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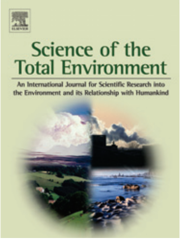

Potential geographic distribution of atmospheric nitrogen deposition from intensive livestock production in North Carolina, USA

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ABSTRACT

To examine the consequences of increased spatial aggregation of livestock production facilities, we estimated the annual production of nitrogen in livestock waste in North Carolina, USA, and analyzed the potential distribution of atmospheric nitrogen deposition from confined animal feeding operations ("CAFO") lagoons. North Carolina is a national center for industrial livestock production. Livestock is increasingly being raised in CAFOs, where waste is frequently held, essentially untreated, in open-air lagoons. Reduced nitrogen in lagoons is volatilized as ammonia (NH_3), transported atmospherically, and deposited to other ecosystems. The Albemarle-Pamlico Sound, NC, is representative of nitrogen-sensitive coastal waters, and is a major component of the second largest estuarine complex in the U.S. We used GIS to model the area of water in the Sound within deposition range of CAFOs. We also evaluated the number of lagoons within deposition range of each 1 km^2 grid cell of the state. We considered multiple scenarios of atmospheric transport by varying distance and directionality.

Modeled nitrogen deposition rates were particularly elevated for the Coastal Plain. This pattern matches empirical data, suggesting that observed regional patterns of reduced nitrogen deposition can be largely explained by two factors: limited atmospheric transport distance, and spatial aggregation of CAFOs. Under our medium-distance scenario, a small portion (roughly 22%) of livestock production facilities contributes disproportionately to atmospheric deposition of nitrogen to the Albemarle-Pamlico Sound. Furthermore, we estimated that between 14–37% of the state receives 50% of the state's atmospheric nitrogen deposition from CAFO lagoons. The estimated total emission from livestock is 134,000 t NH_3 yr^{-1}, 73% of which originates from the Coastal Plain. Stronger waste management and emission standards for CAFOs, particularly those on the Coastal Plain nearest to sensitive water bodies, may help mitigate negative impacts on aquatic ecosystems.

1. Introduction

Agricultural waste is an inevitable byproduct of raising livestock. Historically, farmers have managed this problem by using nutrient-rich livestock wastes as a crop fertilizer. Yet, as small independent farms are increasingly converted to large-scale, industrialized, confined animal feeding operations ("CAFOs"), livestock waste management and disposal becomes more challenging. Here, we address the regional consequences of industrialized livestock production in North Carolina, where

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the number of animals produced has greatly increased while the number of farms is declining (Furuseth, 1997).

North Carolina is one of the leading states in livestock production. Here, we use the term “livestock” to include swine, cattle, and poultry. The state ranks second in the nation in both swine and turkey production, accounting for approximately one-sixth of the U.S. total (North Carolina Department of Agriculture and Consumer Services [NCDA & CS], 2007). Currently, the retention of liquid waste in large anaerobic storage reservoirs (“lagoons”) is the most widespread and least costly treatment method for livestock waste (Barker, 1996). In North Carolina there are over 2500 CAFO lagoons, 85% of which are located in the Coastal Plain (NC Division of Environment and Natural Resources, Division of Water Quality [NCDENR DWQ], 2002a; also see Fig. 1). Unlike the municipal treatment of human waste, these waste management facilities employ few wastewater treatment processes. Recent studies report that CAFOs in the Coastal Plain of North Carolina are major sources of nitrogen to the region’s nutrient-sensitive estuarine and coastal water (Cahoon et al., 1999; Walker et al., 2000; Whitall and Paerl, 2001; Mallin and Cahoon, 2003).

Nitrogen limitation is widespread worldwide, and occurs commonly in terrestrial, freshwater, and marine systems (Elser et al., 2007). Excessive nutrient loading to nitrogen limited waters can create eutrophic conditions, which are linked to noxious phytoplankton blooms and hypoxia (Paerl and Whitall, 1999; Paerl, 2002), changes in fish and benthic macroinvertebrate communities (Burkholder and Glasgow 1997, Glasgow and Burkholder, 2000; Alderman et al., 2005), and outbreaks of harmful aquatic organisms (e.g. Burkholder et al., 1992).

Atmospheric transport is a major pathway by which nitrogen is delivered to riverine, estuarine and coastal ecosystems (Walker et al., 2000; Whitall et al., 2004). Ammonia (NH_3) volatilizes from lagoons and terrestrial systems to which the waste is applied (Barker et al., 2006; Shaffer and Walls, 2005). In the atmosphere, it is transformed to other forms of reduced nitrogen, transported via air movement and atmospheric patterns, and deposited to other ecosystems through both wet and dry deposition. Approximately 80% of NH_3 emissions in the U.S. are generated by livestock waste (Battye et al., 1994).

Atmospheric deposition of nitrogen emissions now accounts for up to 40% of new nitrogen inputs to coastal ecosystems (Paerl et al., 2002). In North Carolina, direct deposition of reduced N is likely to have a large impact on the large estuarine complex including the Albemarle and Pamlico Sounds (Fig. 1), collectively called the Albemarle-Pamlico Sound. Together with its

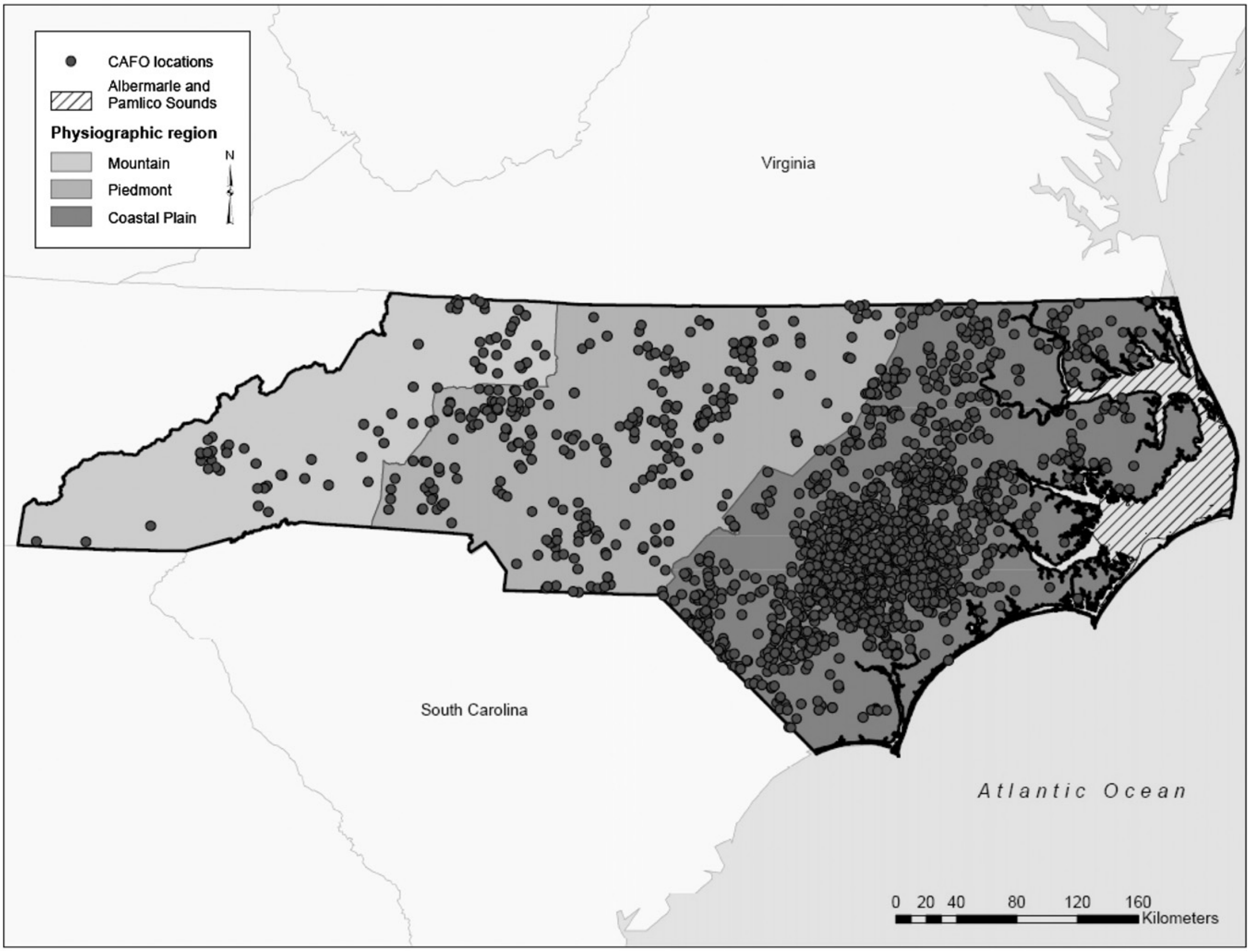

Fig. 1 – Map showing the statewide distribution and aggregation of CAFOs in North Carolina, the physiographic regions of the state, and the Albemarle-Pamlico Sound.

subestuaries, the Sound is the second largest estuarine system in the U.S. It is chronically N-limited, and direct deposition to open water can bypass the mesohaline zone of the estuary, where biological uptake removes much of the N from riverine inputs (Paerl et al., 2002).

National Atmospheric Deposition Program (NADP) data indicate that wet deposition of NH_4^+ has increased in the past decade in southeastern North Carolina, and rates are particularly high in portions of the state's Piedmont and Coastal Plain (NADP, 2006; see Fig. 2). The spatial aggregation of CAFOs in the state's Coastal Plain suggests that nitrogen loading from these operations may be greatest in this region. While CAFO lagoons are considered to be the largest contributors to NH_3 emissions (EPA, 2003), the observed NADP rates (Whitall and Paerl, 2001; Walker et al., 2004) have not been directly linked to CAFO nitrogen emissions.

To better understand the sources of nitrogen deposition, we address two questions. First, how much nitrogen do North Carolina livestock produce in manure, and how much is emitted as NH_3? Second, what is the potential spatial distribution of atmospheric nitrogen deposition from CAFO lagoons? Although management decisions are often made on a statewide basis, few studies have made such assessments at spatial scales larger than single watersheds (but see Paerl et al., 2002; Mallin and Cahoon, 2003; Walker et al., 2004). For this reason, and because North Carolina makes a significant contribution to national livestock production (NCDA & CS, 2007), we seek to address these two questions at the state level.

2. Methods

2.1. Nitrogen production and ammonia emissions from livestock manure

We calculated total annual nitrogen production and ammonia (NH_3) emission rates (in units of metric tons (t) NH_3 yr^{-1}) for three categories of livestock: swine (breeders and growers), poultry (broilers, other chickens and turkeys), and cattle (beef and dairy). We estimated total statewide annual nitrogen

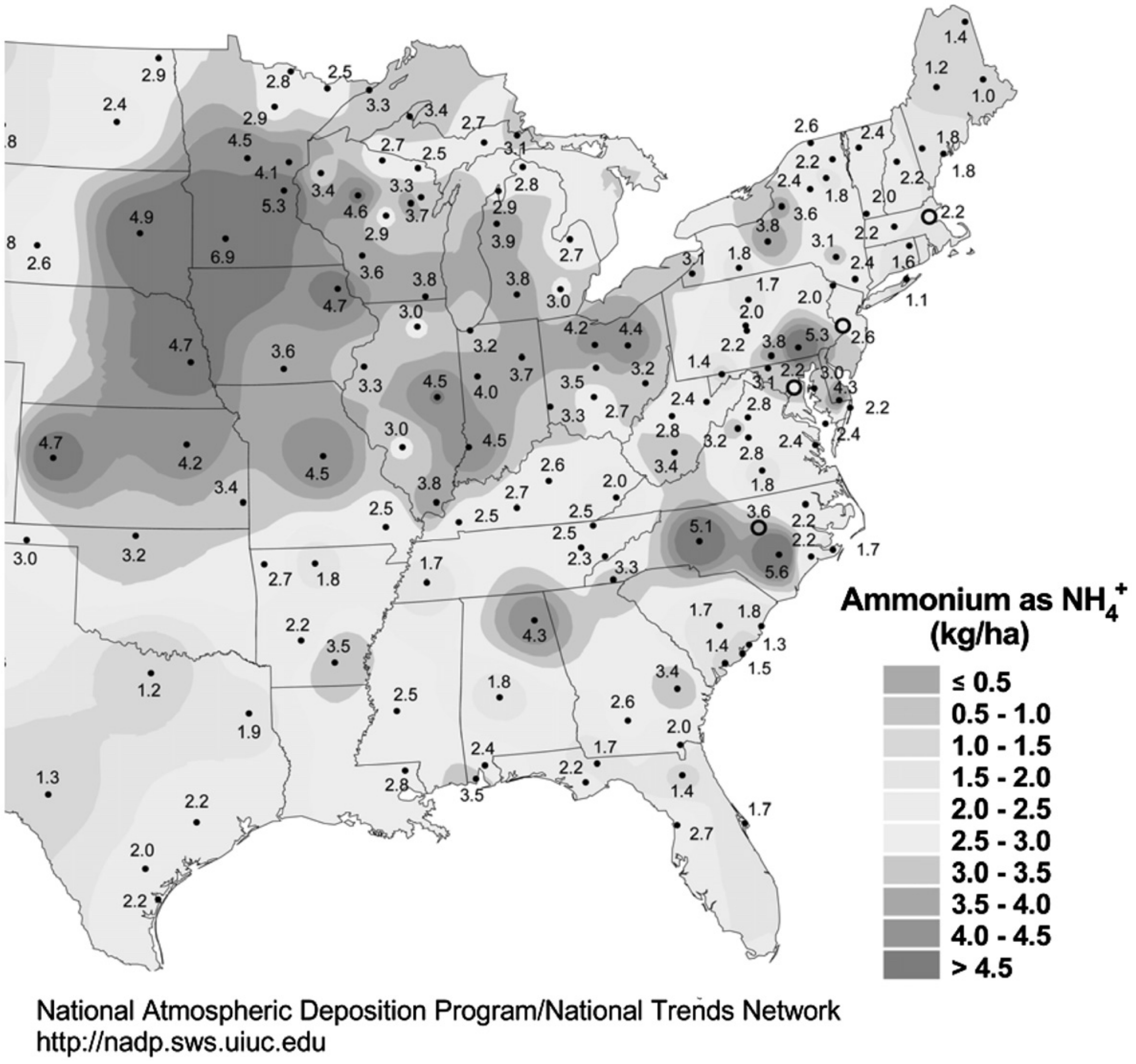

Fig. 2 – Map showing 2005 ammonium atmospheric deposition rate (kg NH_4^+ ha^{-1} yr^{-1}), reproduced from the National Atmospheric Deposition Program (2006).

production for the Mountains, Piedmont, and Coastal Plain physiographic provinces of North Carolina (Fig. 1) following Kellogg et al. (2006). In order to determine nutrient content of manure, we first calculated total manure production. Using 2006 county census of agriculture data, we divided census head counts by the number of animals per animal unit (AU), which represents 1000 lb of live animal weight and serves as a common unit for aggregating over different types of livestock (Kellogg et al., 2006). These standard animal unit conversions are based on the average live weight associated with each livestock category. We then multiplied this value by the mass of "as excreted" manure produced annually per AU to provide an estimate of the total mass of manure produced by all livestock categories. From this value, we determined total nitrogen production in t N yr^{-1} by multiplying metric tons of manure produced by published values for the mass of elemental nitrogen per metric ton of manure (Kellogg et al., 2006).

NH_3 emission rates for all livestock categories were estimated using the Carnegie Mellon University Ammonia Model Version 3.6 (Strader et al., 2004). Source activity data used in the model are from the 2002 Census of Agriculture and emission factors for diary cattle, beef cattle, swine, and poultry are from the EPA National Emission Inventory (2004). The emission factors used in the model are an improvement upon other existing emission inventories (Asman, 1992; Battye et al., 1994; Bouwman and Van Der Hoek, 1997; Doorn et al., 2002), which do not account for seasonal changes in emissions or type of animal production practices used. In addition, most other emission inventories, excluding Doorn et al. (2002), are from European studies and therefore may not be applicable to the U.S. (EPA, 2004).

2.2. *Atmospheric transport of nitrogen from livestock waste lagoons*

To examine the potential spatial distribution of atmospheric nitrogen in the form of reduced N inputs to North Carolina's aquatic ecosystems from CAFO lagoons, we used a geographic information systems (GIS)-based approach. All spatial analyses were performed using ArcGIS Desktop 9.2 software (Environmental Systems Research Institute, 1999–2006). We analyzed short-, medium-, and long-distance nitrogen transport scenarios by assuming the transport radius from each lagoon to be 80 km, 160 km, or 400 km for the three scenarios, respectively. These distances were derived from studies quantifying nitrogen atmospheric transport distances. We modeled an 80 km radius for our short-distance scenario based on Walker et al. (2000), who showed that wet deposition of reduced N can occur at sites up to 80 km away from NH_3 emissions sources in the North Carolina Coastal Plain. We modeled a 400 km radius for our long-distance scenario based on airshed modeling studies (Dennis and Mather, 2001; Paerl et al., 2002) that have estimated the normalized range of influence of ammonia sources, in the prevailing direction of transport, to be 300–450 km. For our intermediate-distance scenario, we modeled a 160 km transport radius based on the airshed modeling studies (Dennis and Mather, 2001; Paerl et al., 2002), but adjusted the distance to account for more restricted transport in directions other than the prevailing one, and for the fact that deposition rates are higher closer to the source.

For each of the three distance scenarios, we used GIS to perform two analyses based on the locations of CAFOs statewide and the number of lagoons used by each CAFO (NCDENR DWQ, 2002a). Our first analysis examined variation in potential atmospheric nitrogen deposition inputs from NC CAFO lagoons to the state as a whole, and to the Albemarle-Pamlico Sound specifically. To calculate potential deposition, we converted a polygon shapefile of North Carolina to a raster with 1 km×1 km grid cells. For each of the distance scenarios described above, we assumed that some of the emitted ammonia would subsequently be deposited in all directions within the given radius from the livestock operation (isotropic transport and deposition). Therefore, for each 1 km^2 grid cell in the state, we summed the number of CAFO lagoons within the given transport radius (i.e. 80, 160, or 400 km) in any direction.

However, because the prevailing direction of air mass transport in North Carolina is generally from the southwest for 10 months of the year (Brook et al., 1995; State Climate Office of North Carolina, 2007), we assumed that transport and subsequent deposition of reduced N from a given CAFO lagoon would be higher to the northeast of the lagoon. We therefore performed a separate calculation to sum only the number of CAFO lagoons to the southwest of a given grid cell (within the 90-degree arc between south and west): the lagoons that would contribute to deposition of reduced N assuming air mass transport was strictly to the northeast. For each distance scenario, we assumed that 50% of transport and deposition is isotropic; that is, it occurs evenly in all directions. The other 50% is deposited in the 90-degree arc between north and east from each CAFO. Combining these two assumptions in our model gave 62.5% of transport toward the northeast, and the other 37.5% of transport in all other directions combined. We then accounted for the area over which deposition of reduced N may occur under each scenario by dividing the weighted count by the deposition area (area=πr^2, where r is 80, 160, or 400 km under the three scenarios, respectively). We report this predicted weighted count of lagoons within transport range as relative deposition intensity.

We performed the same analysis for 1 km^2 grid cells in the Albemarle-Pamlico Sound. We used digital data showing salinity zones for coastal water (NOAA, 1999) and only included polygons corresponding to the portion of the Albemarle-Pamlico Sound that falls in the mixing zone (5–25 parts per thousand salinity). We converted these polygons to a 1 km^2 grid and performed the same analysis as above. While the area analyzed includes the mesohaline zone (5–18 ppt salinity) where much riverine N is biologically filtered, the majority of the area analyzed is open sound, which is predicted be highly sensitive to direct atmospheric deposition of nitrogen (Paerl et al., 2002).

To test how sensitive our results were to the assumption that 50% of transport and deposition is anisotropic, we constructed a scenario in which 70% of transport and deposition occurs only between north and east, and the other 30% is isotropic from each CAFO. Under this assumption, 77.5% of transport and deposition occurs toward the northeast, and 22.5% occurs in all other directions combined.

Additionally, we examined variation among CAFOs in their potential direct deposition of reduced N to the Albemarle-Pamlico Sound. We calculated the surface area of the Sound that fell within each assumed deposition radius (80-, 160-, and 400-km) of each CAFO in the state. We did this analysis twice.

First, for each distance scenario, we summed the area of the Albemarle-Pamlico Sound that fell within the given transport radius, assuming transport and deposition of reduced N from each CAFO is isotropic. Then, we summed the area of the Albemarle-Pamlico Sound that falls within the transport radius only to the northeast of each CAFO (within the 90-degree arc between north and east).

3. Results

3.1. *Nitrogen production and ammonia emissions from livestock waste*

We calculated total nitrogen production and NH_3 emissions for each physiographic region across the state of North Carolina for cattle, swine, and poultry (Table 1). An examination of 2006 county livestock census data for North Carolina shows that there were 860,000 cattle, 9,500,000 swine and 805,701,000 poultry, including broiler chickens, other chickens, and turkeys (NCDA & CS, 2007). This census data highlights the disparity among population sizes of livestock — they are orders of magnitude apart. In addition, the nitrogen content of manure for all categories of poultry (12.17, 12.22, and 13.77 kg N t^{-1} manure for broiler chickens, other chickens, and turkeys, respectively) was at least two times higher than that of swine and cattle manure (breeder pig manure had the next highest nitrogen content, with 6.01 kg N t^{-1} manure). The estimated total nitrogen production from livestock in North Carolina was 494,000 t, approximately 75.0% of which was produced by poultry, followed by swine, then cattle.

The estimated total NH_3 emission from livestock in North Carolina was 134,000 t NH_3 yr^{-1} (Table 2). Swine contribute 78,000 t NH_3 yr^{-1} or 58% of emissions, followed by poultry (50,700 t NH_3 yr^{-1}; 38% of total) and cattle (5000 t NH_3 yr^{-1}; 4% of total), respectively. With respect to total statewide emissions, approximately 72% were generated in the Coastal Plain region for all livestock categories; over half (55%) of total emissions were generated by swine alone. Poultry accounted for 38% of emissions, with nearly equal amounts generated in the Piedmont and Coastal Plain regions.

Table 2 – Estimated regional annual NH_3 emissions (metric tons yr^{-1}) by animal category

Category	Mountains	Piedmont	Coastal plain
Cattle	1400	2900	710
Swine	995	3570	73,500
Poultry	6820	21,000	22,900
Total	9215	27,470	97,110

3.2. *Atmospheric transport of nitrogen from livestock waste lagoons*

Livestock operations in North Carolina are, on average, located 155 km from the nearest portion of the Albemarle-Pamlico Sound. Therefore, in our 160 km and 400 km dispersal scenarios, a majority of CAFOs are within transport distance to the Sound. To examine variation among CAFOs in their potential direct deposition of reduced N to the Albemarle-Pamlico Sound, we ranked each CAFO based on the area of the Sound within the modeled transport distance. In most scenarios, a relatively small percentage of CAFOs contributed disproportionately large atmospheric reduced N inputs to the Sound. Under the 160 km scenario, 70% of CAFOs were within transport distance to the Albemarle-Pamlico Sound, regardless of whether transport was assumed to be isotropic (Fig. 3a) or strictly toward the northeast (Fig. 3b). Furthermore, 22% of CAFOs were in deposition range of one-third or more of the Albemarle-Pamlico Sound when isotropic deposition was assumed (Fig. 3a), and 10% were in deposition range of one-third or more of the Sound when deposition toward the northeast only was assumed (Fig. 3b). In the 80 km scenario,

Table 1 – Estimated annual nitrogen production (metric tons yr^{-1}) by animal category and physiographic province for North Carolina

Category	N content (kg N t^{-1} manure)	Pop. size			Manure amt (metric tons)			Total N (metric tons)		
		M	P	CP	M	P	CP	M	P	CP
Swine										
Breeder	6.01	4317	31,863	940,275	9900	72,700	2,150,000	60	437	12,900
Grower/finisher	5.13	37,683	278,137	8,207,725	61,000	450,000	13,300,000	310	2300	68,200
Poultry										
Broiler chickens	12.17	131,000,000	358,500,000	259,500,000	4,310,000	11,810,000	8,546,000	52,450	143,700	104,000
Other chickens	12.22	4,352,000	9,921,000	4,928,000	199,000	455,000	226,000	2430	5560	2760
Turkeys	13.77	0	5,000,000	32,500,000	0	600,000	3,980,000	0	8000	54,810
Cattle										
Dairy milk	4.85	14,856	29,523	9989	300,000	600,000	200,000	1000	3000	1000
Heifers	2.75	32,414	64,414	21,793	214,000	427,000	140,000	590	1170	380
Beef										
Steer/bulls/calves	4.98	79,684	158,351	53,575	548,000	1,090,000	369,000	2730	5430	1840
Cows	4.97	108,046	214,713	72,644	1,000,000	2,000,000	800,000	5000	10,000	4000

*M = Mountain; P = Piedmont; CP = Coastal Plain. Nitrogen content values are from Kellogg et al., 2006.

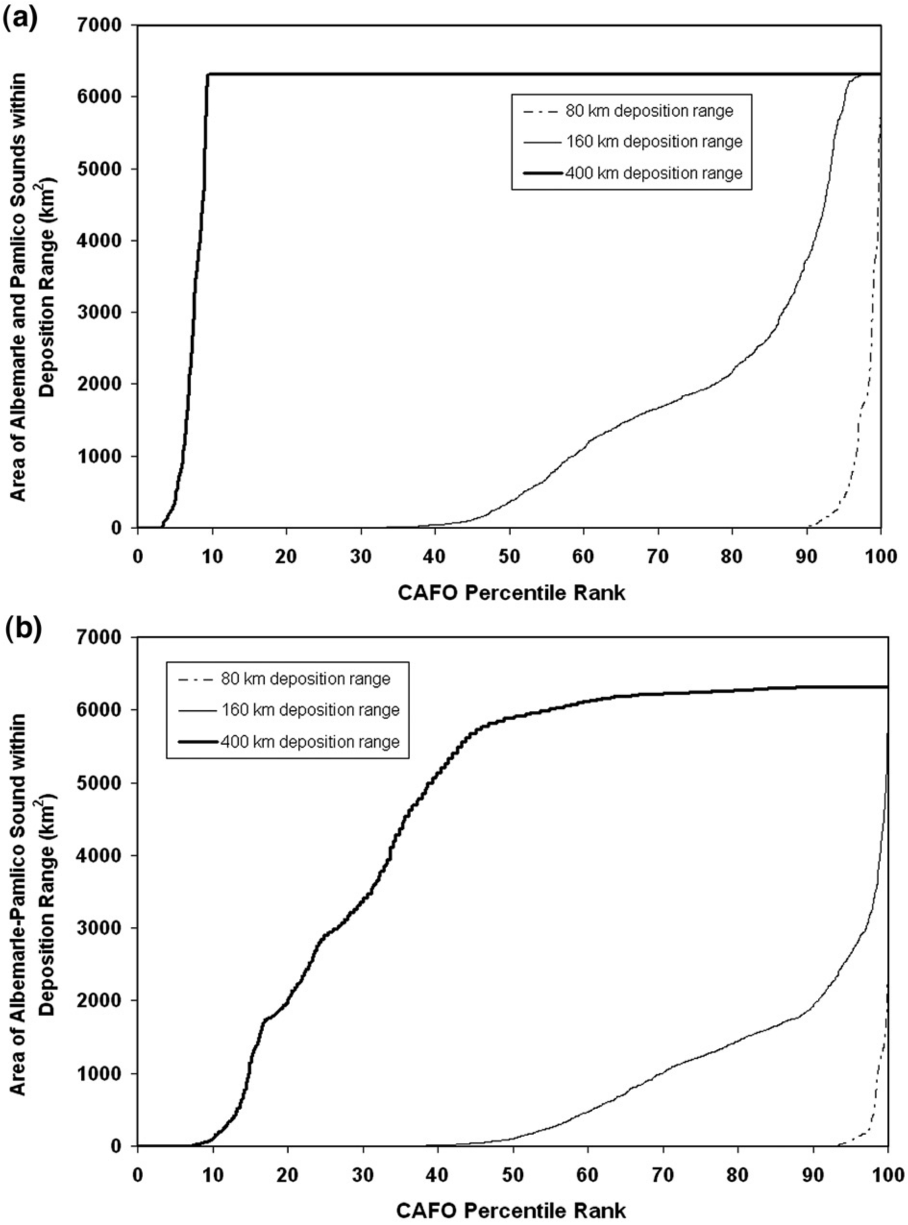

Fig. 3 – Area of the Albemarle-Pamlico Sound within atmospheric nitrogen deposition range of North Carolina CAFOs, for modeled transport distances of 80, 160, and 400 km, assuming (a) isotropic (omnidirectional) transport and deposition from each CAFO, and (b) anisotropic transport strictly toward the northeast of each CAFO.

only the 12% or 9% of CAFOs were within dispersal distance of the Albemarle-Pamlico Sound when isotropic or northeast transport and deposition are assumed, respectively (Fig. 3). Under the assumptions of 400 km transport distance and transport only toward the northeast, 55% of CAFOs were within deposition range of 93% of the Sound (Fig. 3b). In contrast to these five scenarios, under the assumptions of 400 km transport distance and isotropic transport, 90% of CAFOs were within deposition range of the entire Albemarle-Pamlico Sound (Fig. 3a).

We analyzed the spatial distribution of modeled relative deposition intensity both across the state of North Carolina, and within the Albemarle-Pamlico Sound specifically. For the 160 km transport scenario, portions of the Piedmont and Coastal Plain were contained within deposition range of up to 3356 lagoons (Fig. 4a). In addition, portions of the Albemarle-Pamlico Sound were within transport distance of 2645 lagoons. The 80 km scenario produced a qualitatively similar pattern with high relative deposition intensity on the Coastal Plain of North Carolina. Under this scenario (Fig. 4c), portions of the state were within the dispersal distance of up to 2494 lagoons. However, only 320 lagoons are within deposition range of the Albemarle-Pamlico Sound under this scenario (Fig. 4b). Under the short- and medium-distance scenarios, the areas of the state that received the bulk of the loading fall in several major watersheds, including the Tar-Pamlico, Neuse, and Cape Fear watersheds. Under our long-distance scenario, portions of North Carolina were contained within the airshed

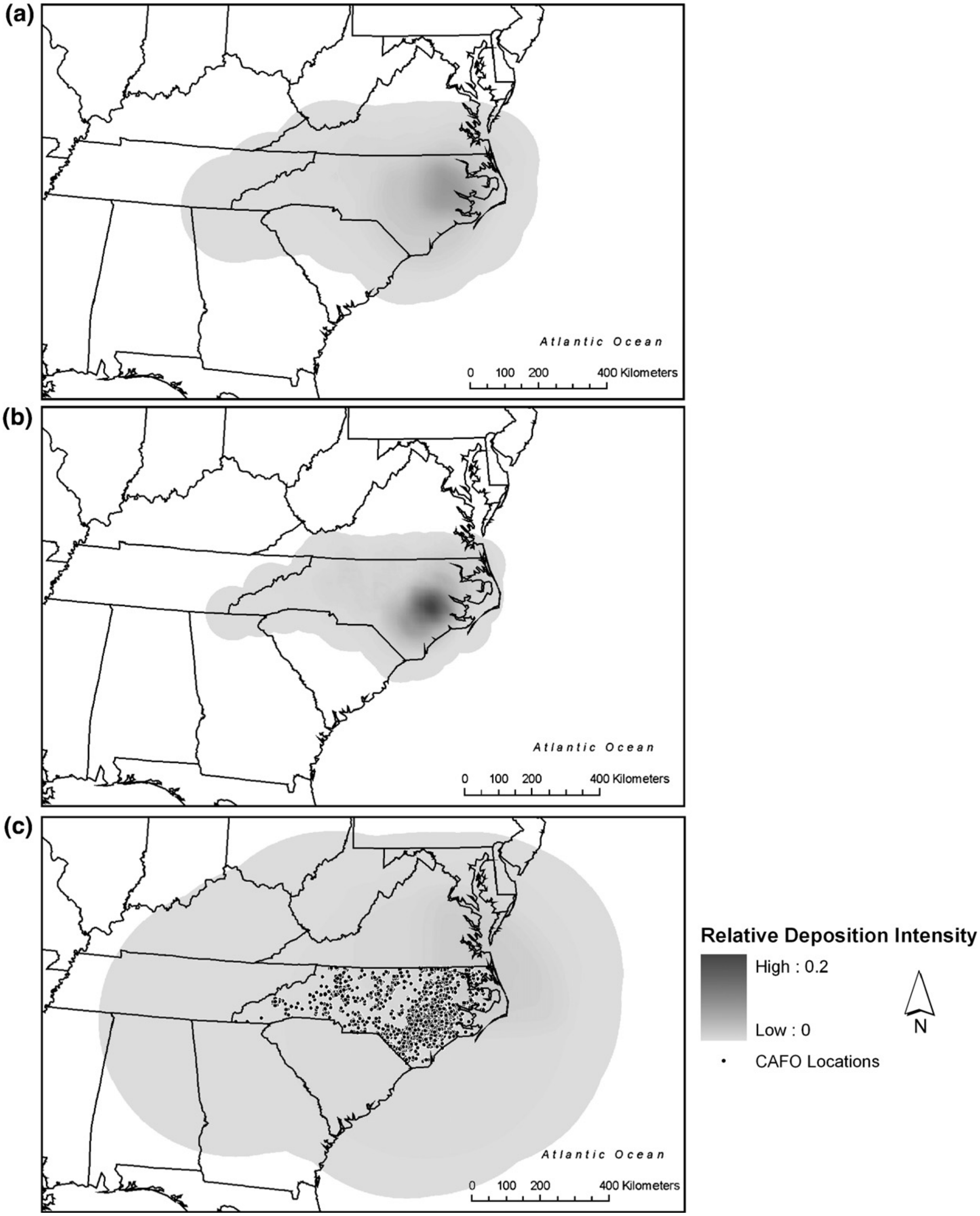

Fig. 4 – Relative deposition intensity for modeled transport distances of: (a) 160 km, (b) 80 km, (c) 400 km. Locations of CAFOs are shown in (c), but are not displayed for (a) and (b) because they would obscure the relative deposition intensity pattern shown on these maps. Atmospheric transport was assumed to be 50% isotropic, and 50% strictly to the northeast of CAFO lagoons.

of up to 3763 lagoons. Finally, we note that the maximum relative deposition intensity varied by an order of magnitude between the short- and long-distance transport scenarios. This is because the same quantity of ammonia emissions from the source is diluted over a larger deposition area as the deposition range is increased.

To further quantify the spatial concentration of reduced N deposition, we ranked each square kilometer of the state based on the number of CAFO lagoons within the modeled transport distance. Overall, we estimated that between 14% and 37% of the state potentially received 50% of atmospheric nitrogen deposition from CAFO lagoons (Fig. 5a). Therefore, a

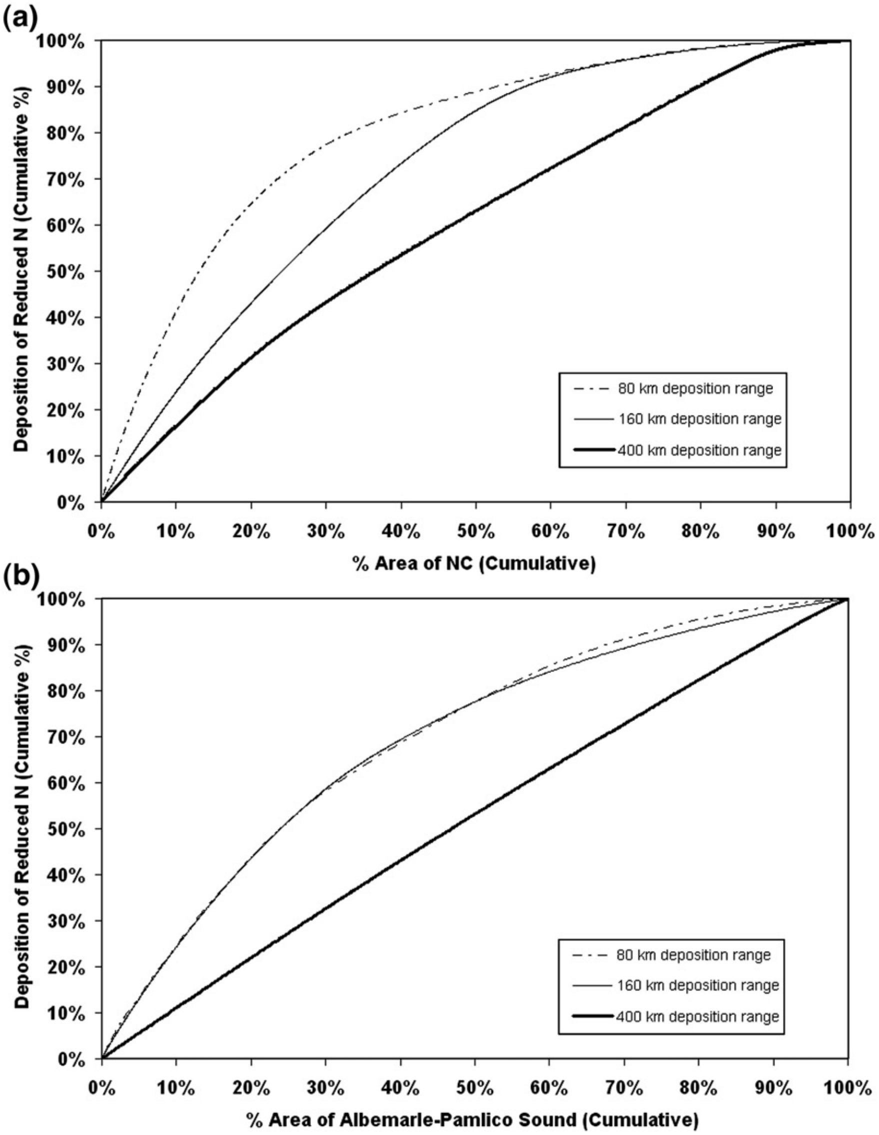

Fig. 5 – The cumulative spatial distribution of atmospheric reduced nitrogen deposition from CAFO lagoons, for modeled transport distances of 80, 160, and 400 km: (a) to North Carolina, and (b) to the Albemarle-Pamlico Sound from CAFO lagoons. Atmospheric transport was assumed to be 50% isotropic, and 50% strictly to the northeast of CAFO lagoons. Percentages are based on the total received by the state and the Sound, respectively.

small portion of the state potentially receives the bulk of the deposition. Under the 160 km scenario, 31% of reduced N may travel outside state boundaries, while in the 80 km scenario, only 10% of reduced N may travel outside state boundaries. However, assuming a 400 km transport distance, up to 77% of the total reduced N originating from CAFO lagoons may travel outside state boundaries. We also ranked each square kilometer of the Albemarle-Pamlico Sound based on the number of CAFO lagoons within transport distance. Between 24% and 47% of the Sound receives 50% of the atmospheric nitrogen deposition from CAFO lagoons (Fig. 5b).

When we modified our assumption of 50% anisotropic and 50% isotropic transport and deposition to 70/30% anisotropic/isotropic, we obtained similar results. Between 12% and 28% of the state potentially receives 50% of atmospheric N deposition from CAFO lagoons, and between 21% and 45% of the Albemarle-Pamlico Sound receives 50% of the deposition. Furthermore, between 10% and 78% of reduced N may travel outside state boundaries under the 80 km and 400 km scenarios, respectively, which is close to the range of values under the 50/50% assumption. Therefore, our results are not very sensitive to the assumption of 50/50% anisotropic/isotropic deposition and transport from CAFO lagoons.

Overall, the eastern portion of North Carolina had the highest number of waste lagoons within atmospheric transport distance regardless of the distance scenario assumed. This is not surprising considering the concentration of CAFOs in this region of the state. However, our results highlight the large number of lagoons within the deposition range of sensitive coastal systems, the concentration of the bulk of nitrogen inputs in a small fraction of the state, and the qualitative robustness of these patterns to variation in atmospheric nitrogen transport distance.

4. Discussion

Industrialized farming and CAFOs have replaced traditional farming practices by increasing livestock populations per farm, which also increases the amount and concentration of animal waste. Our results emphasize (a) the amount of nitrogen produced and emitted by livestock manure in industrialized farms in North Carolina, and (b) the significance of the spatial aggregation of CAFOs in the eastern portion of the state for patterns of atmospheric nitrogen deposition.

Much of the livestock feed originates from out-of-state sources (Cahoon et al., 1999). Thus, most of the nitrogen deposition from CAFOs originates from outside the state and represents a net input to the state's nutrient budget. Poultry contributes the largest percentage of total nitrogen production and is second only to swine in NH_3 emissions across the state of North Carolina. This resulted from both the size of the poultry population in North Carolina and the high nitrogen content in poultry manure. Poultry have significantly lower NH_3 emission rates than cattle and swine (Battye et al., 1994; Doorn et al., 2002), emphasizing the importance of livestock population size on NH_3 emissions. We examined the roles of livestock type and population size; however, NH_3 emissions are also influenced by farm facilities, waste management practices, and meteorological conditions (Battye et al., 1994).

Our results vary from other published figures. Mallin and Cahoon (2003) showed that swine were the top nitrogen producers on the Coastal Plain. However, our analysis also includes the state's Piedmont and Mountain physiographic regions (Table 2). Although swine may contribute the bulk of nitrogen when only CAFOs in the NC Coastal Plain are considered, our analysis includes the state's Piedmont, in which the bulk of poultry are produced. With the exception of poultry, our estimates are comparable with Mallin and Cahoon (2003) for the Coastal Plain region. The disparity for poultry appeared to result from our use of updated census data and animal waste nitrogen production rates.

Our analysis suggests that the aggregation of CAFOs on the Coastal Plain of North Carolina causes the majority of the reduced N deposition to be received by a small portion of the state's area, where aquatic systems are most abundant. In particular, the Albemarle-Pamlico Sound, which is vulnerable to direct deposition of reduced N, is located within transport range of the majority of CAFOs under our medium- and long-distance scenarios. These patterns highlight the relative magnitude of impacts from the aggregation of CAFOs, and underscore the importance of understanding transport distance and fate of NH_3 emitted from CAFOs.

We analyzed multiple scenarios regarding the atmospheric transport of reduced nitrogen originating from CAFOs, including short, medium, and long-distance transport, and varying degrees of isotropic vs. directional transport. Which of these scenarios is most realistic? Like all models, they are all caricatures of reality. Regional-scale atmospheric transport of nitrogen is complex (Walker et al., 2000; Dennis and Mather, 2001; Paerl et al., 2002) beyond what could be simultaneously applied to thousands of individually modeled sources. Deposition rates are higher closer to the source, declining with distance. Transport occurs via air mass movement, and thus is directional at a given time, but when averaged over a year occurs in all directions to some degree. Nonetheless, examining the consequences of different model assumptions begins to provide insight into these more complex processes. For example, while we assumed a constant deposition rate within the modeled transport distance, varying that distance allows some assessment of how deposition varies with distance from a source CAFO. Specifically, areas within the 80 km transport distance can be assumed to receive higher rates of deposition than those within the 160 km transport distance, which would receive higher rates than for the 400 km distance.

The analyses presented here are not intended to represent a detailed model of nitrogen deposition from CAFOs in North Carolina; rather, they are meant to explore the potential effects of a broad range of nitrogen transport scenarios from CAFOs. Our model examines general spatial patterns of potential transport of reduced N for all CAFOs throughout North Carolina, based on a few simple assumptions. First, we assume that all CAFOs and lagoons are equivalent, except in location. For discussion of variation among farms and lagoons, see Battye et al. (1994) and Aneja et al. (2001). Second, we assume that atmospheric reduced N occurs evenly over all landscapes and water types. In fact, the rate of deposition depends on water salinity and landcover type (Paerl et al., 2002). Airshed modeling (Dennis and Mather, 2001) and source-receptor modeling (Walker et al., 2000) have been able to examine in greater detail the transport distance of reduced N to and from a limited number of sites.

Nonetheless, the results of our GIS model agree qualitatively with NH_4^+ deposition maps developed by the NADP. NADP isopleth maps show a high amount of NH_4^+ wet deposition in southeastern North Carolina (NADP, 2006; see Fig. 2), corresponding to the area that is within transport distance of a high number of CAFO lagoons under our 80 km and 160 km transport scenarios (Fig. 4a,b). Our simplified model omitted many relevant factors. Thus, its ability to capture observed patterns of deposition suggests that observed regional patterns of reduced N deposition can be largely explained by the factors that it did include: limited atmospheric transport distance, and spatial aggregation of CAFOs.

We focused on one particular transport pathway in our analysis: atmospheric deposition of reduced N from North Carolina CAFO lagoons to the Albemarle-Pamlico Sound. This coastal system provides ecological goods and services to humans. In particular, it and its upstream estuaries provide a nursery for 80% of the fisheries on the mid-Atlantic U.S. coast (Copeland and Gray 1991). We did not directly consider other pathways such as surface runoff or groundwater transport from CAFO lagoons, riverine transport of nitrogen deposited to terrestrial ecosystems (Paerl et al., 2002), or other sources such as industrial wastewater effluent or agricultural and residential applications of synthetic fertilizers. However, due to the Sound's location downstream of the biological nitrogen sink in the mesohaline zone, direct deposition is likely to have a high impact on ecosystems there (Paerl et al., 2002).

Our analysis of the potential spatial distribution of CAFO reduced N deposition throughout North Carolina indicates that the highest deposition rates are in the eastern part of the state in the Neuse and Tar-Pamlico River watersheds, which are part of the Albemarle-Pamlico Estuarine System. These rivers are considered nutrient-sensitive waters by the State of

North Carolina (NCDENR DWQ, 2002b, 2004). In particular, the Neuse River is subject to the Neuse Basin Nutrient Sensitive Waters Management Strategy, which calls for a 30% reduction in total nitrogen entering the Neuse River Basin (NCDENR, 1997). Furthermore, the Neuse Estuary showed a 500% increase in NH^+ concentration over the period 1993–2004 (Burkholder et al., 2006). Over the same period, the estuary showed a significant decrease in bottom water dissolved oxygen (Burkholder et al., 2006), a phenomenon that can result from nutrient loading to streams (Mallin et al., 2004).

Although we have focused on the Albemarle-Pamlico Sound, our results also have implications for freshwater systems. According to our analysis, heavy deposition of reduced N occurs in and near the Northeast Cape Fear River. This is a blackwater river that has shown increases in NH_4^+ at monitoring stations (Mallin and Cahoon 2003; Burkholder et al., 2006). Experiments in blackwater rivers indicate that because algal production in these systems is N-limited, N additions can increase biochemical oxygen demand, leading to lower dissolved oxygen in these freshwater systems as well (Mallin et al., 2004).

We suggest that these previous findings in both estuarine and freshwater systems are a direct result of the spatial distribution of transport and deposition of reduced N from CAFOs we modeled here. Thus, the increase in direct atmospheric deposition to freshwater, estuarine, and coastal systems can result in significant ecosystem impacts. Overall, our analysis emphasizes the magnitude and spatial distribution of NH_3 production and deposition from CAFOs, a significant source of atmospheric reduced N in North Carolina.

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