Modeling Ammonia Dispersion from Multiple CAFOs Using GIS

Jamie Cajka, RTI International (RTI)
Marion Deerhake, RTI
Chengwei Yao, RTI

Abstract

Ammonia is the most prevalent gas emitted by Concentrated Animal Feeding Operations (CAFOs) raising swine in eastern North Carolina and is a contributor to the degradation of the quality of air and surface water. Calculating ammonia deposition over a large region is difficult because there is little, if any, regional monitoring data. RTI International (RTI) has developed a methodology for modeling the deposition of ammonia that is emitted by multiple CAFOs. The methodology uses readily available, peer-reviewed air dispersion and deposition modeling software, and geographic information systems (GIS) to provide a platform for modeling not only individual operations, but also the cumulative contributions from multiple operations across an entire region. The methodology is enhanced by its flexibility in handling numerous variables, including emission factors for CAFO emission sources by animal growth stage; meteorological and terrain conditions; and facility capacity and acreage.

Introduction

In the late 1980s through the late 1990s, eastern North Carolina experienced an enormous increase in the number of hogs produced in the state. This increase can be attributed to several factors, including the downturn of the tobacco industry, less stringent state regulations as compared to other hog-producing states, improvements in transportation infrastructure, and the close proximity to major east coast markets. Although the number of hog farms in North Carolina decreased from 15,000 in 1986 to 3,600 in 2000, the number of hogs produced in the state increased from 2.4 million to 9.5 million[1] during this same time period because operations became most efficient and economies of scale increased. These CAFOs have greatly increased the amount of ammonia released into the environment. Quantifying the amount of ammonia has been difficult because monitoring data are geographically sparse. The Clean Air Status and Trends Network (CASTNET) maintains only five stations in North Carolina, none of which are in North Carolina's hog farming belt. There are several regional monitoring stations sponsored by academia and the federal government, but these stations are located in or close to urban areas and only measure wet ammonia deposition.

Modeling presents a viable alternative to the high cost and sparse networks associated with ammonia monitoring. Modeling a single swine operation is a relatively simple and fairly common exercise; however, while such modeling may accurately estimate concentration and deposition from a single farm, it does not take into account the contributions from neighboring operations. RTI's study tackled the additive effects of multiple CAFOs by utilizing modeling and GIS. This resulted in cumulative ammonia deposition values over an entire region, as generated by CAFOs of different sizes, animal growth stages, and physical locations.

[1] North Carolina Agricultural Overview: Livestock, North Carolina Department of Agriculture and Consumer Services, Feb. 23, 2001.

Data

The main goal of RTI's study was to model a baseline amount of ammonia deposition that would result from emissions from all the swine operations within the study area. Generating a baseline would allow reductions based on applied alternative waste management practices to be quantified. The study area was defined as the White Oak, Neuse, Cape Fear, New, and Tar-Pamilco River basins. (Figure 1).

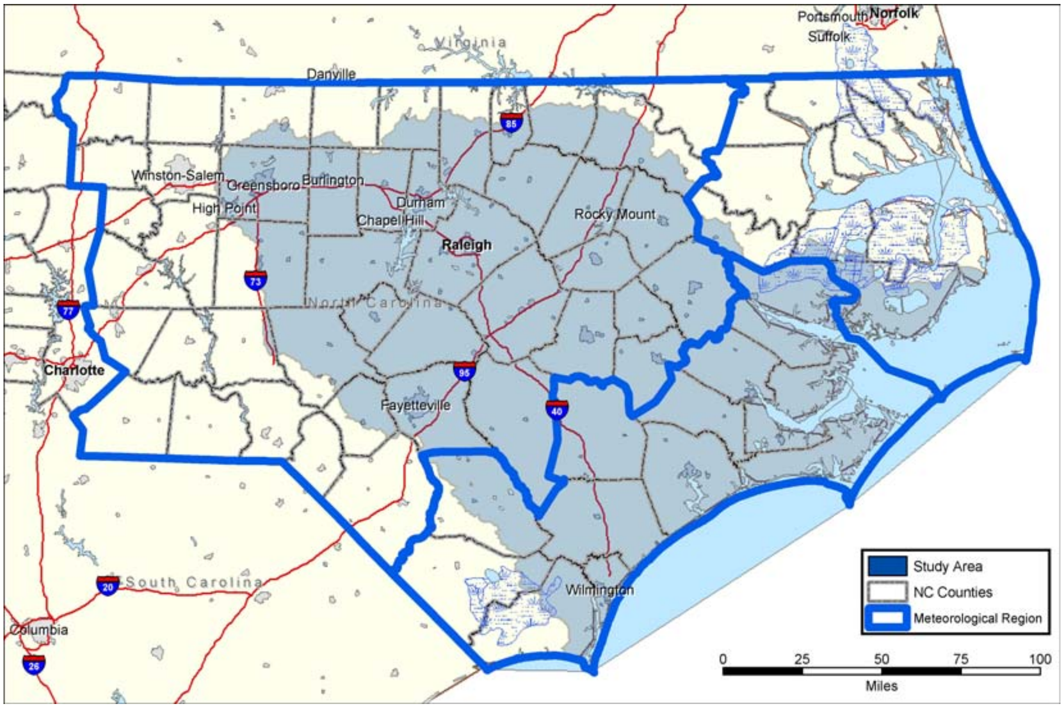

Figure 1. Study Area and Meteorological Regions

In order to sum the cumulative contributions from all CAFOs, information was required for each operation, including the physical geographic location, the meteorological region in which it resided, and the amount of ammonia emitted.

RTI researchers compiled an inventory of North Carolina's swine operations that was provided by the North Carolina Department of Environment and Natural Resources (NCDENR). Among the many variables contained in the file were latitude and longitude coordinates and farm description. Of the 2,295 farms, roughly 10 percent did not have valid latitude and longitude locations. RTI researchers determined these locations using a combination of geocoding, quadrangle maps, aerial photography, and Internet mapping resources, such as LandView™ and Mapquest. Once the locations were determined, all swine CAFOs within a 50 km distance were identified. Because the dispersion and deposition modeling grid has a radius of 50 km, any farm within 50 km of the study area's boundary could have some influence on the study area. This resulted in a total of 2,237 farms. The resulting distribution of swine CAFOs is shown in Figure 2.

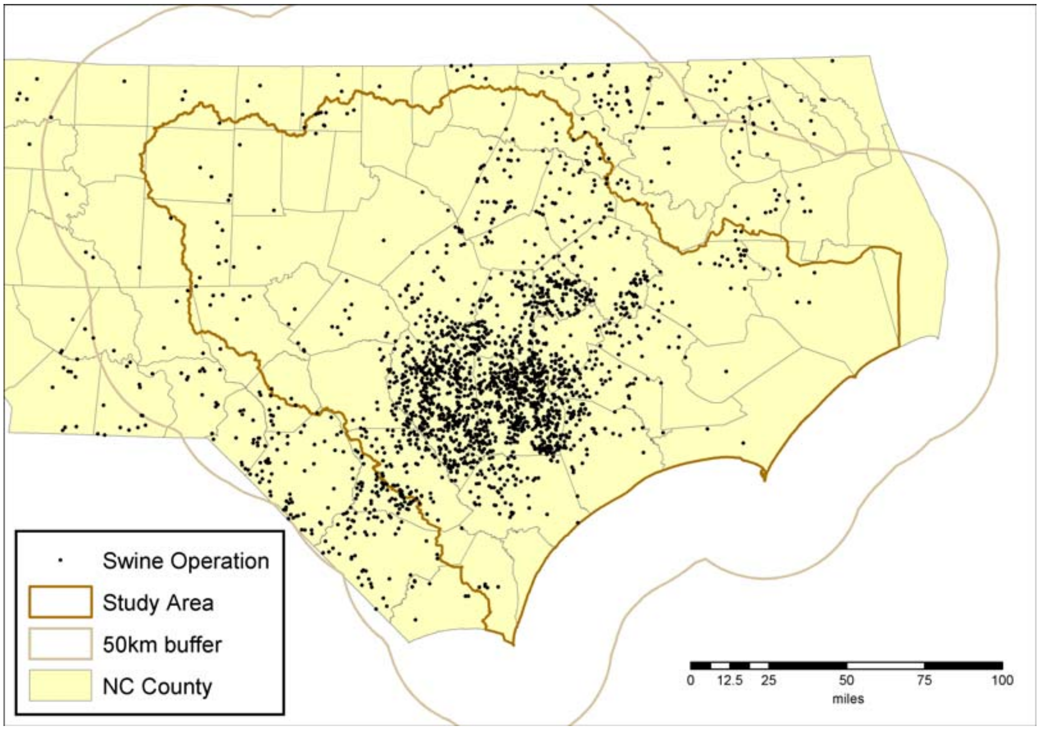

Figure 2. Location of Swine Operations Within Study Area

After locating all North Carolina hog farms, RTI researchers assigned each meteorological region (Wilmington, NC, Raleigh, NC, or Norfolk, VA). This was important in order to input the appropriate wind speed, wind direction, elevation, and surface roughness into the air dispersion and deposition model.

The amount of ammonia emitted by each swine operation depends upon several factors, the most important of which are the number of hogs and the growth stage of each hog. This study used the data supplied by NCDENR to calculate emission factors based on five distinct growth stages:

- Farrow to wean
- Wean to feed
- Farrow to feed
- Farrow to finish
- Feed to finish.

Each farm was designated as raising hogs of one of the above growth stages. Using values obtained from existing literature, RTI researchers calculated emission factors for each growth stage. An ammonia emission rate was then calculated by multiplying the emission factor by the steady-state live weight of hogs onsite during routine operation. This emission rate was the key number in estimating the amount of ammonia deposition from each CAFO.

Methodology

The first step in the GIS process was to create radial grids of the 12 model CAFOs. CAFOs were grouped into four sizes—50, 100, 260, and 500 acres—and designated as falling into one of three meteorological regions. All CAFOs in the same meteorological region were deemed to have the same average wind speed, wind direction, and surface roughness. Four sizes and three meterological regions yielded 12 possible model CAFOs.

RTI researchers output radial grids using EPA's Industrial Source Complex Short Term (ISCST3) air dispersion and deposition model[2]. Inputs into the model included deposition and air concentration point locations, wind speed, wind direction, and surface roughness. Each 50 km radius radial grid was created using 1,086 discreet locations, closely spaced near the origin and decreasing in density towards the outer edge (Figure 3).

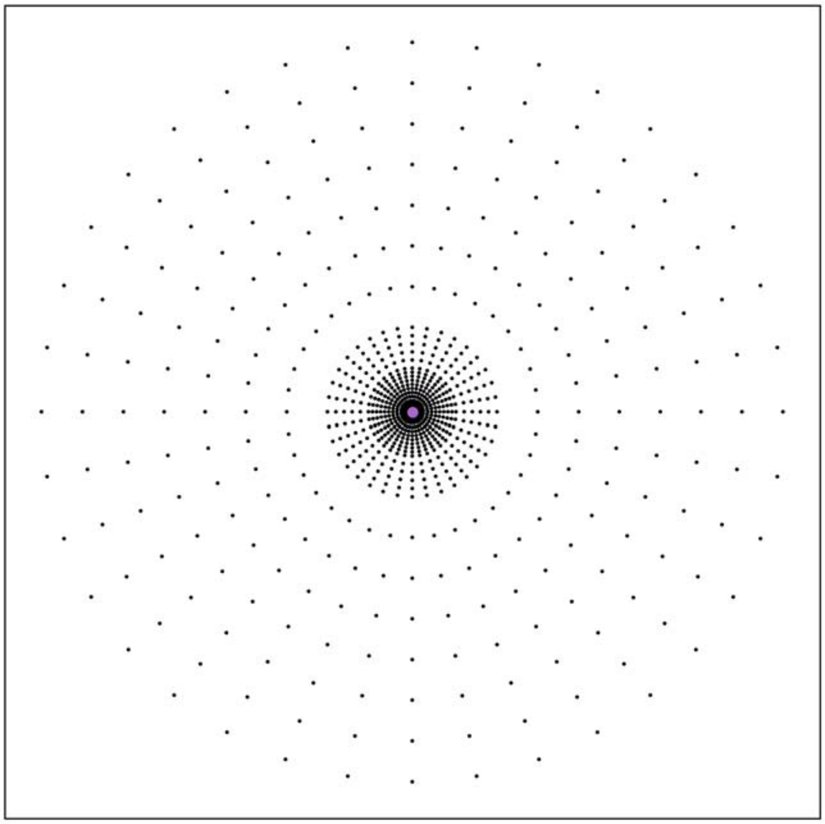

Figure 3. 50 km Radius Radial Grid

This was done to capture the variation in ammonia deposition and air concentration amounts close to the CAFO edges, because these totals drop off quickly as distance away from the origin increases (Figure 4).

---

[2] U.S. EPA (Environmental Protection Agency). 1995. *Draft User's Guide for the Industrial Source Complex (ISC3) Dispersion Models. Volume 1: User Instructions.* (Revised). EPA –454/B-95-003a. Emissions, Monitoring, and Analysis Division, Office of Air Quality Planning and Standards, Research Triangle Park, NC. September.

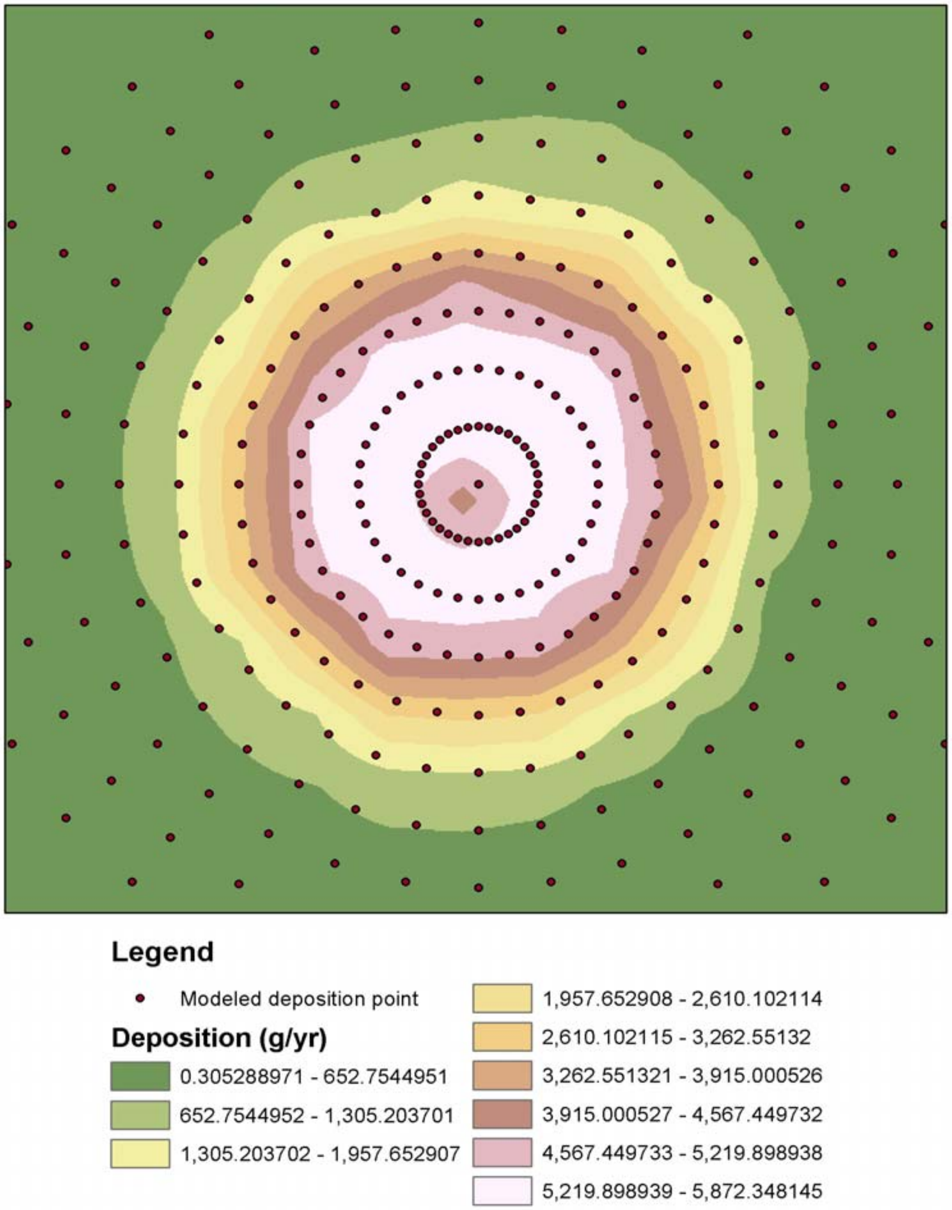

Figure 4. Ammonia Deposition Around Single CAFO

The ISCST3 model calculates ammonia deposition rates and concentrations based on a unitized emission rate. It assumes that ammonia is emitted from the surface of the CAFO at a rate of 1 mg/sec/m^2. When analyzing the output of the model, it is important to note that the values at each point are deposition rates in grams per square meter, per year. This study's main goal was to calculate the deposition amount; therefore, the challenge for RTI researchers became how to convert a deposition rate into an amount. This conversion could only occur before the CAFOs' deposition points were summed. Deposition rates from adjacent CAFOs could not be added together because the contributions were additive, not averaged.

One possibility was to create an Arc/Info GRID using a grid cell size small enough to capture the large variability in ammonia deposition rates close to a CAFO's edge. This would have required a cell size of about 15 meters, which in turn would have required about 6667 X 6667 grid. These measurements represented a large storage requirement and would have necessitated a very fine grid in areas where changes in deposition rates were quite small.

A better alternative was to create Thiessen polygons from the radial dispersion pattern. Thiessen polygons are polygons with boundaries that define the area that is closest to each point relative to all other points (Figure 5).

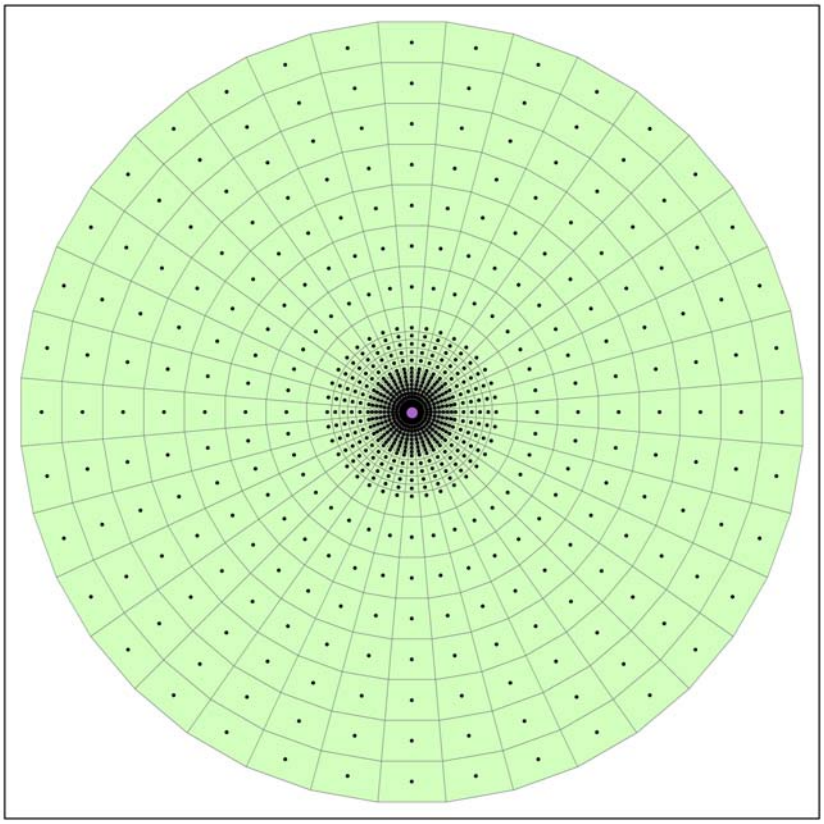

Figure 5. Thiessen Polygons Created From Radial Grid

Thus, each square meter that makes up each Thiessen polygon is closest to the deposition point it bounds. Therefore, the deposition rate (in mg per square meter) could be applied to each square meter in the Thiessen polygon surrounding the modeled deposition point. By multiplying the deposition rate by the number of square meters, RTI researchers calculated a deposition total for each Thiessen polygon for each model farm, based on a unitized emission rate. The polygon label points were then written out to a point coverage. This achieved 12 model CAFO point coverages, with the points representing the ammonia deposition from the Thiessen polygons in which they are centered.

The next step was to process the file of swine operations one by one. The key information captured included

- Farm ID
- Farm size
- Meteorological region
- Latitude

- Longitude
- Emission factor (relative to growth stage).

For each record in the swine operation file, RTI researchers copied the appropriate model CAFO point deposition coverage and renamed the coverage to farm_<Farm ID>. An attribute populated with the farm ID was also added to the coverage. Each deposition amount was then multiplied by the emission rate for that farm (Table 1).

Table 1. Swine Operaton File With Emission Rates by Farm ID

FARM_ID	TOTAL_STEA	GROWTH STAGE	MET STATION	ACRES	AREA (M2)	DESIGN _CAP	EMISS FACTOR kg NH3/yr	EMISS RATE kg/yr/m^2	EMISS RATE mg/sec/m^2
10a1	777600	Feeder to Finish	Wilmington	100	404687.3	5760	43,678.44	0.108	0.00342248
10a18	281450	Farrow to Wean	Wilmington	50	202343.6	650	10,090.81	0.050	0.001581357
10a21	1732000	Farrow to Wean	Wilmington	260	1052187	4000	62,097.29	0.059	0.001871428
10a29	106560	Wean to Feeder	Wilmington	50	202343.6	3552	7,169.18	0.035	0.0011235
10a3	506250	Feeder to Finish	Wilmington	100	404687.3	3750	28,436.48	0.070	0.002228177
10a32	1728000	Feeder to Finish	Wilmington	260	1052187	12800	97,063.20	0.092	0.002925197
10a33	864000	Feeder to Finish	Wilmington	100	404687.3	6400	48,531.60	0.120	0.003802756
10a36	1486550	Farrow to Finish	Wilmington	260	1052187	4610	77,791.50	0.074	0.002344405
10a37	192000	Wean to Feeder	Wilmington	50	202343.6	6400	12,917.43	0.064	0.002024324
10a38	192000	Wean to Feeder	Wilmington	50	202343.6	6400	12,917.43	0.064	0.002024324
10a4	495720	Feeder to Finish	Wilmington	50	202343.6	3672	27,845.00	0.138	0.004363663
10a5	820800	Feeder to Finish	Wilmington	100	404687.3	6080	46,105.02	0.114	0.003612618
10a8	388800	Feeder to Finish	Wilmington	50	202343.6	2880	21,839.22	0.108	0.003422481
10a9	120000	Wean to Feeder	Wilmington	50	202343.6	4000	8,073.40	0.040	0.001265203
13a1	866000	Farrow to Wean	Raleigh	100	404687.3	2000	31,048.64	0.077	0.002432856
13a11	67860	Farrow to Feeder	Raleigh	50	202343.6	130	2,827.26	0.014	0.000443068
13a17	162000	Feeder to Finish	Raleigh	50	202343.6	1200	9,099.67	0.045	0.001426034
15a11	536920	Farrow to Wean	Norfolk	100	404687.3	1240	19,250.16	0.048	0.001508371
15a3	145800	Feeder to Finish	Norfolk	50	202343.6	2235	8,189.71	0.040	0.00128343
16a1	354194	Farrow to Wean	Wilmington	50	202343.6	818	12,698.90	0.063	0.001990077
16a2	188461	Farrow to Finish	Wilmington	50	202343.6	133	9,862.21	0.049	0.001545532
17a1	175500	Feeder to Finish	Raleigh	50	202343.6	1300	9,857.98	0.049	0.00154487
17a3	127530	Farrow to Finish	Raleigh	50	202343.6	90	6,673.67	0.033	0.001045849
19a4	270000	Feeder to Finish	Raleigh	50	202343.6	2000	15,166.12	0.075	0.002376723
19a43	391500	Feeder to Finish	Raleigh	50	202343.6	2900	21,990.88	0.109	0.003446248

Using the latitude and longitude information, the farm was translated and projected into state plane coordinates. These deposition points occupied their correct positions in geographic space, and the coverage was added to a master point coverage. Figure 6 shows the master point coverage after the addition of two CAFOs.

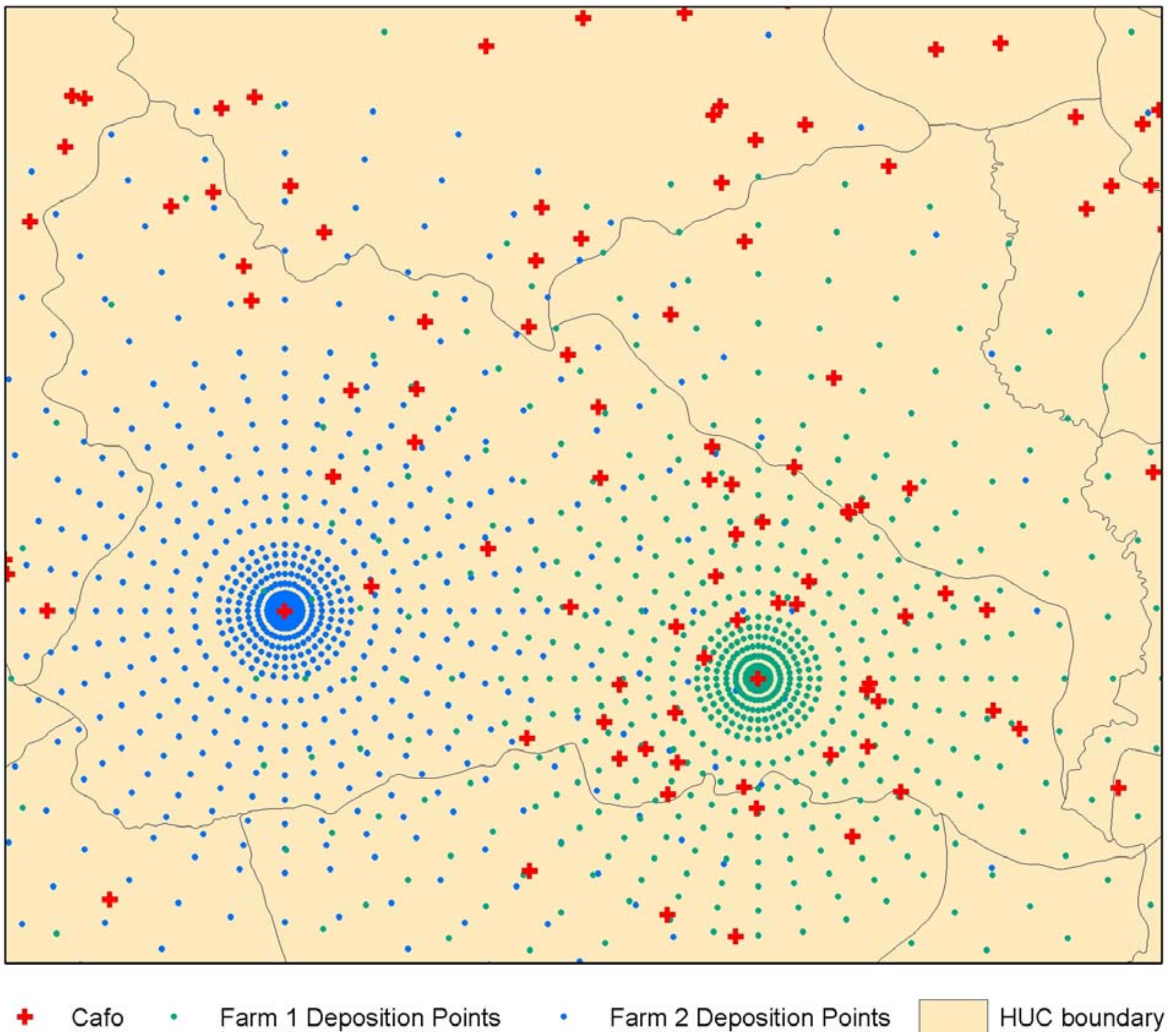

Figure 6. Building the Master Point Coverage

After all 2,237 CAFOs were processed, the master point coverage contained almost 2.5 million deposition points (1,086 points from each of 2,237 CAFOs) (Figure 7).

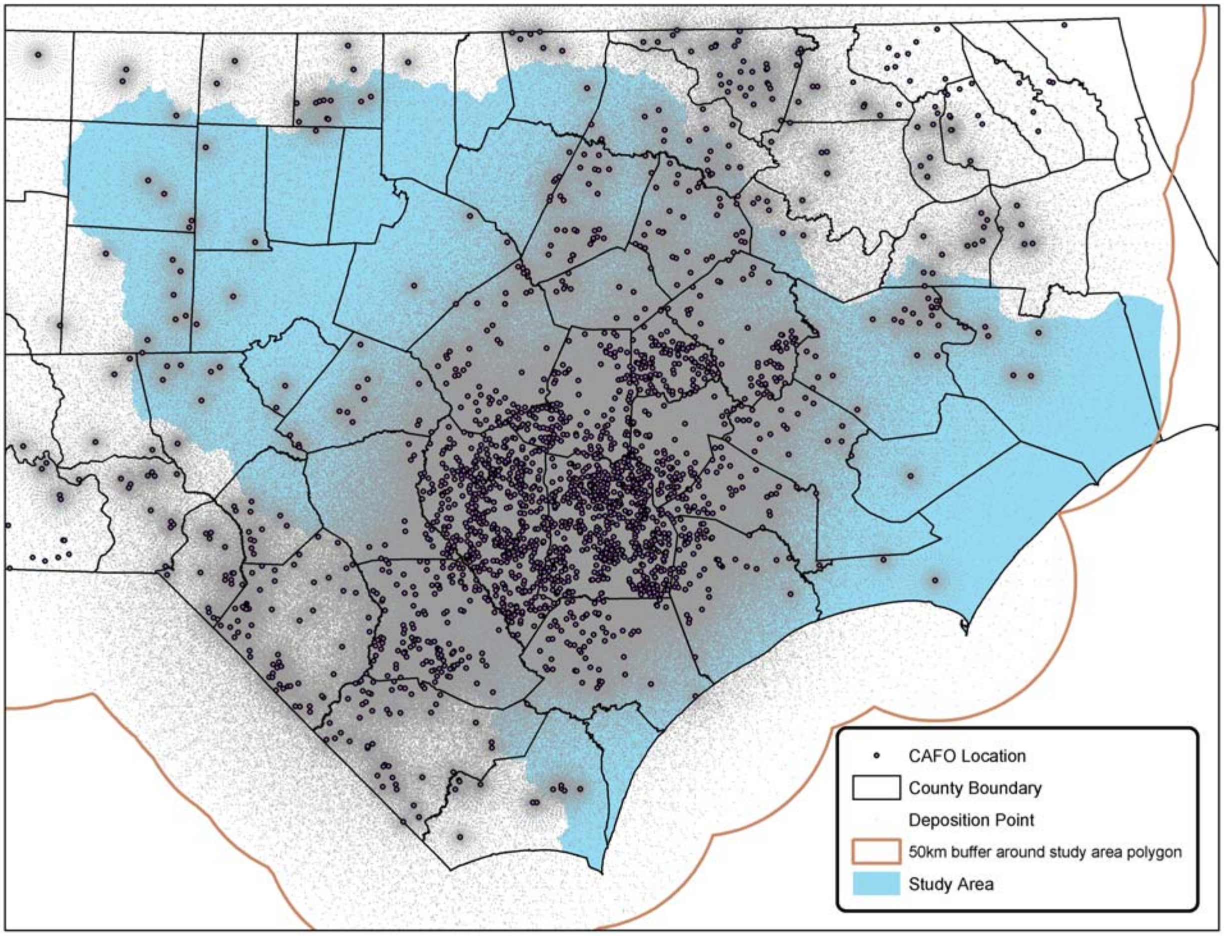

Figure 7. Study Area with All Deposition Points

Results

The main goal of this study was to model the amount of ammonia deposition in the study area. In order to sum the amount of ammonia by hydrologic unit (HUC) and county, RTI researchers performed two overlays on the master ammonia deposition point coverage. The 8-digit HUC code and the county Federal Information Processing Standard (FIPS) codes were transferred to each deposition point. Then, using statistics in Arc/Info, RTI researchers summed the deposition by both HUC and county FIPS. Tables 2 and 3 show the deposition totals in grams by HUC and County FIPS, respectively.

Table 2. Ammonia Deposition Summed by HUC

HUC14_I	FREQUENCY	SUM_TOTAL
Outside study area	364587	7800944405.769000
3020101010010	321	2121475.473440
3020101010020	177	624821.030710
3020101010030	97	629525.763580
3020101010040	54	397449.389600
3020101010050	90	1060942.413400
3020101010060	59	1275434.545870
3020101020010	98	1430128.265060
3020101030010	34	659673.690570
3020101030020	22	481557.466010
3020101030030	34	703612.204080
3020101030040	25	311693.565270
3020101030050	33	643105.224430
3020101030060	76	1128267.876320
3020101030070	70	1109009.089250
3020101030080	29	402342.730830
3020101040010	75	914441.510020
3020101040020	32	718845.931630
3020101040030	44	774518.319850
3020101040040	143	1991613.167080
3020101040050	76	1098582.782520
3020101040060	44	790409.891860
3020101040070	157	2774666.294790
3020101040080	49	709064.794070
3020101040090	68	1145590.386750
3020101050010	322	4247874.028910
3020101060010	201	3345914.716200
3020101060020	217	2658716.758050
3020101060030	67	1273038.924180

Table 3. Ammonia Deposition Summed by County

CO_FIPS	FREQUENCY	SUM_TOTALD
163	439938	7679441530.582000
61	484973	7675805969.493500
17	147464	3207619207.491800
191	157362	2635389206.691700
141	95562	1723253694.241300
107	98193	1652462592.756400
155	64551	1545716716.743900
79	87832	1432705639.634200
101	76763	1265719534.300500
103	57516	1182868165.930600
47	53775	1166196562.456100
147	64324	1153719674.369800
133	77635	1072888161.998700
51	45520	855812236.834470
0	28873	810552018.448380
65	34199	662899588.307400
13	27092	513046508.523210
49	32993	510147620.645140
83	22059	473505803.643180
131	28515	472817046.136570
165	16667	459966357.143660
85	19777	395781809.309250
127	32728	395064837.005230
195	22367	371127241.300770
93	15144	366943748.305960
19	15403	319567919.429400
187	10484	255762256.913200
153	12322	234637134.286330
125	12534	215070103.772180

It was also possible to visualize the ammonia deposition totals in map form. Figure 8 shows the deposition totals by HUC, normalized by area to account for the fact that larger areas will have larger deposition totals. Figure 9 shows the deposition totals by county. Both give a good visual representation of where the areas of highest ammonia deposition are located.

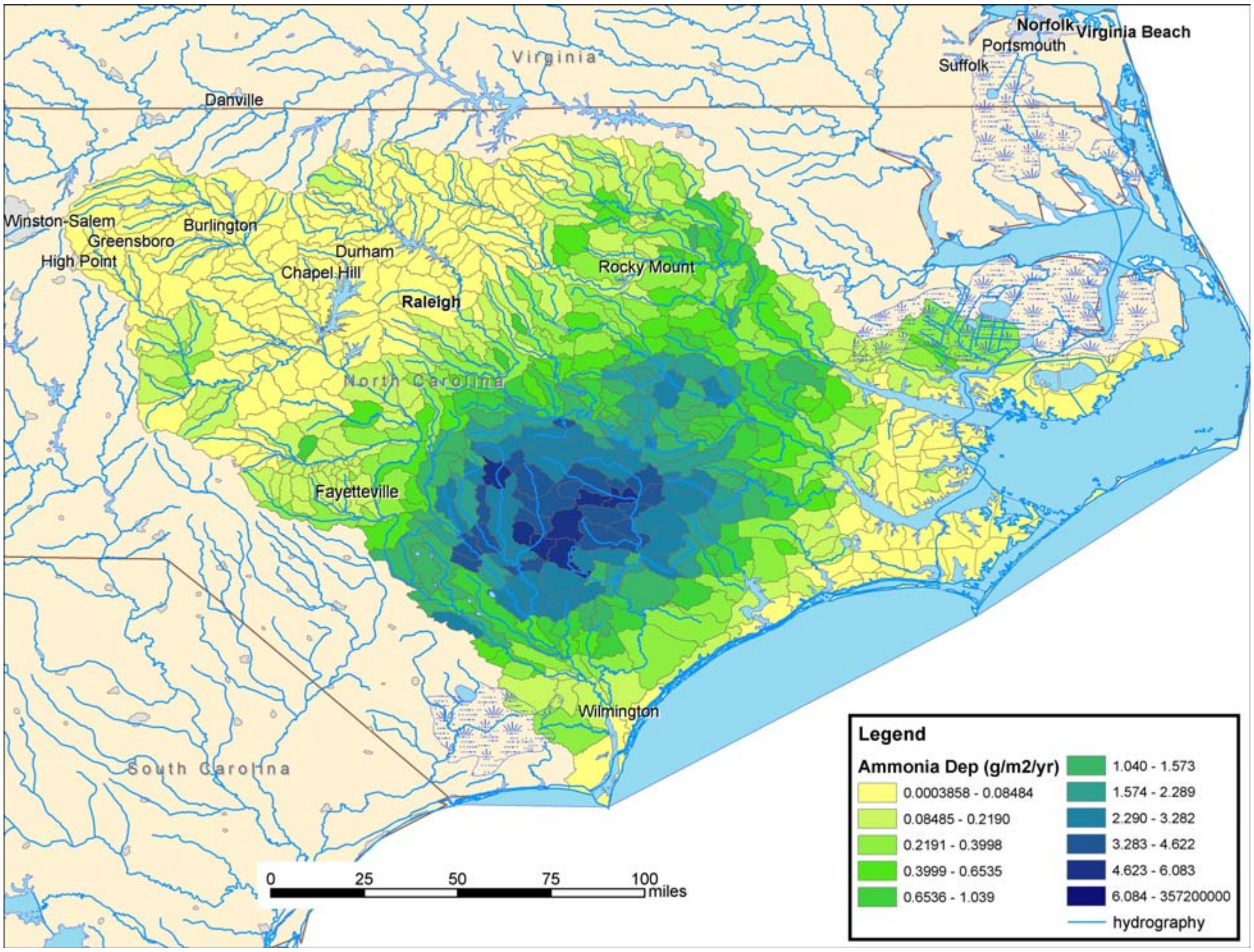

Figure 8. Ammonia Deposition by HUC Normalized by Area

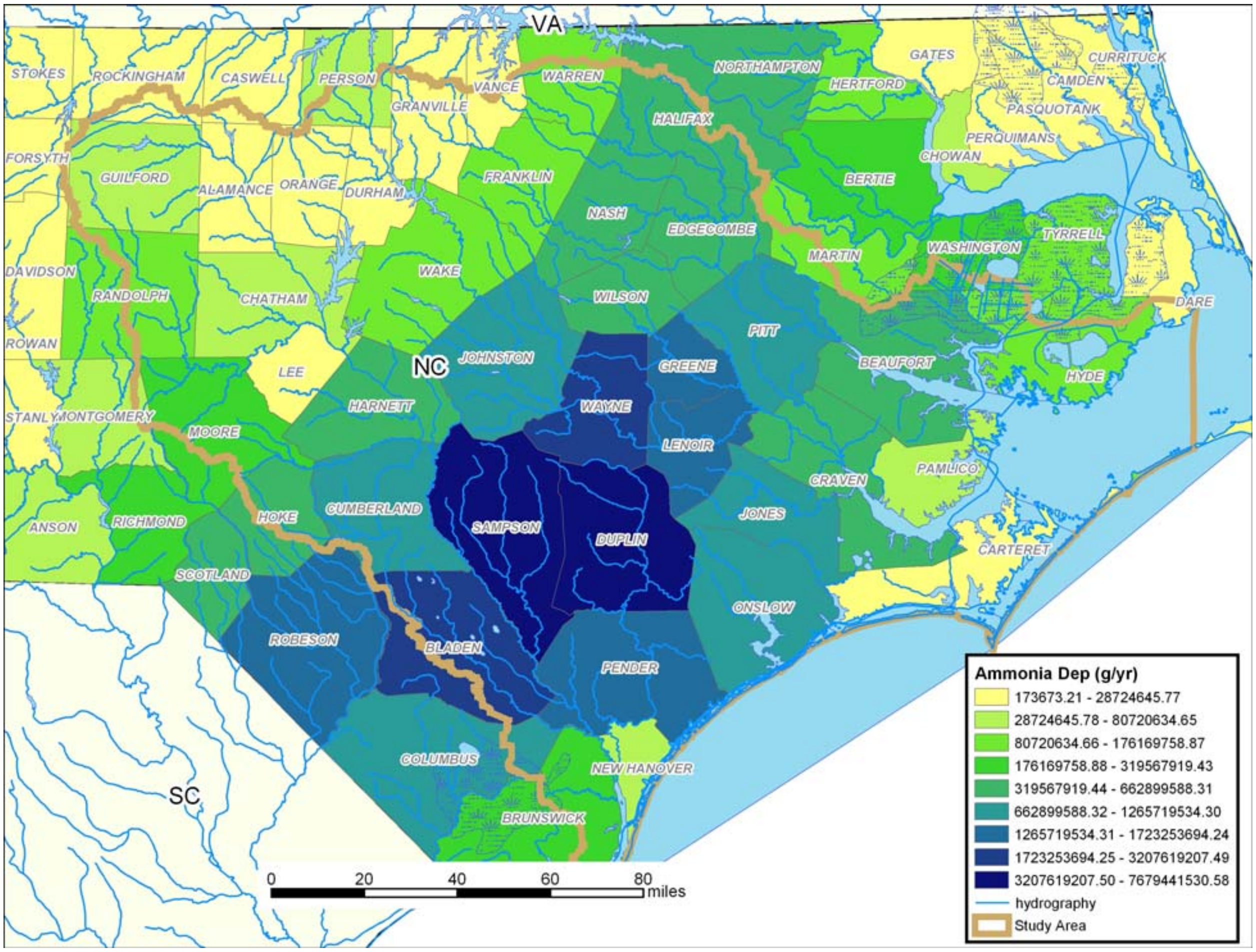

Figure 9. Ammonia Deposition by County Normalized by Area

Conclusions

Using model swine CAFOs coupled with customized ammonia emission factors and known latitude and longitude coordinates, it is possible to model the amount of ammonia air deposition within a study area, taking into account the contributions from all sources. RTI's study focused on swine operations only; however, the study could be adapted to include other types of CAFOs, such as dairy, beef, and poultry farms. This study summed ammonia deposition over HUC and county, but the data could be summed over any polygon feature the study desired.

The software commands and techniques for this modeling technique are relatively simple and straightforward. This technique can also be used to calculate cumulative concentration (rather than deposition) values, although this requires Arc/Info's GRID software and a knowledge of raster processing techniques.

Acknowledgements

RTI would like to thank North Carolina State University's Animal and Poultry Waste Management Center (Mike Williams, Ph.D., Director) for contracting RTI to perform the environmental and economic assessment (RTI, 2003). RTI also thanks its economists – Dr. George Van Houtven and Dr. Brian Murray – for inviting RTI's Environment, Health, and Safety Division to collaborate on this study.

Contact Information

Jamie Cajka
RTI International
3040 Cornwallis Rd.
RTP, NC 27709
Tel: (919) 541-6470
Email: jcajka@rti.org

Marion Deerhake
RTI International
3040 Cornwallis Rd.
RTP, NC 27709
Tel: (919) 541-8680
Email: med@rti.org

Chengwei Yao
RTI International
3040 Cornwallis Rd.
RTP, NC 27709
Tel: (919) 541-6878
Email: yaoc@rti.org