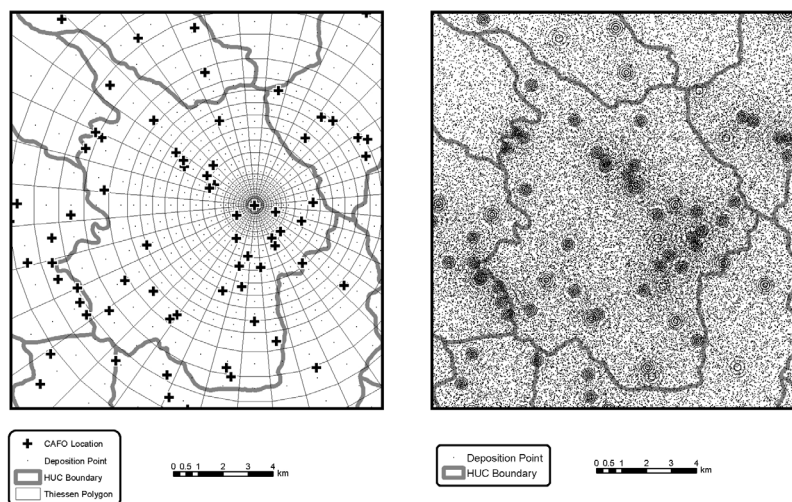


Figure 4. Comparative figures of a generic radial 50 km deposition grid centered on one swine CAFO (left) and the estimated cumulative deposition contribution from all swine CAFOs in the area (right)

GIS mapping of deposition offers a variety of options for study. In addition to hydrologic units, deposition can be mapped by airshed, county or state, climatology, census zone, terrain, industrial zone, natural and cultivated resources, or soil and water conservation districts. Such georeferencing may aid in site selection, evaluation of new waste management technologies, crop planning, and development of site-specific nutrient management plans, for example.

Ammonia-to-Ammonium Conversion

Ammonia reacts with sulfuric, nitric, and hydrochloric acid gases *n* to form aerosols such as ammonium sulfate, ammonium bisulfate, ammonium nitrate, and ammonium chloride. Ammonium salts formed by these reactions can exist as solid particles or liquid droplets, depending on the amount of water vapor in the atmosphere. Ammonia preferentially reacts with sulfuric acid (H_2SO_4) to form ammonium bisulfate (NH_4HSO_4) and ammonium sulfate ($[NH_4]_2SO_4$) through equations 1 and 2:



Ammonia can also undergo an equilibrium reaction with gas-phase nitric acid (HNO_3) in the atmosphere to form ammonium nitrate (NH_4NO_3) as shown in equation 3:



Because sulfuric acid has a low vapor pressure, it seldom exists as a gas when water vapor is available. Nitric acid is much more volatile, so particulate nitrate is believed to be lower in concentration than sulfate (Seinfeld and Pandis, 1998; Pacyna and Benson, 1996). However, particulate nitrate can dominate in PM_{fine} when sulfate is limited.

In Search of Ammonia-to-Ammonium Reaction Rates

The dynamics of ammonium formation are far from understood with the kinetics being too complex to arrive at a conversion factor for the study. Factors such as local meteorology and the availability of sulfates and nitrates in the atmosphere complicate the prediction of ammonium conversion. As a result, RTI turned to the literature to find any monitoring studies of ammonium and ammonia. Robarge et al. (2002) performed a monitoring study in a 5 km radius of multiple swine operations. The measurements were taken at the Clinton Horticultural Crops Research Station located approximately 5 km north and east of Clinton, N.C. Three swine operations are located between 1.5 and 3.2 km east-northeast and east-southeast of the site. Three additional swine operations are located 3.2 to 5 km northwest of the site. Robarge's measurements represent ambient conditions. The fraction of ammonia in total ammonia (NH_x) from Robarge's ambient measurements was greater than 70%. Given the absence of ammonia-to-ammonium conversion factors, RTI decided to apply Robarge's ambient monitoring findings which represented ambient conditions and assume that ammonia gas (NH_3) was 70% of the total ammonia (NH_x) and that ammonium salt (NH_4^+) PM_{fine} was 30% of the total ammonia in this analysis. With this 30% value, we calculated a county annual average ammonium salt (PM_{fine}) concentration by multiplying the county average of ambient ammonia gas by 30%. This exercise estimated only ammonium salt PM_{fine} resulting from swine operation emissions. It did not estimate background ambient PM_{fine} , resulting from other emission sources.

Results and Discussion

Gaseous Ammonia

Results of baseline modeling showed that when accounting for deposition only in the 50 km radius of each CAFO, about 34,000 Mg (over 37,000 short tons) of 2,295 CAFOs' ammonia emissions were deposited in the study area in one year (RTI, 2003). To reiterate, these values represent the sum of each of the 2,295 CAFO's deposition within a 50 km radius of each CAFO, excluding any ammonia that transports and deposits beyond the 50 km radius. As mentioned before, this modeling exercise presumes ammonia remains gaseous throughout its atmospheric dispersion within a 50 km radius. However, a fraction of ammonia may convert to an ammonium salt that is an aerosol (fine particulate). The 37,000 short tons of ammonia estimated by RTI compares well to the State of North Carolina's 1995 estimated statewide emissions (all sources) of 77,700 tons.

Figure 5 depicts the range of deposition by HUC. (There are more than 500 HUCs (or small watersheds) in the study area.) The greatest deposition occurs in counties with the greatest density of swine CAFOs. The 10 HUCs estimated to have the greatest ammonia deposition are all within the Cape Fear River basin. The 10 HUCs total about 5,700 Mg/yr of ammonia deposition, which is about 17% of the study area's total annual ammonia deposition.

The ranking of HUCs is a function of both the animal density and the density and proximity of CAFOs to one another. As Figure 5 demonstrates, when CAFOs are located near one another, the ammonia deposition for each CAFO's 50 km radius can overlap with another CAFO's, thus multiplying the ammonia deposition/loading to HUCs.

RTI's analysis of impacts to water quality from swine operations comprehensively addressed inputs of nitrogen and phosphorus from numerous sources and quantified swine sources independently from other sources. RTI developed methods to estimate watershed inputs for swine facilities both from runoff of nitrogen and phosphorus from land application of waste as well as deposition of ammonia. Additionally, we estimated municipal and industrial wastewater sources and runoff of both nitrogen and phosphorus and deposition of nitrogen from nonswine, nonpoint sources.

To address nitrogen inputs from swine facilities via runoff, we derived land application rates (kg N/yr) for each facility using facility inventory data received from the North Carolina Division of Water Quality and methods developed for the ammonia emissions and deposition assessment. To address atmospheric nitrogen inputs from swine facilities, we compiled output from the ammonia emissions and deposition modeling for each 14-digit watershed. Deposition rates were assumed to be uniformly distributed within each watershed. Direct deposition onto water surfaces for freshwater was calculated based on the watershed's deposition rate and the area in the watershed identified as water based on land cover data.

Indirect deposition was calculated based on an assumption of delivery (pass through) rates for different land cover categories.

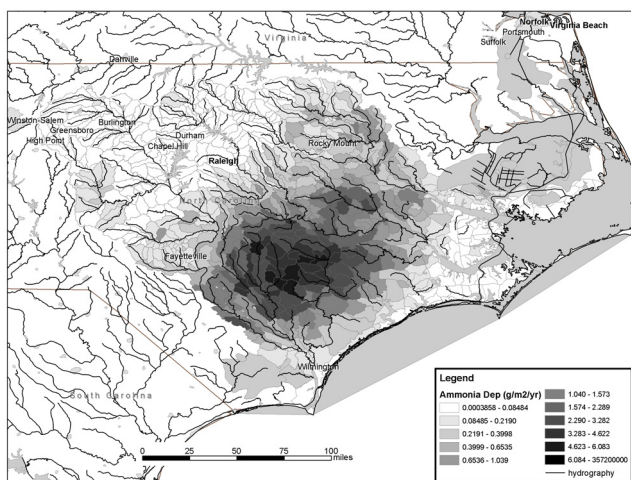


Figure 5. Modeled estimated ammonia deposition by HUC from 2,295 swine CAFOs in Eastern North Carolina

For nonswine atmospheric nitrogen inputs, we developed a method using available wet and dry deposition data from 1996 to 2000 from ambient monitoring sites, along with spatial interpolation. Data were compiled for reduced, oxidized, and organic nitrogen within or near the study area. We calculated total deposition as the sum of wet and dry deposition. We intentionally excluded data from several stations located relatively close to more concentrated swine activity.

Our results indicated that 62 percent of the swine delivery of nitrogen to free-flowing surface waters was estimated to occur via direct runoff, with the remainder through atmospheric deposition of ammonia upstream from estuarine waters. For the entire study area, swine facilities were predicted to contribute 28 percent of the atmospheric nitrogen inputs. Ammonia transported from swine facilities that deposits directly onto estuarine waters is estimated to deposit at rates of 0.01 to 0.04 kg/ha/yr for the different estuaries considered (Pamlico, Neuse, White Oak, and New), accounting for between 0.01 to 0.1 percent of the total estuarine loading. The rate of ammonia direct deposition to estuaries is estimated to be less than 1 percent of the estimated total nitrogen deposition rate accounting for nonswine sources, suggesting that local (indirect) ammonia gas transport and deposition is a more serious concern than ammonia transport directly to estuary waters. However, we cannot draw inferences about ammonium transport from swine facilities to estuaries because we did not attempt to model transport and deposition into the water system of swine waste as ammonium particles.

Ammonium Fine Particulates

RTI's assessment of benefits achieved from reducing CAFO ammonia emissions indicated that PM_{fine} plays a significant role. Table 3 lists the RTI atmospheric modeling exercise's estimated baseline ambient ammonium salt PM_{fine} concentrations attributable to swine operations for each of the counties in the eastern North Carolina study area. These data served as input to RTI's integrated benefits analysis of alternative waste management technologies.

The baseline average (i.e., presuming lagoon and sprayfield waste management) ammonium salt PM_{fine} concentration inside the five-river-basin study area was estimated as $0.592 \mu\text{g}/\text{m}^3$. The county with the maximum estimated annual average ammonium salt PM_{fine} concentration was Duplin County at $3.576 \mu\text{g}/\text{m}^3$. Duplin County's weighted annual arithmetic mean ambient concentration from all sources was $12.6 \mu\text{g}/\text{m}^3$ (N.C. DENR, 2003). (For a point of reference, North Carolina's $PM_{2.5}$ (or PM_{fine}) standard is $15.0 \mu\text{g}/\text{m}^3$ [NCAC 2D.410(a)]).

Table 3. Highlights of Modeled Estimated Average Annual Ambient Ammonium (NH₄⁺) Concentrations (µg/m³) for Selected Counties in the Study Area (descending order)

North Carolina Study Area County	Estimated Average Annual Ambient Ammonium (NH ₄ ⁺) Concentration (µg/m ³)	Number of Swine Operations
Duplin	3.576	514
Sampson	3.115	453
Greene	2.071	105
Wayne	1.915	146
Lenoir	1.551	78
Bladen	1.221	133
Jones	0.915	47
Johnston	0.652	61
Moore	0.081	9
New Hanover	0.051	0
Tyrrell	0.049	5
Wake	0.047	3
Montgomery	0.039	4
Durham	0.004	0
Dare	0.001	0

For ammonium salts PM_{fine}, a traditional EPA benefits estimation model was used to model the benefits of reducing PM_{fine} from swine CAFOs (U.S. EPA, 2003). EPA's model estimates reductions in annual incidence of specific health outcomes associated with reductions in ambient PM_{fine} concentrations.

RTI evaluated scenarios reducing total CAFO-modeled PM_{fine} by 10% and 50%. The largest estimated incidence reductions were for acute conditions, but the total value of these avoided cases was relatively small compared to the value of estimated reductions in premature deaths (on the order of tens to hundreds of millions of dollars). (NOTE: Although EPA's benefits model has been reviewed extensively, the selection and application of concentration reduction functions and valuation methods have uncertainties associated with them, e.g., the value assigned to mortality (\$6-7 million per premature death avoided) (RTI, 2003))

Conclusions

RTI studied the relationship of CAFO ammonia emissions to increased nutrient loadings to surface waters and increased ambient air concentrations of PM_{fine} as part of the Smithfield Settlement Agreement research. The study necessitated a multimedia modeling framework to predict the fate and transport of ammonia. RTI created the framework to enable industry and government decision makers to evaluate the benefits of alternative waste management techniques. RTI applied its multimedia model to more than 2,000 swine CAFOs in eastern North Carolina. This model can be enhanced by applying RTI's recent improvements to the emission model WATER9 for AFOs.

Using dispersion and deposition models for ammonia gas in tandem with GIS and water quality models, RTI estimated the cumulative loadings to more than 500 small watersheds within five major North Carolina river basins. Results of baseline modeling showed about 34,000 Mg (37,000 short tons) of gaseous ammonia from 2,295 swine CAFOs deposited in the SSA study area in one year. This only accounts for deposition within a 50 km radius of each CAFO. These estimates were found to be consistent with state projections and research monitoring studies. Subsequent water quality modeling predicted that the rate of gaseous ammonia's direct deposition to estuaries is estimated to be less than 1 percent of the estimated total nitrogen deposition rate accounting for nonswine sources, suggesting that local (indirect) ammonia gas transport and deposition is a more serious concern than ammonia transport directly to estuary waters. However, we cannot draw inferences about ammonium transport from swine facilities to estuaries because we did not attempt to model transport and deposition into the water system of swine waste as ammonium particles.

RTI did estimate the potential for swine ammonia emissions to convert to ammonium fine particulates. These estimates indicate that a limited number of North Carolina counties with large populations of swine may contribute up to double-figure percentages of total monitored ambient PM_{fine} concentrations. An RTI benefits analysis indicated that substantial benefits (\$3-4 million for each 1 percent of ammonia emissions reduced) can be achieved in terms of human health if ammonia emissions (as a precursor to PM_{fine}) can be reduced.

Efforts to reduce ammonia emissions will subsequently reduce ammonium and PM_{fine} formation, and dramatically increase the value of health benefits of the area. To enhance the understanding of the role of ammonium salts in ambient PM_{fine} concentrations and the role of CAFOs in the health effects from exposure to CAFO-generated PM_{fine} , additional research is needed on ammonium formation kinetics. Equally important is the need for more ambient monitoring studies that can:

- validate ammonium formation theory,
- build a spatial database of ambient observations to determine the role of climate and availability of sulfates, nitrates, and chlorides for salt formation, and
- determine the appropriateness of using ratios of spatially based ambient ammonia to ammonium and generate improved methods of estimation.

It was concluded that implementing waste management technologies to reduce both the CAFO-based ammonia deposition to waters and public exposure to ammonium salt PM_{fine} can result in significant benefits, especially the health benefits of PM_{fine} reduction.

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References

- N.C. Department of Environment and Natural Resources (DENR). 2002. North Carolina Division of Water Quality 1997 Survey of Animal Feeding Operations – Database. Raleigh, NC. Obtained from NC DENR in 2002.
- N.C. Department of Environment and Natural Resources (DENR). 2003. North Carolina's ambient $PM_{2.5}$ monitoring data analysis for the period from July 1999 to December 2001.
- Pacyna, J.M., and S. Benson. 1996. "Gas-to-Particle Conversion of Sulfur and Nitrogen Compounds as Studied at Marine Stations in Northern Europe." *Atmospheric Environment* 30(18):3129-3140.
- Robarge, W.P., Walker, J.T., McCulloch, R.B., and Murray, G. 2002. Atmospheric concentrations of ammonia and ammonium at an agricultural site in the southeast United States. *Atmospheric Environment* 36:1661-1674.
- RTI International. 2003. Benefits of adopting environmentally superior swine waste management technologies in North Carolina: An environmental and economic assessment. Final Report. Prepared for the Animal and Poultry Waste Management Center, North Carolina State University, Designee, Smithfield Foods – Premium Standard Farms Agreement with the North Carolina Attorney General's Office. Research Triangle Park, NC.
- Seinfeld, J.H., and S.N. Pandis. 1998. *Atmospheric Chemistry and Physics from Air Pollution and Climate Change*, New York: John Wiley and Sons, Inc. pp. 523-544.
- U.S. Environmental Protection Agency (EPA). 1995. "User's Guide for the Industrial Source Complex (ISCs) Dispersion Models." EPA-454/B-95-003a. Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina.
- U.S. Environmental Protection Agency (EPA), 2003. National Acid Deposition Program (NADP). <http://nadp.sws.uiuc.edu/> data retrieved in 2003.



Developing Manure-DNDC: Building a Process Based Biogeochemical Tool for Quantifying NH₃, CH₄ and N₂O Emissions from California Dairies

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Abstract

Assessing the environmental impact of manure management is difficult due to high variability in the quality and quantity of animal waste, and in the numerous factors affecting the biogeochemical transformations of manure during storage, treatment and field application. There is an urgent need for scientifically sound, mass balance based, process models for quantifying air emissions from animal feeding operations. Measurement programs are essential, but must be supplemented by process-oriented modeling that incorporates mass balance constraints to extrapolate in both space and time (NRC, 2003). The time is right for moving beyond the inadequate emission factor approach by developing process based models for quantifying air emissions from animal feeding operations.

The dynamics of CH₄, N₂O and NH₃ production/consumption is always controlled by several biochemical and geochemical reactions, namely decomposition, hydrolysis, nitrification, denitrification, ammonium adsorption, chemical equilibriums of ammonium/ammonia, and gas diffusion. These biogeochemical processes are currently simulated in our existing model called DeNitricifation-DeComposition, or DNDC. By tracking C and N dynamics under both aerobic and anaerobic conditions, these processes have been successful in simulating soil C sequestration and trace gas emissions and are well suited for estimating air emissions associated with manure production, storage, treatment and land application.

The current DNDC model has detailed processes for quantifying CH₄, N₂O and NH₃ emissions from agroecosystems with fertilizer/manure application or animal grazing conditions but lacks algorithms for specifying fluxes under drylot, housing and storage conditions. We are now extending DNDC's applications by integrating the fundamental biogeochemical processes with housing and storage management practices. The new developments for our process-based, mass balance approach include (1) integration of detailed biogeochemical processes into the GHG emissions and NH₃ volatilization under drylot, housing or storage conditions; (2) characterization of environmental factors under drylot, housing or storage conditions; and (3) characterization of quantity and quality of dairy waste. This paper provides an overview of our on-going project to develop GIS databases for California dairies, perform a field measurement program and perform model refinements to create a tool for quantifying air emissions from California dairies.

Background

Need for Process-based Biogeochemical Models: Accurate assessment of air emissions from dairies with emission factors is difficult due to: (1) high variability in the quality and quantity of animal waste, and (2) the numerous factors affecting the biogeochemical transformations of manure during collection, storage and field application. Measurement programs are essential but expensive and thus have not been extensively implemented. Therefore, process-based models that incorporate mass balance constraints are needed to extrapolate air emissions in both space and time (NRC, 2003). EPA has not yet developed such a model, relying instead on a simplified methodology for estimating air emissions from individual dairies,

using “model” farms based on typical animal confinement, manure collection, solid separation, manure storage and stabilization, and techniques for land application of manure (EPA 2002).

Although it is well known that constant emission factors are not effective for quantifying GHG, ammonia, and ROG emissions from animal feeding operations (NRC 2003), managers and regulators generally lack access to tools that are both scientifically sound, capture the biogeochemical processes that impact emissions, and are relatively easy to use. There are a number of advantages to developing process-based models of element transformations and emissions from the *combined* components (animal feedlot, manure storage and handling, land application of manure) of animal feeding operations:

- Dynamic, process-based models, developed from laboratory and field studies, **do not rely on constant emission factors**. They assess the impact on emission factors of varying conditions (e.g., climate, storage facility, soils). These models will continue to improve as more field studies are conducted and published, and they do not obviate the need for a strong measurement program.
- By **enforcing a mass balance** in the model (i.e., conservation of mass), the sum of all emission factors are constrained to be $\leq 100\%$ of inputs. This is both good bookkeeping and essential for evaluating trade-offs in mitigation strategies.
- Full system analysis with dynamic, process-based models can inexpensively and efficiently **evaluate mitigation scenarios** under various conditions, and can help target mitigation toward facility component(s) and/or operation(s) that cause the greatest emissions.
- Simultaneously provide estimates of all emission for **comprehensive assessments** of mitigation efforts. For example, *efforts to reduce methane (e.g. enhance aerobic manure management) may result in increased nitrous oxide emissions that could more than offset gains from methane reductions and result in a net increase in total greenhouse gas emissions*. Therefore, **well validated models are critical for comprehensive analyses that capture all emissions to air and water**.

The following is a brief description of our efforts in building GIS databases for characterizing soil, climate conditions, and locations of California dairies, a brief outline of our field measurement plans for obtaining calibration and validation data for our biogeochemical process model, and our Manure-DNDC modeling framework.

GIS Database Development

To run the emission models and create an easy to use emission modeling system, spatially explicit data on dairy locations, soils, climate and general agricultural land use are needed. Access to these GIS data layers will enable users to perform statewide, air district, county and even individual dairy emission simulations. We are building a tool to automatically access, retrieve and process CIMIS (California Irrigation Management Information System) climate station databases (daily min T, max T, precipitation, and solar radiation) into Manure-DNDC model format. Manure-DNDC requires, at a minimum, temperature, precipitation, relative humidity, and wind speed. N deposition data derived from the National Atmospheric Deposition Program (NADP) maps will be built into the system to estimate mean deposition rates at the sub-county scale. Soil characteristics will be obtained from the NRCS STATSGO (1:250,000) and SUSRGO (1:12,000 to 1:63,000) databases. Area weighted ranges on soil pH, bulk density, texture and SOC will be compiled on a dairy and individual field basis using land use boundary derived from aerial photography (see insert in figure 1). These crop and dairy location maps have been obtained from California Department of Water Resources (DWR) land use products. In addition, agricultural census data on livestock counts will be incorporated into the GIS.

For the majority of the counties in California the spatial extents of dairies will be derived from the California DWR GIS database. Dairy cow density was calculated for each county by dividing total dairy cows in each county derived from the NASS database by the total area in dairies as defined by the DWR database. Dairy cows were distributed across the DWR dairy location polygons by multiplying the county dairy cow density by the DWR dairy location polygon areas. A map of dairy cows distributed across the DWR database is given in Figure 1.

A few counties are still missing or only partially covered in the DWR database including Sonoma, San Bernardino and Riverside Counties. All three counties have moderate to large dairy operations. In the case of these counties additional datasets will be used to locate dairies including a dairy facility street address

database provided by the South Coast Air Quality Management District for San Bernardino and Riverside Counties. USGS Digital Line Graph (DLG) files at a scale of 1:100,000 will be employed to address match the dairy locations to available street addresses.

Field Measurement Program

Model calibration and validation is critical and requires high quality field data. Field data, funded by this and other projects will be collected at several operating dairies and the UC Davis Emission Testing Facility:

- CH₄ and NH₃ measurements will be collected using active denuder/filter packs and two tunable diode laser systems.
- An open path FTIR system and canister samples will be used to collect N₂O emissions following land application of manure.
- The UC Davis emission testing facilities will be used to measure CH₄, NH₃, N₂O emissions under a wide range of animal housing and manure treatment/storage facilities using a INNOVA 1412 Photoacoustic Field Gas-Monitor.

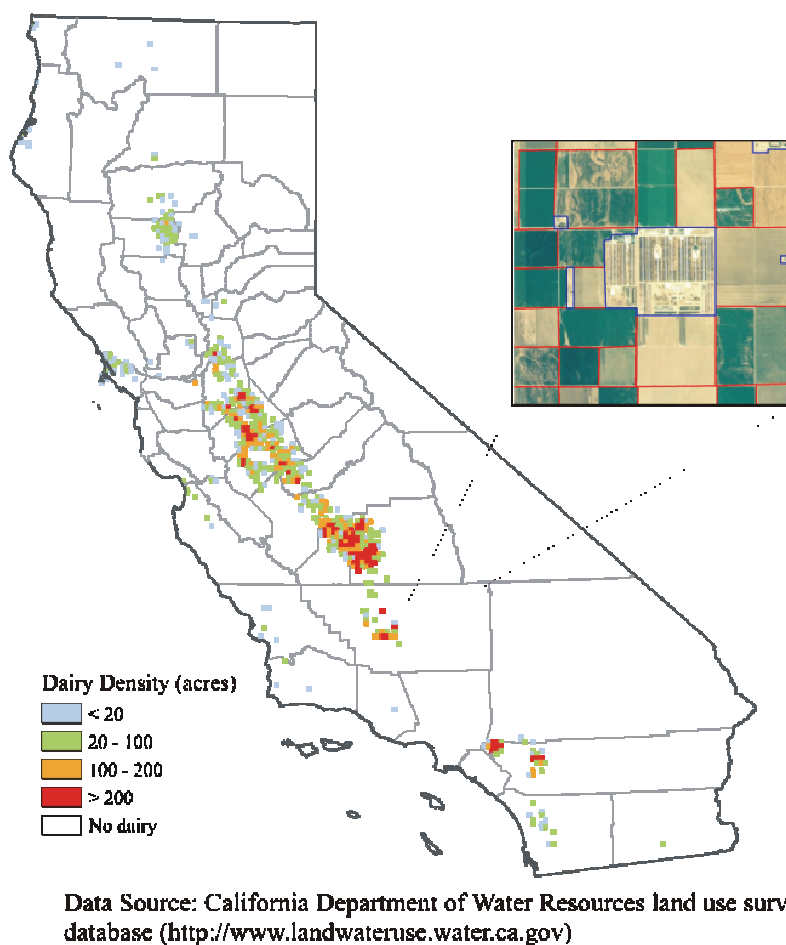


Figure 1. Dairy cow distribution in California

DeNitrification-DeComposition Model (DNDC) Refinement

Over the past decade, multi-agency support from EPA, NASA, USDA and NSF has guided the development, testing, and application of a research biogeochemical model of nitrogen (N) and carbon (C) cycling in soils. The process-oriented computer simulation model, Denitrification-DeComposition (DNDC), was developed based on the biogeochemical concepts for predicting soil biogeochemistry (Li et al. 1992, 1994, 1996; Li 2000). DNDC consists of two components. The first component (see figure 2), consisting of the soil climate, crop growth and decomposition sub-models, predicts soil temperature, moisture, pH, redox potential (Eh) and substrate concentration profiles (e.g. ammonium, nitrate, dissolved organic carbon) based on ecological drivers (e.g., climate, soil, vegetation and anthropogenic activity). The second component, consisting of the nitrification, denitrification and fermentation sub-models, predicts nitric oxide (NO), nitrous oxide (N₂O), methane (CH₄) and ammonia (NH₃) fluxes based on the environmental variables in the soil. Classical laws of physics, chemistry and biology, and empirical equations generated from laboratory observations, were used in the model to parameterize each specific reaction. The entire model forms a bridge between basic ecological drivers including management of agro-ecological systems, and water, carbon, and nitrogen cycles. DNDC utilizes GIS databases with spatially and temporally differentiated information on climate, soil, vegetation and farming practices for local, regional and national scale analyses.

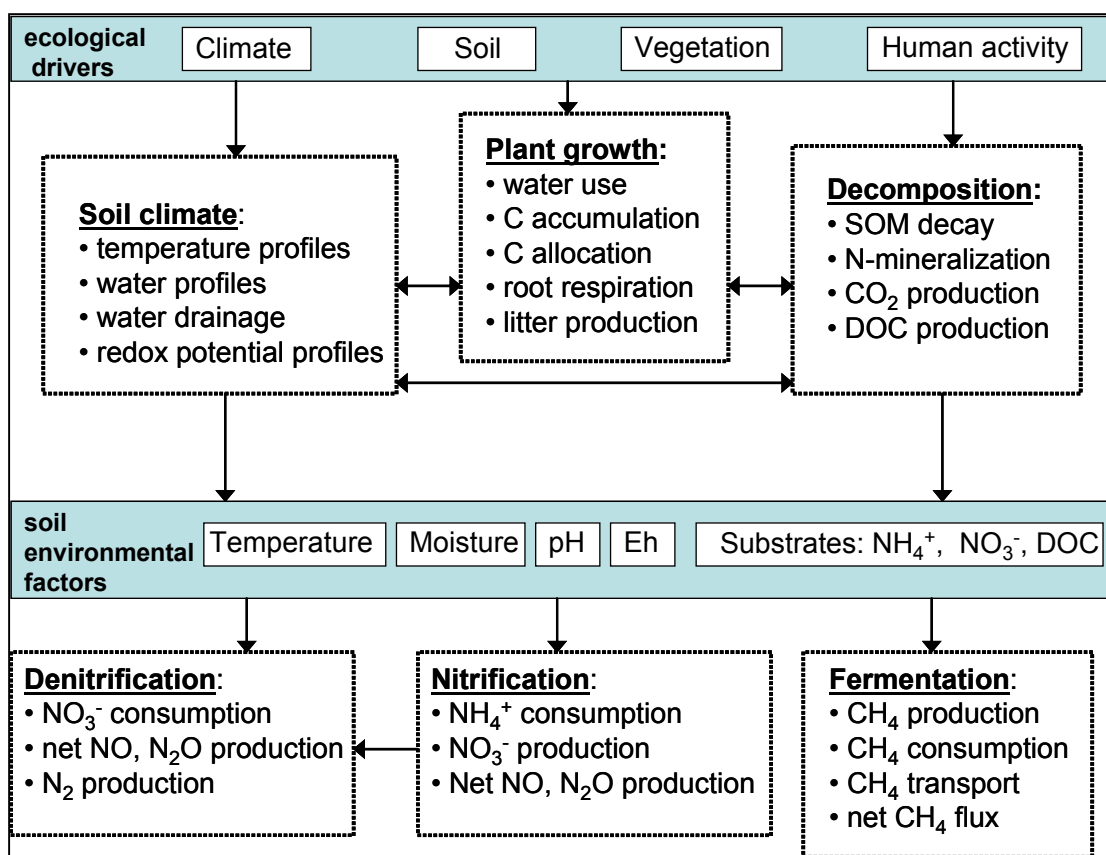


Figure 2. DNDC Model Framework

The core of DNDC is a soil biogeochemical model, which can be linked to vegetation models to predict carbon sequestration and nitrogen cycling for different ecosystems. DNDC has been linked to a crop model (Zhang et al. 2002, Li et al. 2004) to simulate crop growth, soil organic carbon (SOC) dynamics and emissions of dinitrogen (N₂) and several trace gases including N₂O, NO, NH₃ and CH₄ from both upland and wetland agricultural ecosystems. DNDC is a unique process-based biogeochemical model because it

(1) simulates both aerobic and anaerobic conditions, (2) tracks redox potential (Eh), (3) can provide a relatively complete suite of nutrient releases to air and water, including emissions of ammonia, greenhouse gases and nitrate leaching, and (4) contains tools for examining sensitivity and uncertainties in emission estimates. These capabilities are critical for quantifying whole farm emissions from California dairies. This model has been independently tested and validated by many researchers and under a wide range of conditions worldwide and now is utilized for national trace gas inventory studies in the U.S., Canada, the U.K., Germany, Italy, New Zealand, China, India, Japan, Thailand and the Philippines. The extensive validation and applications worldwide indicate that the fundamental processes embedded in DNDC have provided a sound basis for modeling C and N dynamics across a broad range of climatic zones, soil types and management regimes.

Example Modeling Framework for Estimating Ammonia Emissions from Dairies

Ammonia (NH₃) emissions are a common phenomenon in terrestrial ecosystems although the flux magnitudes vary greatly. High NH₃ fluxes have been observed in many agro-ecosystems due to the N cycling enhanced by either livestock husbandry or manure/fertilizer application in farmlands. Animal excretion under confinement or grazing conditions, manure storage, and manure/fertilizer application is a significant source of N into the agroecosystems. For example, the N existing in form of urea in animal urine can be hydrolyzed by urease in the soils at feeding lot, grazed pasture, or storage stand to form ammonium (NH₄⁺). NH₄⁺ can convert to NH₃ through several chemical reactions driven by the equilibriums between NH₄⁺, NH₃ in liquid phase (NH₃(l)) and NH₃ in gas phase (NH₃(g)). This conversion usually takes place in several hours or several days. The N existing in solid organic matter in animal dung will undergo decomposition (or mineralization) first, which is the major process converting the organic N into inorganic NH₄⁺, before the N can join the soil NH₄⁺ pool to continue its transformation to NH₃. This conversion usually takes several weeks or months. Both of the fast and slow paths are important to NH₃ emissions from agricultural sources. The fast path usually constitutes high, episodic NH₃ fluxes following animal excretion, manure amendment or fertilizer application; and the slow path supports the consistent “background” NH₃ emissions at broad scale resulting from decomposition of organic matter from manure or crop residue. However, no matter through which path, the dynamics of NH₃ production is always controlled by several biochemical or geochemical reactions, namely decomposition, hydrolysis, nitrification, denitrification, ammonium adsorption, chemical equilibriums of ammonium, and ammonia gas diffusion. These fundamental reactions exist in DNDC to quantify both the spatial and temporal variability and non-linear nature of NH₃ volatilization from dairies.

The entire process of elemental transformations from fresh animal wastes to inorganic nutrients dispersing in the air, soil or water is controlled by a suite of above-listed reactions. As soon as fresh waste is excreted from animals, it will begin to undergo a series of biochemical and geochemical processes including decomposition, ammonification, nitrification, denitrification, ammonia volatilization, and leaching. Regardless of location (e.g. freestalls, dylots, storage sites, or crop fields), rates of these processes are controlled by environmental factors, including: gravity, radiation, temperature, moisture, pH, redox potential (Eh), and substrate concentration gradients. Quantifying how these environmental factors affect the biogeochemical processes, as well as how the primary drivers (e.g., climate, soil, vegetation and management) affect environmental factors, is our core task for modeling the life cycle of manure at dairies in California. Our modeling approach and framework for estimating NH₃ emissions, as an example, from dairies is presented in Figure 3. This approach and the DNDC general modeling framework shown in Figure 2 and as outlined in Table 1 is currently being implemented to create the Manure-DNDC dairy tool for California.

Workshop on Agricultural Air Quality

	Manure Production	Manure Storage/Processing	Manure Application
Environmental factors	Air temperature Precipitation Wind speed/direction	Air temperature Precipitation Wind speed/direction	Meteorological data Soil properties Vegetation type
Management factors	Manure quantity and quality Freestall, exercise pens, drylots Temperature Ventilation Duration before removal Removal technique (flushing, scrape)	Temperature Moisture Manure texture Additions Duration before land application	Crop type/rotation Tillage depth Manure application rate Manure C&N content Other fertilization Irrigation Weeding Grazing
Model Simulations	Manure temp., moisture, pH, C&N content Decomposition Denitrification NH3 volatilization N2O, NO, N2, CH4 emissions N & C leaching	Manure temp., moisture, pH, C&N content Decomposition Denitrification NH3 volatilization H2S, N2O, NO, N2, CH4 emissions N & C leaching	Manure temp., moisture, pH, C&N content Decomposition Denitrification N uptake by plants NH3 volatilization N2O, NO, N2, CH4 emissions N & C leaching

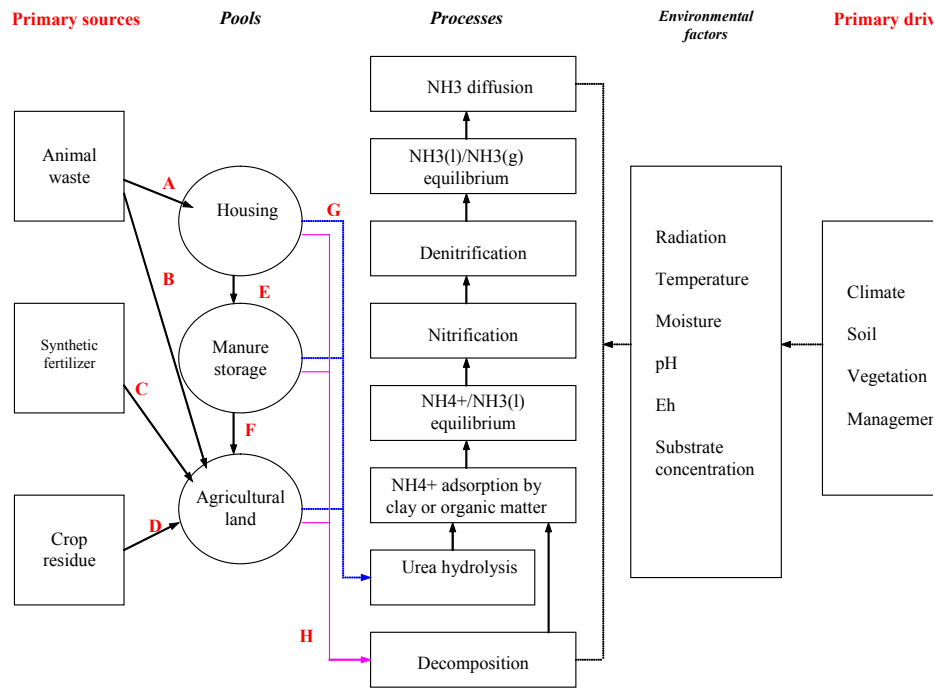


Figure 3. Framework of a process-based ammonia model for agricultural sources. A- Animal housing; B- Grazing; C- Fertilization; D- Crop residue incorporation; E- Manure storage; F- Manure application; G- Dissolved N (e.g., urea etc.) in liquid phase; H- Solid manure or soil organic matter.

Expected Results

From this project we anticipate the following results:

- Field measurements of CH₄, N₂O and NH₃ emissions from 5 operating dairies,
- CH₄, N₂O and NH₃ emissions from controlled facility (UC Davis) with complete mass balance
- Database on manure management practices for California dairies.
- Process-based model for spatially explicit estimates of CH₄, N₂O and NH₃ emissions from manure production, storage, processing and land application phase of manure management. Model will operate at scales ranging from individual dairies to air districts.
- Statewide emission inventory estimate of CH₄, N₂O and NH₃, VOC and H₂S (VOC and H₂S estimates based on best available emission factors).

References

EPA 2002. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000*. EPA 430-R-02-003, Office of Atmospheric Programs, Washington, DC.

Li, C., 2000. Modeling trace gas emissions from agricultural ecosystems, *Nutr. Cycl. in Agroecosys.* 58:259-276.

Li C., Frolking, S., and T.A. Frolking, 1992. A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity, *J. Geophys. Res.* 97:9759-9776.

Li, C., Frolking, S., and R.C. Harriss, 1994. Modeling carbon biogeochemistry in agricultural soils. *Global Biogeochemical Cycles*, 8:237-254.

Li, C., Narayanan, V., and R. Harriss, 1996. Model estimates of nitrous oxide emissions from agricultural lands in the United States, *Global Biogeochemical Cycles*, 10:297-306.

Li et al., 2004, Modeling greenhouse gas emissions from rice-based production systems: Sensitivity and upscaling. *Global Biogeochemical Cycles* 18: GB1043, doi:10.1019/2003GB002045.

NRC (National Research Council), 2003, *Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs*, National Academies Press, Washington, DC.

Salas, W, Froking, S and C. Li, 2002, Air Emissions from Animal Feeding Operations: A Scientific Review and Assessment of CARB Ammonia and Reactive Organic Gas Emission Factors, Applied Geosolutions Report # AGS-61-02-01, 17pp.

Zhang, Y., C. Li, X. Zhou, and B. Moore III, 2002. A simulation model linking crop growth and soil biogeochemistry for sustainable agriculture. *Ecological Modeling* 151:75-108.

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Considerations for Detailed Land Surface/Vegetation Representation in Air Quality Models

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Abstract

We discuss the significance of vegetation (particularly the treatment of canopy resistance and seasonality of vegetation density) and land surface representation on the different aspects of coupled meteorological and environmental modeling with specific focus on air quality models.

An overview of the land – atmosphere coupling and the evolution in representing the land surface/vegetation will be discussed. Using specific example, we will illustrate the implication of the surface representations on meteorological forecasts at various scales. We will then focus on the impact of different methods to represent vegetation in the coupled weather/land-surface model on the dry deposition modeling and the need for considering detailed photosynthesis-based canopy schemes for reducing the uncertainty with deposition estimation.

Recent developments with a dry deposition modeling approach that includes vegetation-atmosphere interactions through photosynthesis/carbon assimilation in a coupled soil-vegetation-atmosphere transfer (SVAT) model, together with various methods to specify the seasonal variation of vegetation density, will be presented. Results from the coupled model studies to estimate observed deposition velocity estimates for ozone over agricultural fields, and the enhancements needed to model the bi-directional exchange for ammonia deposition near an animal agricultural facility will be presented. The presentation will conclude with specific recommendations regarding various land surface/vegetation parameterizations for agricultural air quality models.

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Measuring Gas and Odor Emissions from Swine and Dairy Manure Using a Microtunnel

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Extended Abstract

Preliminary work using a 250-ml Erlenmeyer flask, which air was blown into the flask containing 100 ml of manure to measure gas concentrations gave encouraging results that emission rates can be determined in a laboratory setting. The next steps were to determine the gas capture efficiency of the setup through a mass balance approach and develop an air collection device resembling a field wind tunnel used to collect air samples.

Ammonia Mass Balance

A mass balance approach was used to determine the amount of ammonia captured using a boric acid trap and ammonia distillation. To evaluate the capture efficiency, a known amount of ammonium chloride solution was used instead of manure so that all of the ammonia in the solution could be accounted for.

Problems were encountered in the first trials at 2.0 L/min airflow and 9.0-pH solution. Initially, a lack of airflow failing to capture the ammonia emitted from the solution was thought to be the problem. Increasing the airflow to 4.0 L/min, showed a difference in the amount of ammonia remaining in the solution versus the amount of ammonia emitted, which led to the conclusion that the error was not in the airflow rate. As a result, the airflow rate was returned to 2.0 L/min showing a low ammonia capture efficiency of 17-27% with no repeatability. Increasing the solution pH to 12.0 to emit more ammonia from the solution resulted in a capture efficiency of 29%. The next step was to increase the test length to 240 minutes. This increased the capture efficiency to 70-90%, but repeatability was not achievable. A phosphate buffer was added to the solution to stabilize the pH throughout the testing, but similar poor results were found. A second boric acid trap was added to catch the excess ammonia, if any, but did not increase the capture efficiency. Next, sulfuric acid was used instead of boric acid, and no difference was found between the two solutions (boric vs. sulfuric).

Direct titration of the boric acid solution was compared to indirect titration through the distillation of the sulfuric acid solution. Analysis determined there were some losses due to direct titration, but was not enough to warrant the use of the indirect method. The phenate method of ammonia capture was also compared, but from these tests, repeatability could not be attained. Overall, the methods were not sensitive enough to prove differences from initial to final concentrations in emissions.

Because the laboratory containing the setup increased in room temperature due to outdoor climatic conditions, the entire setup was moved into an air-conditioned lab to better control the temperature. However, the temperature and air movement within the air-conditioned lab were still highly variable. Thus, the entire setup was moved into an incubator with more precise air temperature control and more control over air movement. The capture setup was tried for 18 hours to see if overall emissions and repeatability improved. There was a significant difference in the amount of ammonia found in distillation compared to the amount of ammonia found in the boric acid traps, thus prohibiting the determination of an accurate capture efficiency and test repeatability. After these discouraging results, the gas bubbler technique was abandoned and an alternate method was investigated.

Microtunnel Design and Development

After being discouraged in using the bubblers, a switch was made to use ammonia and hydrogen sulfide analyzers, which are more accurate and can determine instantaneous concentrations. In addition, the tunnel method was tried to better mimic the airflow moving across a manure surface instead of using flasks.

The microtunnel is a square aluminum tube 1.4 cm by 1.4 cm with a 1.0 cm by 1.0 cm square hole cut in the middle of the tube on the bottom. This tunnel was placed on top of an Erlenmeyer flask full of manure.

Air was blown through the tube exhausting into the room. Each analyzer pulled 0.5 L/min of air from a tap on the tunnel. Ammonia and hydrogen sulfide concentrations along with air and manure temperatures were recorded.

The first tests compared an open vs. closed ended tunnel. The open-ended tunnel worked best by allowing higher airflows without pushing manure out the bottom of the tunnel by reducing backpressure within the tube. Differences in emissions throughout the tube were smaller, concluding that there was better mixing of air through the open-ended tunnel.

Next the location of the air tap to ensure complete air mixing was determined. Four taps were drilled into the top of the tunnel and plugged with a rubber stopper when not in use. The tap located 3.9 cm from the end was the most repeatable and did not allow diluted air to enter from the end of the tunnel. In addition, the type of tap was also analyzed comparing a circular holed tap placed in the middle of the tube to a slit tap from the top of the tube to the bottom. Testing showed better repeatability and lower concentrations using the slit due to a better representative sample being taken.

Finally the overall tunnel length was determined. Getting laminar flow at typical airflow rates is nearly impossible, leading to complete air mixing. The tube was lengthened to see the effects on hydrogen sulfide and ammonia concentrations. The longer tube had slightly lower concentrations, but the variability (standard deviation) was lower. Thus, the longer tube was assumed to have better air mixing properties throughout the tube instead of having the odorous air concentrated in the middle of the tube. This setup was used for the rest of the experiments.

Experimental Design and Testing Protocol

Observed data over a 16-hour period from the hydrogen sulfide and ammonia analyzers determined that concentration values stabilized (became constant) during the second 10 minutes of testing. Thus, a ten-minute warm up period was used to allow the analyzers and manure to stabilize followed by a ten-minute period for gas concentration recording. Airflow rates ranged from 2-10 L/min. Each analyzer required an input of a 0.5 L/min, so 2.0 L/min was determined to be the minimum rate. A Teflon bag air collection was added to the end of the 20-minute test for evaluation by an odor panel. Finally, solid phase micro extraction (SPME) fibers were exposed in the tunnel for the final ten minutes of testing. SPME Analysis was performed by Iowa State University.

Preliminary Results

Preliminary testing has shown dairy manure to crust within minutes of placing in the flask impeding emission. Solids removal by filtering prevents crusting from occurring. Manure collection and handling techniques proved important, showing differences in gas concentration depending on how the manure was collected and if the manure samples were fresh, refrigerated, or frozen. Samples were tested 24-48 hour from collection, and never refrigerator nor frozen before testing.

Correlations have been determined between airflow rates and ammonia, hydrogen sulfide, or odor concentrations in preliminary testing. Little or no correlation has been observed with the SPME fibers and airflow rates so far with these results. Additional testing with manure collected from various dairy and swine operations is currently being analyzed. In the future, the results will also be compared with emission modeling papers.



Validation of Odor Dispersion Measurements and Modeling

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Abstract

Nuisance issues related to odor dispersion from livestock and poultry production systems are a factor limiting growth and viability of these industries. The typical state or local regulatory approach to handle odors, assuming one exists, is the sliding scale method based on animal units where separation distance requirements depend upon facility size and manure management practices. However, this method does not address the influence of multiple sources in a community and the effect of receptor location relative to localized weather patterns.

Regulatory agencies, county and state planners need tools that can be easily implemented to help site new production systems or to approve/disapprove the expansion of existing production systems. This research effort is devoted to the evaluation of low-level odor measurement methods development and the subsequent use of field collected odor dispersion data to help develop an odor-based siting model. It is felt that an approach to siting that considers localized meteorological patterns, terrain, existing sources, location of receptors, operation size, and manure management practices would be a substantial improvement to the siting of operations that currently focus only on a distance-only separation requirement. The development of a process-based odor “footprint” siting method was the focus of this research project.

Introduction

Odor and gas dispersion in a community containing livestock and poultry production units is a complicated process that depends on many factors such as production system design, animal density, season, localized weather patterns, terrain, and any other sources in a community. The National Research Council (NRC, 2003) suggested that one of the two major ways to deal with the effects of airborne emissions from animal feeding operations was to replace the current emission factor approach with process-based modeling. While models that describe odor dispersion have been developed using a wide variety of techniques, to date no standardized approach for describing odor dispersion in a community has been developed. A method describing odor dispersion would be very useful for communities to aid in the siting of new production units or the expansion of current production units. This would also be of value to producers of all livestock and poultry commodities to have a method for determining, in advance, the likely improvement in community air quality resulting from implementation of best management practices for air pollution control. There is a great need for model development and validation in order to provide rural communities and the livestock and poultry industries with the tools needed to incorporate science and objectivity into the odor management decision-making process. The objectives of the research project were to:

- 1). Compare and standardize ambient level odor measurement methods from livestock and poultry production systems for evaluation of atmospheric dispersion models (ADM) for odor and
- 2). Incorporate existing odor dispersion modeling techniques into one consistent tool capable of handling multiple sources in a community of multiple receptors, and incorporating localized weather patterns, terrain, production size, and manure management techniques.

Source Emission of Odors

Odor must first be quantified to determine emission rates from a source. The most common and frequently reported measure of odor is detection threshold concentration. Diluting air samples with a known amount of odor-free air and presenting the dilutions to a panel of people using an olfactometer, which is an air dilution device, determines this value. Detection threshold concentration is the volume of odor-free air required to dilute a unit volume of odorous sample air to the point where it can be detected by 50% of a

trained group of panel members (Nören, 1987). Odor units (OU) are defined as the volume of dilution air divided by the volume of odorous sample air at detection and are thus dimensionless. However, the odor concentration of a sample is often expressed as odor units per cubic meter (OU/m^3) for calculating the conveyance of odor emission rates (European Committee for Standardization, 2002). If this convention is followed, then odor emission rates (OU/s) from a livestock building or manure storage unit are the product of the ventilation airflow rate (m^3/s) through the barn or over the storage unit and the odor concentration (OU/m^3) in the exhaust air (Lim *et al.*, 2001). In terms of quantifying source emissions, the use of olfactometers to describe “dilutions-to-threshold” has become the agreed upon standard in both the U.S. and Europe.

Models that describe the dispersion of odors in agricultural communities would help in siting of new animal production systems. However, to validate odor dispersion models one must be able to quantify the downwind, i.e. ambient level, concentration as it relates to odor sensation. One of the major challenges in assessing the odor impact in a community containing animal and poultry production systems is how best to quantify the low-level ambient odors present downwind from an odor source.

Downwind (Ambient) Level Odor Characterization

Before odor dispersion models can be utilized appropriately, not only must source emission rates for odor be quantified, but the ambient odor concentration must be quantified as well. The real difficulty is in quantifying the low-level concentration of odors, resulting from compounds that the human nose can detect in the parts-per-trillion range (O'Neill and Phillips, 1992).

Several methods have been proposed for quantifying ambient-level odor concentration. One method, used by Jacobson *et al.* (2003), uses trained human sniffers to assess ambient-level odor strength downwind from odor sources. This method uses the human nose calibrated to known concentrations of n-butanol, and assigned intensity levels ranging from 0 to 5, with 0 being undetectable to 5 that implies an extremely strong and annoying odor. These intensity scales are further correlated against dynamic dilution olfactometry to assign a detection threshold value from which dispersion modeling results can be compared.

Hoff and Bundy (2003a) employed a technique where a scentometer is used by a trained sniffer to quantify the detection threshold directly by mixing, *in situ*, known parts of filtered fresh air with ambient air downwind from an odor source. The “dilutions-to-threshold” measured from a scentometer are then used directly to assess modeled downwind odor concentrations.

Hartung *et al.* (2003) recognized the extreme lack of downwind odor concentration data for use in calibrating odor dispersion models. They developed a procedure to measure the downwind odor concentration using trained sniffers calibrated to known concentrations of n-butanol, similar to the method used by Jacobson *et al.* (2003). In addition, an SF_6 (sulfur hexafluoride) tracer was used at the odor emission source and SF_6 concentrations were measured simultaneously with odor concentration measurements. Downwind odor concentrations were assigned intensity scales from 1 to 6 corresponding to n-butanol scales which in turn were correlated to odor detection thresholds. The results indicated that well-planned experiments and appropriately trained panelists could produce high quality data sets for calibrating odor dispersion models.

DeFoer and Van Langenhove (2003) introduced a relatively new concept in quantifying downwind odor strength with the use of “sniffing units”. The sniffing unit is intended to quantify the maximum odor perception distance from animal farms. Sniffing units (SU) were defined between 0.5 and 2 SU/m^3 and represent various levels that a human nose would define as a “no-effect” odor level. A factor of two was proposed to translate an SU to a dilutions-to-threshold level. In other words, 2 SU/m^3 corresponds to an olfactometer level of 4 OU/m^3 . They proposed that the no-effect level was equal to 1 SU/m^3 which would correspond to an olfactometer level of about 2 OU/m^3 , which has been proposed by others (Misselbrook *et al.*, 1993) as the “barely detectable” odor threshold level. The main objective was to devise a procedure whereby the no-effect distance separation from an odor source could be determined, and they assigned a level of 1 SU/m^3 as this threshold or boundary.

Dispersion Modeling

Current siting requirements for new livestock and poultry production systems in the U.S. are based mainly on animal units and distance to the nearest neighbor. This strategy has resulted in negative impacts to the animal and poultry industries. Separation distance alone does not account for existing odor sources in a community, the influence of localized meteorological factors on odor transmission, nor the use of improved odor management practices. A better approach would be to provide the animal industry and community planners a procedure or tool for making prudent decisions on where a facility of a given size could be placed in a community with an existing odor load. In this manner, decisions could be made on not only separation distance, but also as it relates to long-term meteorological conditions, size of production facility, odor control measures implemented, and existing odor levels (multiple-odor sources) in a community.

Dispersion modeling has been used to predict the concentration of odors and other animal housing contaminants downwind from production site sources since the early 1980s (Janni, 1982; Carney and Dodd, 1989; Ormerod, 1991; Chen *et al.*, 1998; Jacobson *et al.*, 2003; Hoff and Bundy, 2003a; Koppolu, *et al.*, 2002). The use of dispersion models to assist in the determination of setback distances based on air quality criteria requires knowledge of odor emission data from animal buildings and associated manure storage units, long-term meteorological data, and the tolerance level of neighbors for livestock odors.

Atmospheric dispersion models (ADMs) are mathematical tools that predict the movement of pollutants for air quality management. ADMs are used for regulatory purposes and in policy making. They can also be used to evaluate control technologies. Most models associated with gas dispersion use some form of the Gaussian plume theory (Turner, 1994). Although arguments for and against this modeling framework have persisted over time, this approach provides a reasonable and consistent procedure that could be applied to many different production strategies.

Models describing the dispersion and transport of air pollutants can be classified in various ways. For example, Zannetti (1990) categorized dispersion models as either plume-rise, Gaussian, semi-empirical, Lagrangian or stochastic. The primary components of interest in modeling contaminant dispersion are the total mass of pollutant emitted into the atmosphere, the spatial and temporal distribution of the pollutant, transport and transformation processes in the atmosphere, and deposition processes. Air pollution dispersion phenomena are influenced by atmospheric processes, which are commonly grouped with respect to their spatial scale. Macroscale (> 1000 km), mesoscale (between 1 and 1000 km) and microscale (< 1 km) are the various scales proposed by Orlanski (1975). Topographic considerations are also taken into account when using most modern dispersion models.

Using ADMs for the assessment of odor impacts has some significant challenges. These can be attributed, in part, to differences in odor perception by the human nose (receptor) and by variations at the source of the odor. Odor is characterized by four factors, namely frequency, intensity, duration, offensiveness (FIDO). Odors are a result of complex combinations of compounds. Schiffman *et al.* (2001) reported 310 chemicals as being present in the air around livestock facilities. Such a complex mixture of chemicals can result in unpredictable interactions leading to masking, enhancing, or synergistic effects with respect to the total odor response. Insensitization (odor fatigue) or diminished response of a subject to an odor following prolonged or repeated exposure makes it difficult to determine the likelihood of occurrence of an odor nuisance. A summary of some of the odor dispersion modeling approaches follows:

STINK: Smith (1993) developed a program called STINK as a research tool with which to estimate near source concentrations from a ground level area source of width X and finite length Y.

OFFSET: The University of Minnesota has released a tool for siting livestock facilities. The Odor From Feedlots Setback Estimation Tool (OFFSET; Jacobson *et al.*, 2003) was developed based upon odor concentration predictions from a dispersion model called INPUFF-2. The OFFSET tool, a paper-based product (Figure 1) useable by producers or county planning officers, has been implemented in several Minnesota counties for advising county planning processes.

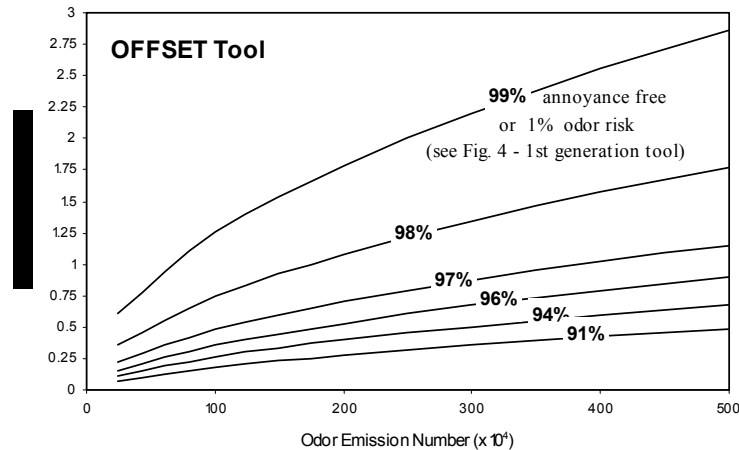


Figure 1. The OFFSET tool, which is referred to as the 1st generation tool

INPUFF-2, a USEPA model (Petersen and Lavdas, 1986) (Bee-Line Software Co., Asheville, NC), which is a Gaussian puff model, is one approach used to simulate the dispersion of odors from animal production sites. Puff models are well suited to predict agricultural odors because odor moves as a series of puffs rather than flowing as a continuous stream (McPhail, 1991). Gassman (1992) suggested that puff models represent real odor perception since the cycling of the odor actually increases odor perception to an observer so that threshold and peak concentrations will greatly exceed average concentrations for a short time period. The inputs to the model include locations of odor sources and receptors, odor source emission information (emission rate, source height, source area, emission temperature and velocity, etc.), and weather information (Pasquill-Gifford stability class, temperature, wind direction, wind speed, mixing height, etc.).

CAM: Iowa State University researchers have developed a Community Assessment Model (CAM) for predicting odor dispersion in a community of multiple odor sources and multiple receptors (Hoff and Bundy, 2003a). This model was based on Gaussian plume theory adjusted for predicting the volumetric flow rate of the downwind plume (m³/s) resulting in the maximum ground-level odor concentration. For predicting downwind odor strength, a knowledge of the source emission rate of odors (OU/s), and the volumetric flow rate of the plume at any given downwind distance (m³/s) yields an estimate of downwind odor strength (OU/m³). The power of CAM is not in the complexity of the model, rather that multiple sources and multiple receptors in a community can be evaluated on a month-by-month basis to assess the annual odor load of each receptor from each source.

AERMOD: AERMOD is a near-field steady-state plume model. AERMOD is EPA's newly developed regulatory model, which incorporates planetary boundary layer concepts. AERMOD (Cimorelli *et al.*, 1998) is based on the convention that the plume is split into an updraft and a downdraft, which are associated with a vertical upward or downward velocity, respectively. The source contributions at any receptor are considered to consist of a direct source, an indirect source and a penetrated source. Terrain in AERMOD is accounted for by using the concept of a horizontal plume state and a terrain responding state. Factors determined from micrometeorological similarity theory and measured data are used to estimate the vertical profiles of wind speed, lateral and vertical turbulence fluctuations, potential temperature gradient, potential temperature, and the horizontal Lagrangian time scale. These are then used to compute the concentration at a receptor. A University of Nebraska research team has been working with AERMOD to address odor and gas emission issues associated with Nebraska livestock facilities. The team has had success with AERMOD for defining downwind concentrations of selected volatile fatty acids (Koppolu, *et al.*, 2002) and odor levels.

Model Validation

Most odor modeling research within communities has been strictly theoretical with little field verification of a model's predictions. The exception to this is the effort by the University of Minnesota to validate INPUFF-2 predictions. This effort included both short-range and long-range verification (Zhu *et al.*, 2000 and Guo *et al.*, 2001).

The short-range verification effort involved a panel of seven odor sniffers who recorded odor observations at 100-meter intervals between 100 and 400 meters directly downwind of the odor source. These individuals were trained to recognize odor intensity on a scale of 0 to 5 (based upon an n-butanol standard) and record those intensities downwind of 28 livestock facilities (Wood *et al.*, 2001). The team also developed an empirical relationship between odor intensity and an olfactometry-based measure of odor units. The odor sniffer data was compared against INPUFF-2 predictions of odor units. A scaling factor was applied to the odor source to adjust the model output to fit the empirical observations.

The long-range verification effort in Minnesota (Guo *et al.*, 2001) involved residents within a rural community recording odor observations over a five-month period. A community consisting of an area of 4.8 x 4.8 km was identified with 19 non-livestock residents and 20 livestock operations to complete this evaluation. Rural residents were asked to record odor intensity, timing, and duration of observations on a scale similar to that used in the short-range verification effort. Simultaneously, the INPUFF-2 model was used to predict the timing, duration, and intensity of odor for each rural resident's sensing event. Observations and predictions were compared. The INPUFF-2 model accurately predicted the low intensity observations but was less accurate in predicting high intensity observations. Since identification of recommended setback distances by OFFSET was based upon a low intensity odor threshold, it was concluded that the INPUFF-2 model and the resulting OFFSET tool provided satisfactory predictions.

Dispersion Modeling and Spatial Planning

The ultimate goal of odor dispersion modeling for this project was to develop a tool that could be used to accurately assess community odor loads for new and expanding livestock and poultry production systems. As an example, OFFSET represents a conservative non-directionally dependent siting tool for limiting the percentage of exposure time to annoying odors. This tool can be considered a 1st generation model as shown in Figure 2. An improvement on this procedure would be to include regional meteorological data to develop a directionally sensitive siting tool. This procedure could be considered a 2nd generation siting tool (Figure 2). A further refinement would be to further incorporate localized meteorological data, topography and facility specific information for site-specific planning. This procedure could be considered a 3rd generation tool (Figure 2).

In all, the goal would be to develop a procedure that could be used in any localized area that has associated with it historical weather data to develop an odor "footprint" based on an accepted odor load. Further, this footprint could be modified to incorporate the influences of multiple sources in a community, much like the efforts developed in CAM. The ultimate goal would be to prepare a user-friendly interface with a state of the art and appropriate model, to accomplish this task. This would allow producers or planning officials to model site-specific conditions for a proposed facility (including topography) and define the risk-based odor exposure footprint for an individual facility (Foot Print tool – 3rd generation, Figure 2).

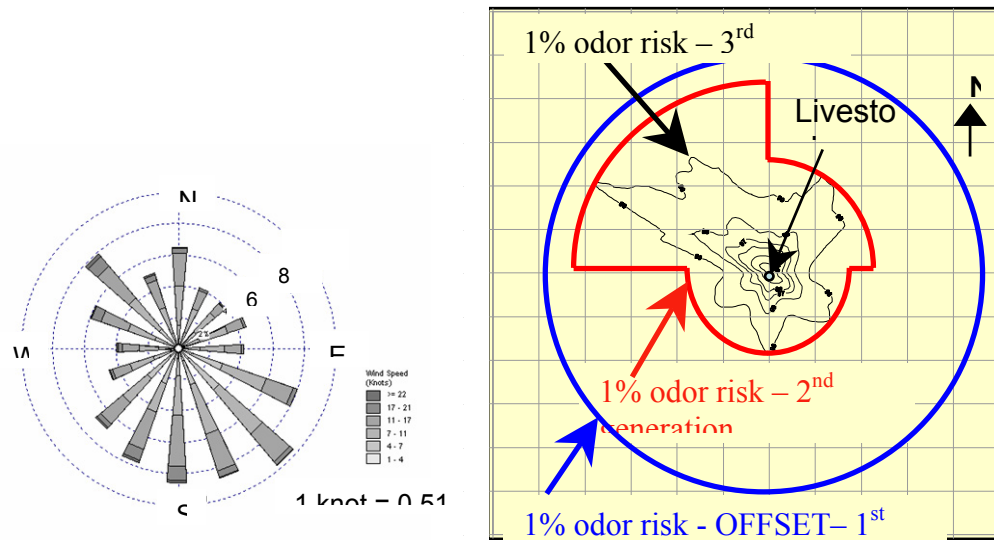


Figure 2. Predicted odor risk based on 3 generations of Footprint Tools for a livestock facility (St. Paul, MN weather conditions as indicated with accompanying wind rose).

Methods

Comparison of Ambient Level Odor Measurement Methods

Many of the techniques used to assess ambient level odor concentration were identified and discussed previously. It is felt that the methods cited have merits in their own right, but to accurately assess an odor dispersion model a standardized and consistent approach that truly reflects the sensation of odors at a receptor is required. The overall success of any odor dispersion model depends on the successful quantification of odor strength and odor perception in the community.

Two methods were used to assess proposed techniques for assessing low-level odor measurements typical of ambient downwind conditions. The first method was to use a controlled atmospheric chamber (Air Dispersion Laboratory [ADL], Iowa State University) to generate an odor from the headspace of pig slurry and distribute this odorous air to a series of panelists using three odor measurement techniques, namely, 1). direct olfactometry from sampled air, 2). olfactometry *via* n-butanol defined levels of intensity evaluated by trained human sniffers, and, 3). Nasal Ranger scentometry (St. Croix Sensory, Inc) using trained human users. Pig slurry was mixed in various dilutions, stirred, and ventilation air entering the ADL entrained this odor providing a uniform exposure of odor to the various measurement methods. This pre-test of the proposed odor measurement methods was used to provide a base-line assessment of the correlations between measurement methods. The second method used was to conduct actual field measurements from a well-instrumented source. For this method, a series of source emission and simultaneous downwind odor concentration measurements from an instrumented deep-pit swine finishing facility in central Iowa was conducted. Measurements of ambient odor concentration were made based upon the three methods mentioned previously. Simultaneously, on-site meteorological data (MET) was collected to accurately define the atmospheric stability, a requirement crucial for accurate dispersion modeling. Figure 3 outlines the odor emission site for the field measurement experiments conducted.

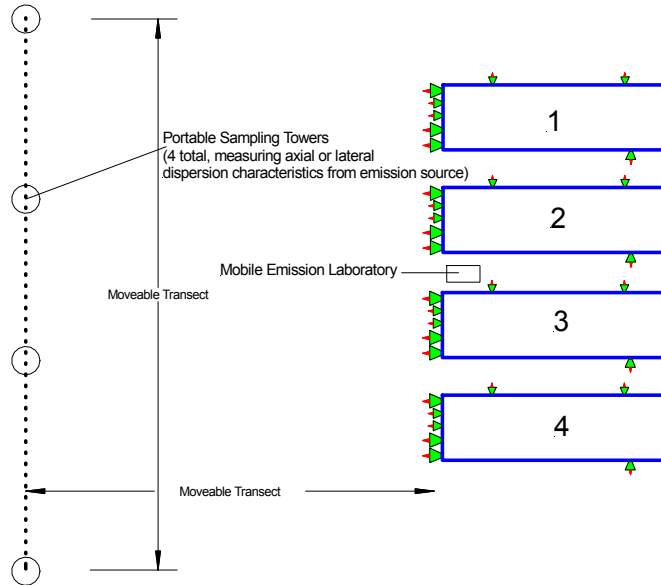


Figure 3. Top view of emission site currently instrumented and available for simultaneous emission and downwind odor measurements

Each barn of the emission site (Figure 3) is 13.7 m wide x 61.0 m long, with 19.8 m separation between buildings. Each barn houses 960 finishing pigs with a deep-pit manure handling arrangement. A mobile emission laboratory (Figures 3, 4) was used to collect emission data continuously at 10-minute increments from barns 2 and 3.



Figure 4. Mobile emission laboratory at the central Iowa emission site

The central Iowa emission site shown in Figures 3 and 4 is surrounded by fields, in a flat agricultural terrain, with a spacing of 400 m to the east and 800 m to the north and very few odor sources within 3,500 m of this site. In Iowa, predominant winds during summer are from the south to south-south-east, thus the 800 m of available space to the north is well suited for odor dispersion work. In addition, significant fall and spring weather patterns originate from the west quadrants, making the 400 m separation to the east ideal as well.

In-Field Source Emission and Ambient (Downwind) Measurements

Simultaneous source emission and downwind odor concentration data was collected in three intensive sessions between June 2004 and November 2004 where twelve distinct atmospheric events were monitored encompassing several distinct atmospheric stability classes. Each measurement event consisted of the

arrangement of four grid points downwind from the emission site, arranged in sequential downwind distances. At each sampling grid point, two panelists using intensity-based measurements, two panelists using a Nasal Ranger scentometer, and two 10-L Tedlar bag samples for subsequent dynamic dilution olfactometry evaluation were collected. In addition, exhaust air samples from the barns were collected in 10-L Tedlar bags for assessing source strength. Each measurement session consisted of a 10-minute sampling interval, and this measurement session was repeated within 15-minutes resulting in two measurement sessions per downwind event. The Tedlar samples were transported and analyzed for odor strength within 24 hours using a venturi-type dynamic dilution olfactometer (AC'SCENT[®] International Olfactometer, St. Croix Sensory, Inc., Stillwater, MN) at either the Iowa State University or University of Minnesota Olfactometry Laboratories. Odor detection threshold, defined as the concentration that the panelist first detects a difference in the air sample compared to two clean samples, was measured in accordance with ASTM Standard E679-91 using trained panelists.

All field odor sampling events were coordinated in time with data acquisition from two on-site MET stations. One permanent 10-m high MET station fixed at the emission source and a second mobile MET station were used to assess atmospheric stability. The mobile MET station was used to measure parameters needed to evaluate atmospheric stability and to calculate on-site dispersion coefficients. These include total wind speed (3 components) at 10Hz for eddy covariance calculations, relative humidity (RH) and temperature (T) at two heights, total insolation, and net radiation for energy balance calculations.

Results and Discussion

Controlled Chamber Odor Measurement Results

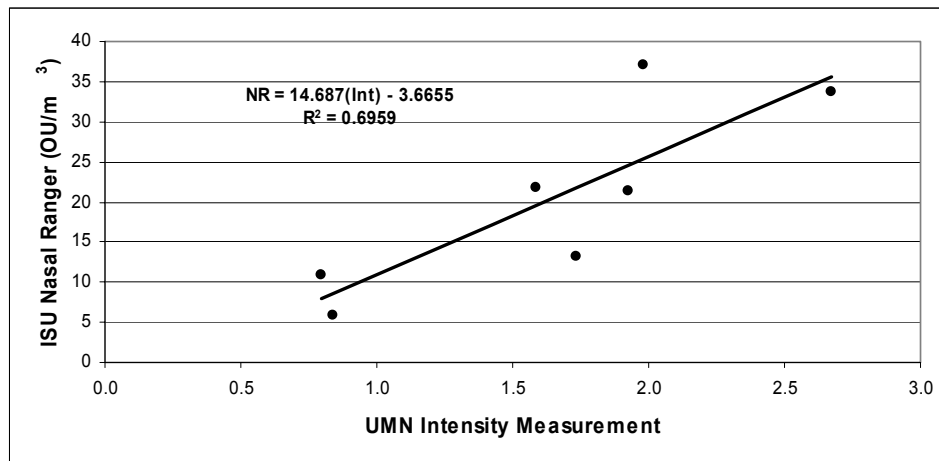
A summary of the comparison between odor measurement methods using the generated odors in the Iowa State University ADL is given in Figure 5. The results shown in Figure 5B indicate the correlation measured between the Nasal Ranger scentometer and the intensity method used by the University of Minnesota. In general, for the limited data set shown the relationship was consistent between methods. For example, if the Nasal Ranger measurement recorded a 25 OU/m³, this would correspond to an intensity measurement of 2.0.

In-Field Odor Measurement Results and Downwind Dispersion

A summary of the comparison between in-field odor measurement results from the emission site shown in Figure 3 is given in Figure 6. As shown in Figure 6B considerable variability was found between the Nasal Ranger and intensity-based odor measurement methods. On average, the in-field Nasal Ranger measurement of 25 OU/m³ corresponded to an intensity-based measurement of about 3.0, much different than the controlled chamber intensity-based measurement of 2.0 for a Nasal Ranger measurement of 25 OU/m³.



A

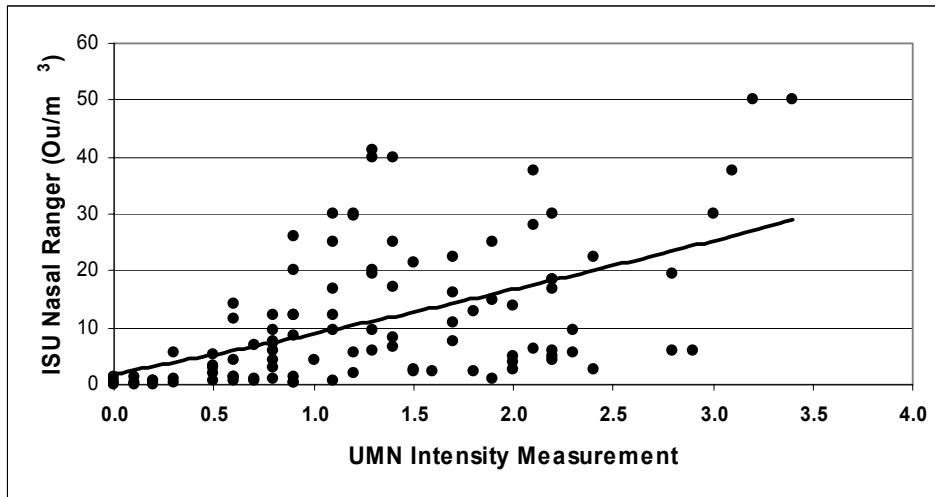


B

Figure 5. (A) Panelists positioned in the ADL measuring generated odors using and (B) the correlation between the Nasal Ranger and the intensity-based measurements



A

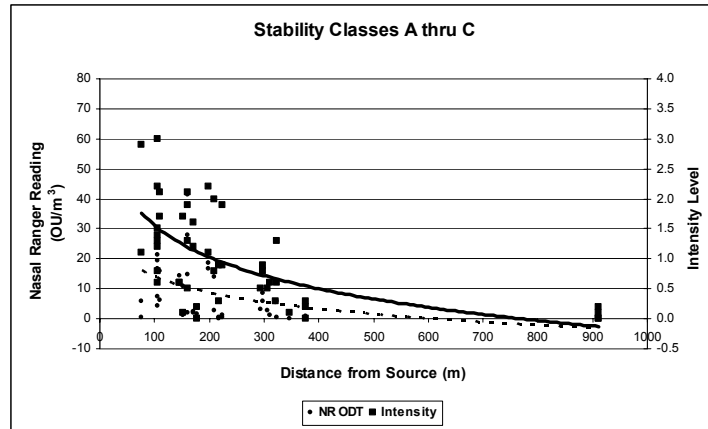


B

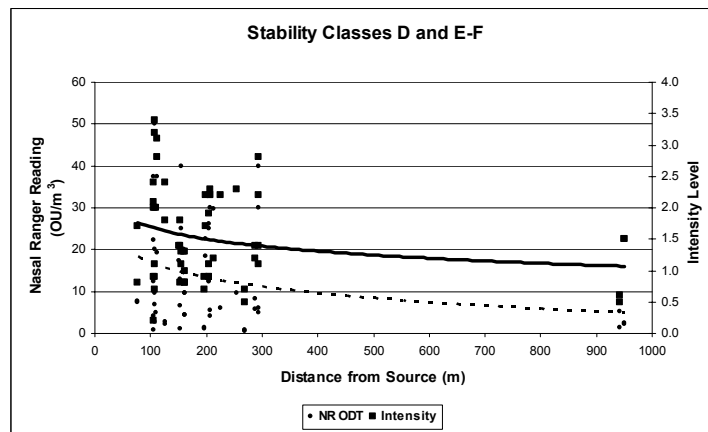
Figure 6. (A) Panelists positioned at one of four downwind grid points at the emission site shown in Figure 3 and (B) the correlation between the in-field Nasal Ranger and the intensity-based measurements

In-Field Odor Dispersion Results for Modeling Calibrations

Twelve distinct odor measurement events were measured using the emission site shown in Figure 3. Figure 7 shows the results obtained from these measurement events. The odor dispersion curves presented give both the Nasal Ranger and intensity-based measurements recorded for two distinct atmospheric stability conditions. Figure 7A summarizes data collected for relatively unstable atmospheres (Classes A to C) and Figure 7B summarizes the results for relatively stable atmospheres (Classes D to F). Significant variation at any downwind measurement was recorded, although decay curves are evident and were measured with both the Nasal Ranger and intensity-based methods. The distinction between odor dispersion with distance and atmospheric stability is clearly evident.



A



B

Figure 7. In-field downwind odor measurements for all measurement events classified as (A) Stability Classes A, B, or C, and (B) Stability Classes D, E, and F

Conclusions

An on-going research project designed to develop a livestock and poultry siting tool based on odor dispersion is being developed. This paper discussed measurements conducted designed to assess the various low-level odor measurement techniques being used today in both a controlled laboratory setting and using in-filed measurements at various atmospheric stability conditions. These results are currently being evaluated for use in the calibration of a comprehensive odor dispersion model designed to assess livestock and poultry siting decisions, taking into account terrain, local historical weather patterns, operation size, existing sources, and the location of receptors relative to the sources.

The field data collected to date shows a fairly good agreement between low-level odor measurements using the Nasal Ranger scentometer and the intensity measurement method using n-butanol as the calibration gas. Downwind odor measurements based on stability class followed traditional dispersion decay trends with atmospheric stability although a great deal of variability, as expected, was measured. Odor dispersion models that account for stable atmospheres is a necessity in order to capture the longer-range odor concentrations expected during these periods. The authors would like to thank the USDA-NRI research program for funding this on-going research project.

References

- Carney, P.G. and V.A. Dodd. 1989. A comparison between predicted and measured values for the dispersion of malodours from slurry. *J. Agric. Eng. Res.* 44: 67-76.
- Chen, Y.C., D.S. Bundy and S. Hoff. 1998. Development of a model of dispersion parameters for odour transmission from agricultural sources. *J. Agric. Eng Res.* 69: 229-238.
- Cimorelli, A. J., S.G. Perry, A. Venkatram, J.C. Weil, R.J. Paine, R.B. Wilson, R. F. Lee, and W.D. Peters. 1998. AERMOD: Description of Model Formulation. Draft Document. Computer File.
- Defoer, N. and H. Van Langenhove. 2003. Determination of odour emissions from pig farms for regulatory purposes in Flanders. In: *Proceedings of the International Symposium on Gaseous and Odour Emissions from Animal Production Facilities*. Horsens, Denmark. June 1-4, 2003. pp 152-160.
- European Committee for Standardization. 2002. Air quality - Determination of odour concentration by dynamic olfactometry. EN 13725. European Committee for Standardization, Brussels.
- Gassman, P. W. 1992. Simulation of odor transport: a review. ASAE Paper No. 92-4517. St. Joseph, MI: ASAE.
- Guo, H., L.D. Jacobson, D.R. Schmidt, R.E. Nicolai. 2001. Calibrating INPUFF-2 Model by Resident-Receptors for Long-Distance Odor Dispersion from Animal Feedlots. *Applied Engineering in Agriculture (ASAE)*. Vol. 17(6): 859-868.
- Hartung, E., G. Brose, W. Bachlin, and T. Jungbluth. 2003. Development and provision of a well-documented data set to validate odour distribution models. In: *Proceedings of the International Symposium on Gaseous and Odour Emissions from Animal Production Facilities*. Horsens, Denmark. June 1-4, 2003. pp 302-309.
- Hoff, S.J. and D.S. Bundy. 2003a. Modeling odor dispersion from multiple sources to multiple receptors. In: *Proceedings of the International Symposium on Gaseous and Odour Emissions from Animal Production Facilities*. Horsens, Denmark. June 1-4, 2003. pp 331-339.
- Jacobson, L.D., H. Guo, D. Schmidt and R.E. Nicolai. 2000. Calibrating INPUFF-2 Model by Resident Panelists for Long-Distance Odor Dispersion from Animal Feedlots. In: *Proceedings of the Second International Conference on Air Pollution From Agricultural Operations*. Des Moines, Iowa, October 9-11. pp. 278-286.
- Jacobson, L.D., H. Guo, D.R. Schmidt, R.E. Nicolai, and J. Zhu. 2003. Development of OFFSET (Odor from Feedlots-Setback Estimation Tool) for determination of odor annoyance free setback distance from animal production sites. In: *Proceedings of the International Symposium on Gaseous and Odour Emissions from Animal Production Facilities*. Horsens, Denmark. June 1-4, 2003. pp 320-330.
- Janni, K.A. 1982. Modeling dispersion of odorous gases from agricultural sources. *Trans. of the ASAE* 25: 1721-1723.
- Koppolu, L., D.D. Schulte, S. Lin, M.J. Rinkol, D.P. Billesbach and S.B. Verma. 2002. Comparison of AERMOD and STINK for dispersion modeling of odorous compounds. ASAE Paper No. 02-4015. St. Joseph, MI: ASAE.
- Lim, T.T., A.J. Heber, J.Q. Ni, A.L. Sutton, and D.T. Kelly. 2001. Characteristics and emissions rates of odor from swine nursery buildings. *Transactions of ASAE* 44(5):1275-1282.
- Lin, S. 2002. Modeling and Evaluating the Atmospheric Dispersion of Odors from Agricultural Sources. M.S. Thesis. University of Nebraska. Lincoln, NE.
- McPhail, S. 1991. Modeling the dispersion of agricultural odours. *Proceedings of a workshop on agricultural odours*. Toowoomba, Queensland, Australia. Feedlot Services Group, Queensland Department of Primary Industries, AMLRDC Report No. DAQ 64/7.
- McMullen, R.W. 1975. The Change of Concentration Standard Deviations with Distance. *JAPCA*, October 1975.

Workshop on Agricultural Air Quality

- Misselbrook, T.H., C.R. Clarkson, B.F. Pain. 1993. Relationship between concentration and intensity of odours for pig slurry and broiler houses. *J. Agric Engng Res*, 55: 163-169.
- NRC. 2003. The scientific basis for estimating emissions from animal feeding operations. National Research Council. Washington, D.C.
- Norèn, O. 1987. Odours from animal production. In *Animal Production and Environmental Health*, ed. D. Strauch, 1-20. New York: Elsevier Science Publishers.
- O'Neill, D.H. and V.R. Phillips. 1992. A review of the control of odour nuisance from livestock buildings: Part 3, properties of the odorous substances which have been identified in livestock wastes or in the air around them. *J. Agric. Engng. Res.* (53):23-50.
- Orlanski, J. 1975. A Rational Subdivision of Scales for Atmospheric Processes. *Bulletin of Americal Meteorological Society*. 56: 527-530.
- Ormerod, R.J. 1991. Modeling emissions and dispersion of feedlot odour: a case study. Proceedings of a workshop on agricultural odours. Toowoomba, Queensland, Australia. Feedlot Services Group, Queensland Department of Primary Industries, AMLRDC Report No. DAQ 64/7. 87-108.
- Petersen, W.B. and L.A. Lavdas, 1986. INPUFF-2.0 A multiple source Gaussian puff dispersion algorithm. Users Guide. EPA/600/8-86/024. August.
- Schiffman, S. S., J. L. Bennett, and J. H. Raymer. 2001. Quantification of odors and odorants from swine operations in North Carolina. *Agricultural and Forest Meteorology*. 108:213-240.
- Smith, R.J. 1993. Dispersion of Odours From Ground Level Agricultural Sources. *Journal of Agricultural Engineering Research*. 54:187-200.
- Turner, D.B. 1994. Workbook of atmospheric dispersion estimates: An introduction to dispersion modeling, 2nd Edition. CRC Press, Inc. Boca Raton, FL. 33431.
- Wood, S.L., K.A. Janni, C.J. Clanton, D.R. Schmidt, L.D. Jacobson and S. Weisberg. 2001. Odor and air emissions from animal production systems. ASAE Paper No. 014043. St. Joseph, MI: ASAE.
- Zannetti, P. 1990. *Air Pollution Modeling: Theories, Computational Methods and Available Software*. New York: Van Nostrand Reinhold.
- Zhu, J., L.D. Jacobson, D.R. Schmidt and R. Nicolai. 2000. Evaluation of INPUFF-2 model for predicting downwind odors from animal production facilities. *Applied Engineering in Agriculture*. Vol. 16(2):159-164.