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ORIGINAL ARTICLE

Hydrogen sulfide concentrations at three middle schools near industrial livestock facilities

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Safe school environments are essential for healthy development, yet some schools are near large-scale livestock facilities that emit air pollution. Hydrogen sulfide (H_2S) from decomposing manure is an indicator of livestock-related air pollution. We measured outdoor concentrations of H_2S at three public middle schools near livestock facilities in North Carolina. We used circular graphs to relate H_2S detection and wind direction to geospatial distributions of nearby livestock barns. We also used logistic and linear regression to model H_2S in relation to upwind, distance-weighted livestock barn area. Circular graphs suggested an association between upwind livestock barns and H_2S detection. The log-odds of H_2S detection per 1000 m^2 increased with upwind weighted swine barn area (School A: β-coefficient (β) = 0.43, SE = 0.06; School B: β = 0.64, SE = 0.24) and upwind weighted poultry barn area (School A: β = 0.05, SE = 0.01), with stronger associations during periods of atmospheric stability than atmospheric instability (School A stable: β = 0.69, SE = 0.11; School A unstable: β = 0.32, SE = 0.09). H_2S concentration also increased linearly with upwind swine barn area, with greater increases during stable atmospheric conditions (stable: β = 0.16 parts per billion (p.p.b.), SE = 0.01; unstable: β = 0.05 p.p.b., SE = 0.01). Off-site migration of pollutants from industrial livestock operations can decrease air quality at nearby schools.

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INTRODUCTION

A healthy school environment is important for both proper physiologic development and maximal educational performance. Children spend many hours each week at schools where pollutants can impact their health.[1,2] Schools in low-income communities of color are especially vulnerable to pollutants and there is a lack of federal policies in the United States to protect schools.[1,3] Good air quality is a key determinant of healthy school environments.

One source of air pollution in rural North Carolina (NC) is industrial livestock production facilities. Over the past several decades, the majority of livestock agriculture in NC and across the United States has shifted from small farms with relatively few livestock and complementary crop production to industrialized facilities with large barns housing thousands of animals in confinement. In NC, 99.8% of swine are produced at facilities selling at least 2000 swine annually, and 99.6% of broilers (meat chickens) are produced at facilities selling at least 30,000 broilers or more annually.[4] Such facilities are concentrated in Eastern NC, an area that includes the 10 most swine-dense counties in the United States.[5]

Although numerous studies indicate that children who grow up on farms have a lower incidence of allergy and asthma-related symptoms,[6,7] other studies have found detrimental effects from exposures related to industrial livestock production. Excess asthma-related outcomes have been associated with home exposures to swine facilities, especially among children growing up on swine farms that add antibiotics to feed for growth promotion.[8] In addition, children whose residences are frequently downwind of industrial swine facilities have increased prevalence of physician-diagnosed asthma and self-reported wheeze medication usage compared with children with lower relative swine facility exposures.[9] Several cross-sectional studies have reported excess asthma or asthma symptoms among children who attend schools near industrial swine facilities.[10,11] In NC, there are higher proportions of low-income children and children of color at schools near industrial swine facilities than at more distant schools.[12]

Livestock facilities produce a mixture of harmful pollutants, including hydrogen sulfide (H_2S), respirable particulate matter, and ammonia. H_2S is an odorous gas generated by anaerobic decomposition of manure[13,14] and can serve as a marker for this mixture. Ammonia, another odorant compound, is released from urinary urea and fecal urease enzymes in animal waste.[14] In addition, hundreds of volatile organic compounds (VOCs) contribute to characteristic malodors associated with concentrated animal feeding operations (CAFOs).[15] Particulate matter $< 10\,\mu m$ in aerodynamic diameter (PM_{10}) is generated directly from animal feed, fecal matter, dander, endotoxins, bacteria, and molds, as well as indirectly from gaseous emissions. Ammonia can react with acidic atmospheric species and form fine particulates.[13,14,16,17] The ventilation of barns, the storage of animal waste, and the spraying or spreading of waste on fields release these particles and gases into the air.

To further investigate school exposures, a team of researchers from the University of North Carolina at Chapel Hill (UNC) and

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members of the Rural Empowerment Association for Community Help (REACH) collaboratively developed the Rural Air Pollutants and Children's Health (RAPCH) study. We aimed to measure industrial livestock-related air quality at schools in rural eastern NC and potential associations with acute student health outcomes, while also providing educational benefits to students and their communities.[18] Here, we summarize the measured pollutant concentrations at school sites and quantify their relationships with the geospatial distributions of nearby industrial animal confinements and concurrent meteorological conditions.

MATERIALS AND METHODS

School Recruitment

In 2008, REACH staff contacted local school administrators and recruited four schools to participate in a pilot study to determine whether we could measure livestock-related pollutants onsite. In 2009, two schools from the pilot study plus a third school recruited by REACH were invited to participate in a longer exposure assessment study. After administrators approved participation, representatives from both REACH and UNC met with school staff to review study protocols and discuss logistics such as data collection schedules and placement of air quality monitors. The UNC institutional review board (IRB) annually reviewed and approved study activities.

Air Pollutant and Meteorological Data

We monitored H_2S and PM_{10} during three time periods in 2009: 21 February to 20 March, 28 March to 8 May, and 6 September to 25 November. Each sampling period lasted at least 4 weeks and consisted of measurements at a single school. We placed a set of active air monitors outside the school buildings at a site recommended by school staff. Instruments were stored in large cases with intake tubing for protection from tampering and weather.

We used MDA Scientific Single Point Monitors (SPMs) (Honeywell Analytics, Lincolnshire, IL, USA) to measure 15-min concentrations of H_2S in parts per billion (p.p.b.) at all three schools. The SPM had a limit of quantification (LOQ) of 1.0 p.p.b. determined via laboratory tests by UNC researchers (M Boundy, personal communication). At School A, we also deployed a more sensitive Thermo Hydrogen Sulfide—Sulfur Dioxide Analyzer (Thermo Fisher Scientific, Waltham, MA, USA) to measure H_2S alongside the SPM. The Thermo had recently become available for use and had an LOQ of 0.5 p.p.b. for 5-min concentrations, similar to the minimum reported odor threshold of 0.5 p.p.b.[19] For both H_2S monitors, we retained all detected values that were recorded, including those below the LOQ. We replaced non-detected values for the SPM with $LOQ/\sqrt{2}$.[20–22] For example, in 1 h with 15-min concentration readings of non-detect, 0.58, 1.85, and 3.52 p.p.b. from the SPM, we would have reported an hourly average H_2S concentration of $((1/\sqrt{2})+0.58+1.85+3.52)/4 = 1.66$ p.p.b. We also performed sensitivity analyses for SPM results in which all non-detected values were (1) replaced with 0, (2) replaced with LOQ/2, and (3) replaced with the LOQ.

We also used DustTrak Aerosol Monitors (TSI, Shoreview, MN, USA) to measure PM_{10} concentrations as low as 1 $\mu g/m^3$ every 5 min. Observed measurements were divided by 2.41 to account for the difference in light scatter between Arizona road dust, to which the DustTrak is calibrated, and particulates in rural eastern NC (J Tarman, unpublished results). REACH staff members checked instrument function almost daily and notified UNC staff of malfunctions for prompt resolution. Every week we downloaded data and performed quality control procedures, including using a high and low standard to verify the performance of the optical system. H_2S instruments were calibrated using varied H_2S permeation tubes with a range of concentrations (1.59, 3.28, 4.29, 6.19, 11.13, 54.2, and 75 p.p.b.) before deployment.

We obtained meteorological data for weather stations nearest to the schools from the online NC Climate Retrieval and Observations Network of the Southeast (CRONOS) database operated by the NC State Climate Office and NC State University. We used hourly data from two NC Environment and Climate Observing Network (ECONet) weather stations, assigning the closest weather station to each school (13.7–17.4 km away). We downloaded solar radiation, wind speed, and wind direction data. We used solar radiation and wind speed to generate hourly Pasquill–Gifford atmospheric stability categories ranging from A to F using the Solar radiation/delta-T (SRDT) method.[23] During the day—defined as time when solar radiation was >0 W/m^2—classification of atmospheric stability was based on solar radiation and wind speed (in m/s). During the night—defined as time when solar radiation was equal to 0 W/m^2—atmospheric stability classification was based solely on wind speed because data on vertical temperature gradient were not available. Using these measurements, we then collapsed categories to generate a binary atmospheric stability variable for every hour with categories A–C as "unstable" and categories D–F as "stable." We then created hourly records by merging pollutant concentrations, meteorological variables, and atmospheric stability class by date and hour.

Geospatial Data on Livestock Barn and Waste Lagoon Locations

There are no publicly available data with geospatial information for all livestock operations in NC. Therefore, we used high-resolution digital aerial imagery data (henceforth, orthoimagery)[24] to generate an original database containing information on the location and size of livestock barns and swine waste lagoons near the participating schools. We obtained complete orthoimagery for eastern NC through the NC OneMap Geospatial Portal,[25] a publicly available online source for geographic information systems (GIS) data. We downloaded tiled raster data (GeoTIFF format, 6-inch ground resolution) published online in December 2010 by the Geospatial and Technology Management Office in the NC Department of Crime Control and Public Safety;[26] no accurate orthoimagery for our study area was available before 2010. All data were referenced to the NC State Plane Coordinate System, NAD83, North American Datum, readjusted to the National Spatial Reference System of 2007. To integrate the NC OneMap orthoimagery with data for geocoded schools and weather stations, we created a file geodatabase in ArcGIS software, version 10.1, Service Pack 1 for Desktop.[27] We made a mosaic data set from the tiled raster data, compressed it using the LZ77 lossless method,[27] and used the closest equivalent spatial reference available in ArcGIS to overlay all data.

After establishing the geodatabase, we defined three distinct study areas by demarcating a circle with radius of 5 km around each school's geocoded central point; this 5-km radius corresponds to the documented distance H_2S can travel from large swine facilities[28] as well as the proximity of industrial livestock facilities in previous studies that documented excess asthma-related symptoms.[9,10] Within each school's surrounding 79-km^2 circle, we visually inspected orthoimagery in ArcGIS (at scale 1:15,000) to identify swine and poultry barns and swine waste lagoons.

We identified livestock barns based on their unique shapes and sizes, and by the presence of adjacent feed towers; we were careful not to include greenhouses, hoop houses, or storage sheds. We assumed any livestock barns without a nearby waste lagoon were poultry barns that typically use a dry waste system.[29] To convert the imagery to data on the size and location of each livestock barn, we manually added a polygon feature to the geodatabase (at scales ranging 1:200–1:800) over the boundary of each barn.

We identified swine waste lagoons based on their color, shape, size, and proximity to swine barns. Although farm ponds are common at swine facilities, their varied shapes and locations are easily distinguished from the standard border types for swine waste lagoons near barns. We used state permit data from NC Department of Environment and Natural Resources Division of Water Quality to ensure that we did not misclassify any poultry layer operations—which also produce liquid waste—as swine facilities. Just as we did for livestock barns, at scales ranging 1:200–1:2500, we encoded a polygon feature over the boundary of each swine waste lagoon. Using the polygons to represent barns and lagoons, we calculated the area of each barn and lagoon, as well as the location of the feature's centroid relative to its corresponding school.

Data Analysis

Lacking accurate data on the number and weight of animals at each facility during the study period, we used barn area, which typically reflect a standard density of animals, as a proxy for the intensity of pollution-generating activities. We used hourly measurements of meteorological conditions and time-fixed geospatial data on livestock barn locations to compute hourly values for inverse distance-weighted livestock barn area located upwind of each school. Our computations were based on a previously published method for generating an exposure index.[9]

Within the circle around each school defined by a 5-km radius, we measured the area of each barn, A, in m^2 and the distance, d, between the barn centroid and the school centroid in m. We computed the weighted area for each barn by multiplying its area by the inverse of distance-squared ($1/d^2$), assuming non-linear distance decay.[28] For each hour of the day, using compass directions in degrees (°) to characterize the average

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wind direction and barn locations, we defined upwind barns as those having a centroid within 15° of the average wind direction. Thus, for each school we computed hourly values for the sum of distance-weighted upwind barn area, $E(h)$, separately for swine and poultry barns as follows,

$$E(h) = \sum_{i=1}^{n} \frac{A_i}{d_i^2} I[w(h) - 15 \leq c_i < w(h) + 15]$$

where n is the number of barns around the school, A is the area of barn i, and d is the distance between the centroid of barn i and the school centroid. A barn centroid, c_i, has to fall within 15° of the hourly wind direction at hour h, $w(h)$, to contribute to the sum of distance-weighted upwind barn area. Therefore, $I[w(h)\text{-}15 \leqslant c_i < w(h)\text{+}15]$ returns a value of 1 if $w(h)$ is within 15° of c_i, else 0. To conceptualize this degree-based criterion using distance, the required proximity (in km of arc length) of a barn to the hourly wind direction is given by $15/360 \times 2\pi d$; for example, a barn $d = 3.6$ km from a school must be $\leqslant 0.94$ km from the hourly wind direction to contribute a detected value to that school's $E(h)$ measure in that hour.

For the circular graphs, we plotted the locations of swine and poultry barns within 5 km of each school, as described above, using ArcGIS software.[27] For clarity of display, we clustered barns together when located within 76.2 m (250 ft) of one another and represented the summed area of clustered barns with proportionately sized symbols. We categorized hourly average wind direction into 72 overlapping 30° categories, with the center of each subsequent category increasing 5°, for example, centered on 0° and ranging 345–15°, centered on 5° and ranging 350–20°, and so on. We then generated figures showing the wind rose for each school's data collection period. These show the relative frequency of average hourly wind directions and atmospheric stability for each direction, using 12 categories for wind direction for clarity of display. We generated a third series of figures showing the proportion of hourly records with $H_2S \geqslant$ LOQ, using 72 categories for wind direction. The wind rose and circular plots were generated using R software (R Foundation for Statistical Computing, Vienna, Austria) with the following packages: plotrix[30] and openair.[31]

We used logistic and linear regression models to compare upwind weighted barn area (independent variable) with measured H_2S concentrations (dependent variable). Dependent variables in logistic regression models were detection *versus* non-detection of H_2S detection *versus* non-detection (i.e., SPM: $\geqslant 1.0$ p.p.b. *versus* < 1.0 p.p.b.; Thermo: $\geqslant 0.5$ p.p.b. *versus* < 0.5 p.p.b.) in relation to upwind weighted barn area (per 1000 m^2 increase in barn area); these models were fit separately for swine and poultry barns.

For School A, where the Thermo instrument provided more sensitive H_2S detection, we also used linear regression to model changes in H_2S concentration (p.p.b.) in relation to upwind weighted barn area (per 1000 m^2 increase in barn area). For analysis at School A, we also ran separate models under each classification of atmospheric stability (i.e., stable and unstable), fit separately for swine and poultry barns. We used SAS software Version 9.3 (SAS Institute, Cary, NC, USA) to run regression models.

Because our study involved neither random sampling nor random allocation, results may be due to the factors under investigation, unmeasured factors, or measurement error, but not chance. Therefore, we do not report P-values or confidence intervals.[32,33] For logistic models, we report β-coefficients and SE; 95% confidence intervals can be calculated by adding and subtracting $1.96 \times$ SE from β. We also report χ^2 test statistics with 1 degree of freedom (d.f.). Higher χ^2 values indicate greater improvement in model fit upon addition of the variable for upwind weighted barn area; in a randomized study with 1 d.f., χ^2 values > 3.84 would indicate a two-tailed $P < 0.05$. For linear regression models we report β, SE, and t-values (i.e., β/SE) as indicators of improved model fit. With large sample sizes, as in this study using hourly measurements, t-values > 1.96 would approximate a two-tailed $P < 0.05$ in a randomized study.

Code availability. SAS code for computing distance-weighted upwind barn area and conducting regression analyses can be obtained by contacting the corresponding author.

Table 1. School exposure characteristics and student enrollment.

Characteristic	*School A*	*School B*	*School C*
Total number within 5 km			
Swine barns	95	68	68
Swine lagoons	29	31	29
Poultry barns	70	31	43
Total area within 5 km (1000 m^2)			
Swine barns	60.6	60.3	58.6
Swine lagoons	150.4	163.1	140.8
Poultry barns	130.5	70.3	67.5
Distance from schools (km)			
Swine barns			
Minimum	0.9	1.0	2.3
25th percentile	2.3	3.0	3.3
Median	2.7	3.9	4.1
75th percentile	4.3	4.6	4.4
Maximum	5.0	5.0	4.8
Swine lagoons			
Minimum	0.9	0.9	2.2
25th percentile	2.3	2.4	3.4
Median	3.0	3.2	4.3
75th percentile	4.4	4.6	4.6
Maximum	5.0	4.9	4.9
Poultry barns			
Minimum	0.5	1.0	1.9
25th percentile	2.8	3.4	3.9
Median	3.5	4.6	4.2
75th percentile	4.2	4.7	4.4
Maximum	4.9	4.8	4.9
Days of data collection	69	35	28
Hours of data collection	1588	798	648
Student enrollment for 2009–2010	428	493	223

RESULTS

School A had both the greatest number of livestock barns nearby and the closest barns (Table 1). Despite differences in total numbers, the cumulative swine barn area was similar across schools because individual swine barns around School A were smaller than around other schools (median: School A = 636 m^2; School B = 822 m^2; School C = 774 m^2). The ratio of total swine lagoon area to barn area was consistent across schools (range: 2.4–2.7). The larger total area of the poultry barns reflects their

Table 2. Frequency of hydrogen sulfide (H_2S) detection and mean hourly concentrations (p.p.b.).

School (instrument)	*Number of hourly records (N = 3034)*	*Number (%) of hours with $H_2S \geqslant LOQ$*[a]	*Mean (SE) concentration for hours with $H_2S \geqslant LOQ$ (p.p.b.)*[b]	*Number (%) of hours with detected H_2S*	*Mean (SE) concentration for hours with $H_2S > 0$ (p.p.b.)*[b]
School A (Thermo)	1325	764 (57.7)	0.79 (0.02)	1325 (100.0)	0.53 (0.02)
School A (SPM)	1546	94 (6.1)	1.35 (0.11)	533 (34.5)	0.81 (0.02)
School B (SPM)	797	5 (0.6)	1.12 (0.28)	67 (8.4)	0.71 (0.02)
School C (SPM)	647	25 (3.9)	1.26 (0.11)	204 (31.5)	0.78 (0.02)

[a]LOQ for Thermo was 0.5 p.p.b.; LOQ for SPM was 1.0 p.p.b. [b]Mean of observed detected measurements and, for the SPM, replacement of zeros with LOQ/$\sqrt{2}$.

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larger size per barn in comparison with standard swine barns (median: School A = 2032 m^2; School B = 2528 m^2; School C = 1383 m^2). The longest data collection period was at School A.

For most records, 15-min H_2S concentrations measured with the SPM were below the LOQ. Therefore, we present the number and percentage of hours with detected H_2S, followed by the mean concentrations only among these hours (Table 2). However, using the more sensitive Thermo at School A, 58% of hours had measured concentrations above the LOQ, and 100% of hours had mean concentrations >0 p.p.b. Schools' hourly mean concentrations were more similar when detected values below the LOQ were retained and non-detected values were replaced by LOQ/$\sqrt{2}$. SPM results were similar regardless of the method used to replace values below the LOQ.

Mean hourly PM_{10} concentrations ranged from 9.47 $\mu g/m^3$ (SE = 0.18) at School B to 12.74 $\mu g/m^3$ (SE = 0.24) at School C, and based on the 95th percentile the greatest hourly concentration was 29.15 $\mu g/m^3$ at School A. Hourly PM_{10} values were low, on average, and we observed little association with upwind livestock barn area in circular plots and regression models (data not shown).

Figure 1 shows data for School A regarding the geographic distribution of surrounding swine and poultry barns (Figure 1a), the wind rose demonstrating atmospheric stability measurements during data collection (Figure 1b), and the proportion of measurements with detected H_2S by direction based on the SPM (Figure 1c) and Thermo (Figure 1d) instruments. Swine and poultry barns were frequently collocated around School A, with most barns located to the southwest, south, and southeast of the school (Figure 1a). During the study period, the wind infrequently came from the directions with the greatest concentration of livestock barns (Figure 1b). Although there were relatively fewer livestock barns within 5 km northeast of the school, the wind most

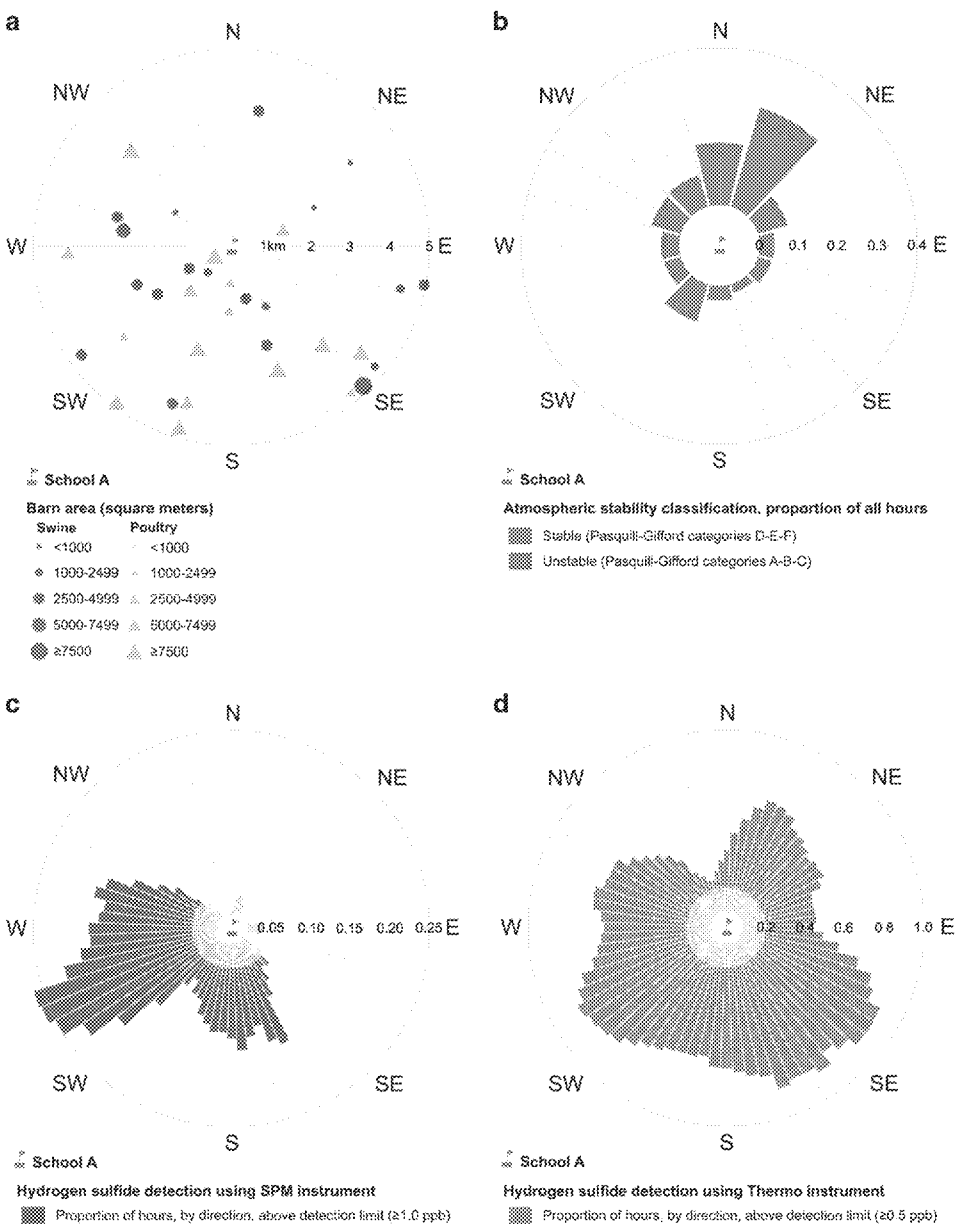

Figure 1. School A. (a) Livestock barns within 5 km, (b) wind rose and atmospheric stability by wind direction during data collection, (c) hydrogen sulfide detection ($\geqslant$1.0 p.p.b., SPM instrument) by wind direction, and (d) hydrogen sulfide detection ($\geqslant$0.5 p.p.b., Thermo instrument) by wind direction.

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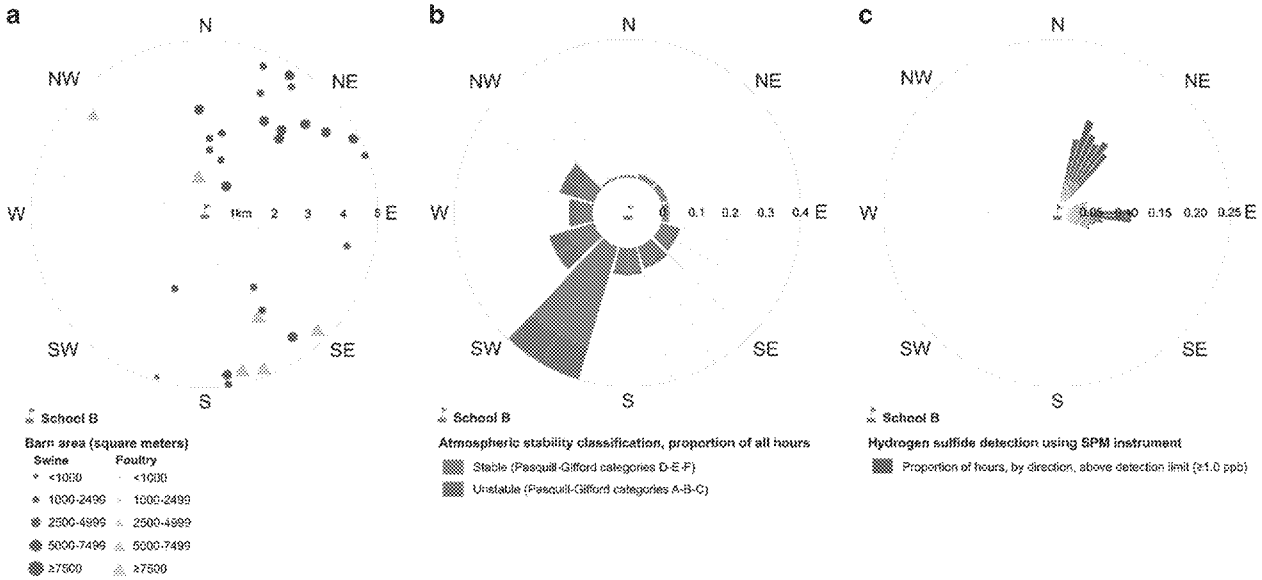

Figure 2. School B. (a) Livestock barns within 5 km, (b) wind rose and atmospheric stability by wind direction during data collection, and (c) hydrogen sulfide detection (⩾1.0 p.p.b., SPM instrument) by wind direction.

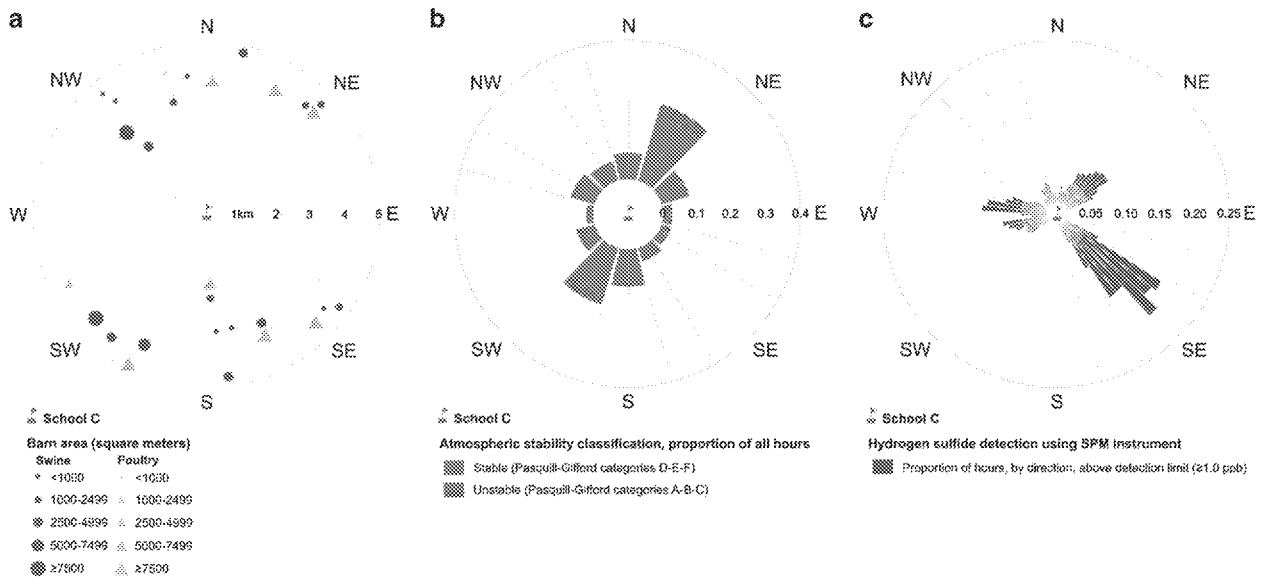

Figure 3. School C. (a) Livestock barns within 5 km, (b) wind rose and atmospheric stability by wind direction during data collection, and (c) hydrogen sulfide detection (⩾1.0 p.p.b., SPM instrument) by wind direction.

frequently came from that direction, sometimes with wind speeds >16 km/h (10 mph) (Figure 1b) that could facilitate the transport of pollutants and increase the occurrence of detected concentrations.[34] We observed a high proportion of records with detected H_2S ⩾ LOQ when the wind was from the southwest, south, and southeast (often in excess of 0.70, based on Thermo measurements). The proportion of hours with detected H_2S ⩾ LOQ was lower for the SPM instrument (Figure 1c) than the Thermo (Figure 1d). Using the Thermo instrument, we also observed a high proportion of records with detected H_2S ⩾ LOQ when the wind was coming from the northeast (Figure 1d).

For School B, most nearby swine barns were located in the northeast quadrant, several poultry barns were in the southeast, and few livestock barns were in close proximity to the school (Figure 2a). During data collection the wind mostly originated from the southwest (Figure 2b), an area with few livestock barns within 5 km (Figure 2a). Using the SPM, the proportion of measurements with detected H_2S ⩾ LOQ was very low (Figure 2c), measured during the infrequent hours when wind originated from the northeastern and eastern directions.

For School C, there were livestock barns toward both north and south, but none were less than 2 km from the school (Figure 3a). Wind direction was more evenly distributed for School C than for the other schools (Figure 3b). We observed lower proportions of SPM measurements with detected H_2S ⩾ 1.0 p.p.b. by wind direction at School C compared with SPM measurements at

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Table 3. Change in log odds of hydrogen sulfide (H_2S) detection per 1000 m^2 increase in upwind weighted livestock barn area at each school.

School (instrument)	*Swine*			*Poultry*		
	β	*SE*	*X^2 (1 d.f.)*	*β*	*SE*	*X^2 (1 d.f.)*
School A (Thermo)	0.43	0.06	46.00	0.05	0.01	24.84
School A (SPM)	0.43	0.05	66.82	0.07	0.01	61.10
School B (SPM)	0.64	0.24	6.96	−1.94	3.33	0.34
School C (SPM)	−0.94	0.69	1.88	−0.27	0.36	0.57

School A, and we did not see a consistent pattern between detected H_2S and upwind barn locations (Figure 3c).

In Table 3, we present the results of separate logistic models for swine and poultry barns that quantify relationships between H_2S detection (⩾ LOQ) and upwind weighted barn area. At School A, which had the longest data collection and the most sensitive H_2S instrument, the log-odds of H_2S detection increased by 0.43 (SE = 0.06) with each additional 1000 m^2 of upwind weighted swine barn area, and 0.05 (SE = 0.01) for each additional 1000 m^2 of upwind weighted poultry barn area. The large χ^2 values (1 d.f.) for these coefficients are indicative of the substantial contribution of upwind weighted livestock barn area to prediction of H_2S detection. The log-odds for upwind weighted swine barn area increased by 0.64 (SE = 0.24) at School B; upwind weighted poultry barn area was negatively associated with H_2S detection, but this relation was imprecise. Relationships for School C were negative but imprecise for both upwind swine and poultry area. We repeated these analyses including observed concentrations below the LOQ and replacing SPM 15-min non-detects with LOQ/$\sqrt{2}$; β-coefficients and SEs were within 0.01.

We also assessed relationships between upwind weighted barn area and H_2S concentrations across strata of atmospheric stability at School A, the only school with sufficient data for this analysis (Table 4). For swine barns, we observed a greater increase in log-odds of H_2S detection during stable conditions ($\beta = 0.69$, SE = 0.11) compared with unstable conditions ($\beta = 0.32$, SE = 0.09). Using linear regression to model H_2S concentration at School A, we found that an increase of 1000 m^2 of upwind weighted swine barn area was associated with an additional 0.16 p.p.b. of additional H_2S (SE = 0.01) during stable conditions; during unstable conditions, we observed an attenuated ($\beta = 0.05$ p.p.b., SE = 0.01) positive association between upwind weighted swine barn area and H_2S p.p.b. We observed similar patterns with upwind poultry barns, although the β-coefficients for increases in log-odds of H_2S detection and H_2S concentration were considerably smaller.

DISCUSSION

Ambient air pollution at schools is a particular concern for children because of their developmental susceptibility to pollutants and high breathing rates compared with adults.[35] Furthermore, during the academic year, children spend a substantial proportion of their waking hours at school. The concentration of livestock production since the mid-1900s has brought industrial air pollution problems, formerly the province of urban areas, to rural farming communities including public schools attended by a majority of children.

H_2S is one of many chemical compounds released by industrial livestock facilities. It is also emitted by other industrial facilities including petrochemical refineries, paper mills, wastewater treatment plants, and landfills;[36] however, it is not a ubiquitous regional pollutant. There are no other point sources of hydrogen sulfide within the 5-km radii around each school; the closest potential source is a wastewater treatment plant 10.1 km from one

Table 4. Change in log odds of hydrogen sulfide (H_2S) detection (using logistic regression) and change in H_2S concentration (using linear regression) per 1000 m^2 increase in upwind weighted livestock barn area at School A, stratified by atmospheric stability classification.

	Swine			*Poultry*		
Detection (⩾0.5 p.p.b.)	*β*	*SE*	*X^2 (1 d.f.)*	*β*	*SE*	*X^2 (1 d.f.)*
All stability categories	0.43	0.06	46.00	0.05	0.01	24.84
Stable	0.69	0.11	42.86	0.07	0.02	20.68
Unstable	0.32	0.09	12.84	0.05	0.01	11.96
Concentration (p.p.b.)	*β*	*SE*	*t-value*	*β*	*SE*	*t-value*
All stability categories	0.12	0.012	10.45	0.02	0.002	9.39
Stable	0.16	0.014	11.11	0.03	0.003	10.07
Unstable	0.05	0.011	4.28	0.01	0.002	4.30

All hydrogen sulfide data from the Thermo instrument.

of the study schools. Therefore, we consider detection of this compound as an indicator of the presence of livestock-related air pollution at school. Furthermore, using hourly concentrations and wind direction we demonstrated strong spatial and temporal associations between the size and distance of upwind livestock facilities and H_2S concentrations. Our analysis did not account for temporal autocorrelation between H_2S measurements. At the study school with the largest numbers of measurements and the more sensitive monitor, we found that associations between H_2S and upwind weighted barn area were stronger during stable compared with unstable atmospheric conditions. These data provide convincing evidence that upwind livestock facilities were the source of H_2S at the study schools.

H_2S is only one component of a complex mixture of gases and particles emitted by livestock facilities, including over 300 VOCs and ammonia.[13,15,16] H_2S concentrations were low outside of study schools, but indicated the presence of livestock-related plumes. H_2S concentrations have been used as a specific marker of the complex mixture of swine-related air pollution in studies of adult neighbors that have found H_2S to be related to reported hog odor,[34] mucous membrane irritation and respiratory symptoms,[37,38] stress and anxiety,[39] and increased blood pressure.[40] Because of its relatively low concentration and the co-occurrence of a large number of other pollutants, these effects on health and quality of life cannot be attributed to H_2S *per se*, but rather to the complex mixture of which H_2S is a part.

Although these studies have found harmful effects from air pollution exposures related to industrial livestock production, other studies have found livestock-related air pollution exposure to be protective, even in adults who do not live on farms.[41] One study found a lower prevalence of chronic obstructive pulmonary disease among adults living near farms, although adults already diagnosed with COPD were more likely to experience exacerbations.[42] Conflicting results may occur because of differences in livestock operation size, livestock production practices, microbial exposures, or susceptibility of nearby populations.

Although PM_{10} is another component of this mixture, we did not find it to be related to upwind weighted livestock barn area. There are several possible explanations for this finding. PM_{10} is a ubiquitous air pollutant that is not specific to livestock production. In addition to common stationary and mobile sources, PM_{10} arises from common agricultural activities including tilling, planting, fertilizing, harvesting, and burning. We did not have measures of these sources for the present study. Furthermore, gases can persist longer and travel farther than coarser particles.[13] The average hourly PM_{10} concentrations we observed (9.47–12.74 $\mu g/m^3$ across schools) are within range of expected values in this rural area. The closest US Environmental Protection Agency ambient air quality

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monitor reports 22 and 28 $\mu g/m^3$ as the annual second maximum 24 h average for 2009 and 2010 respectively.[43]

In this study we lacked measurements of many key variables that contribute to H_2S concentrations at schools. These include operating schedules at individual livestock facilities (use of ventilation fans, opening side walls, flushing liquid manure, or removing dry manure), three-dimensional wind speed and direction between the livestock facilities and schools, presence of barriers (like forests), and extent of oxidation of H_2S into sulfur dioxide (SO_2) and sulfate compounds.[36] Such information would potentially improve the modeling of H_2S concentrations at schools downwind of livestock facilities. Furthermore, we were not able to monitor H_2S for extended time periods (multiple seasons at each school), and the prominent wind directions during the study did not correspond to the directions of higher livestock density. This is not a reflection of the annual wind directions in the areas; rather, it is a consequence of the time periods of monitoring.

In conclusion, we detected H_2S, a signature livestock-related air pollutant, at school sites and found it to be associated with upwind livestock barn area. In the rural study area, which lacks other point sources of H_2S, this evidence shows that air pollution from industrial livestock operations reaches nearby public schools. H_2S serves as a marker for a complex mixture of emissions from livestock operations that may be harmful to the respiratory health and educational experience of children who live in communities in eastern NC. In addition, children attending these schools are disproportionately low-income students of color, and therefore these exposures constitute an environmental injustice. Future research should explore the impacts that school exposures to livestock-related air pollutants have on health and educational outcomes.

CONFLICT OF INTEREST

SW and JJ provided a report in a civil rights complaint regarding re-permitting of industrial hog operations in NC. SW provided a declaration for plaintiffs in federal suits regarding community exposures to industrial hog operation air pollution. Neither received nor expects any financial compensation for these activities. The other authors declare no conflict of interest.

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REFERENCES

1 Paulson J, Barnett C. Who's in charge of children's environmental health at school? *New Solut* 2010; **20**(1): 3–23.
2 Scammell MK, Levenstein C. School health and environment. *New Solut* 2010; **20**(1): 1–2.
3 Sampson N. Environmental justice at school: understanding research, policy, and practice to improve our children's health. *J Sch Health* 2012; **82**(5): 246–252.
4 United States Department of Agriculture. 2012 Census of Agriculture: North Carolina State and County Data. 2014; AC-12-A-51.
5 Hog density by county. Feedstuffs. 2010. Accessed 5 May 2015. Available at http://fdsmagissues.feedstuffs.com/fds/PastIssues/FDS8221/fds14_8221.pdf. and http://fdsmagissues.feedstuffs.com/fds/PastIssues/FDS8221/fds15_8221.pdf.
6 von Mutius E. 99th Dahlem conference on infection, inflammation and chronic inflammatory disorders: farm lifestyles and the hygiene hypothesis. *Clin Exp Immunol* 2010; **160**(1): 130–135.
7 Fuchs O, Genuneit J, Latzin P, Buchele G, Horak E, Loss G *et al.* Farming environments and childhood atopy, wheeze, lung function, and exhaled nitric oxide. *J Allergy Clin Immunol* 2012; **130**(2): 382–388.
8 Merchant JA, Naleway AL, Svendsen ER, Kelly KM, Burmeister LF, Stromquist AM *et al.* Asthma and farm exposures in a cohort of rural Iowa children. *Environ Health Perspect* 2005; **113**(3): 350–356.
9 Pavilonis BT, Sanderson WT, Merchant JA. Relative exposure to swine animal feeding operations and childhood asthma prevalence in an agricultural cohort. *Environ Res* 2013; **122**: 74–80.
10 Mirabelli MC, Wing S, Marshall SW, Wilcosky TC. Asthma symptoms among adolescents who attend public schools that are located near confined swine feeding operations. *Pediatrics* 2006; **118**(1): e66–e75.
11 Sigurdarson ST, Kline JN. School proximity to concentrated animal feeding operations and prevalence of asthma in students. *Chest* 2006; **129**(6): 1486–1491.
12 Mirabelli MC, Wing S, Marshall SW, Wilcosky TC. Race, poverty, and potential exposure of middle-school students to air emissions from confined swine feeding operations. *Environ Health Perspect* 2006; **114**(4): 591–596.
13 Iowa State University and the University of Iowa Study Group. Iowa Concentrated Animal Feeding Operations Air Quality Study. 2002. Accessed 17 May 2006. Available at http://www.public-health.uiowa.edu/ehsrc/cafostudy.htm.
14 National Research Council (NRC). *Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs*. National Academies Press: Washington, DC, 2003.
15 Schiffman SS, Bennett JL, Raymer JH. Quantification of odors and odorants from swine operations in North Carolina. *Agric For Meteorol* 2001; **108**(3): 213–240.
16 Aneja VP, Blunden J, James K, Schlesinger WH, Knighton R, Gilliam W *et al.* Ammonia assessment from agriculture: U.S. status and needs. *J Environ Qual* 2008; **37**(2): 515–520.
17 Cole D, Todd L, Wing S. Concentrated swine feeding operations and public health: a review of occupational and community health effects. *Environ Health Perspect* 2000; **108**(8): 685–699.
18 Guidry VT, Lowman A, Hall D, Baron D, Wing S. Challenges and benefits of conducting environmental justice research in a school setting. *New Solut* 2014; **24**(2): 153–170.
19 Wang XR, Pan LD, Zhang HX, Sun BX, Dai HL, Christiani DC. Follow-up study of respiratory health of newly-hired female cotton textile workers. *Am J Ind Med* 2002; **41**(2): 111–118.
20 Glass DC, Gray CN. Estimating mean exposures from censored data: exposure to benzene in the Australian petroleum industry. *Ann Occup Hyg* 2001; **45**(4): 275–282.
21 Helsel D. Much ado about next to nothing: incorporating nondetects in science. *Ann Occup Hyg* 2010; **54**(3): 257–262.
22 Hornung RW, Reed LD. Estimation of average concentration in the presence of nondetectable values. *Appl Occup Environ Hyg* 1990; **5**(1): 46–51.
23 U.S. Environmental Protection Agency (EPA). Meteorological Monitoring Guidance for Regulatory Modeling Applications. 2000; EPA-454/R-99-005.
24 NC OneMap. North Carolina Orthoimagery Program. 2013. Accessed 1 October 2013. Available at http://www.nconemap.com/OrthoimageryforNorthCarolina.aspx.
25 NC OneMap GeoSpatial Portal. 2010 North Carolina Statewide Digital Orthoimagery- Download. 2015; Available at http://data.nconemap.com/geoportal/catalog/search/resource/details.page?uuid={89BC136A-D247-4E7A-AB52-794CABED3F7E}.
26 North Carolina Center for Geographic Information and Analysis. North Carolina Statewide Orthoimagery 2010 Final Report. Durham, NC, 2011. Available at http://www.nconemap.com/Portals/7/documents/StatewideOrthoimagery2010_FinalReport.pdf.
27 Environmental Systems Research Institute (ESRI). ArcGIS Help 10.1—Mosaic dataset properties. 2013. Available at http://resources.arcgis.com/en/help/main/10.1/index.html#//009t00000038000000.
28 O'Shaughnessy PT, Altmaier R. Use of AERMOD to determine a hydrogen sulfide emission factor for swine operations by inverse modeling. *Atmos Environ* 2011; **45**(27): 4617–4625.
29 United States Environmental Protection Agency. Poultry production. 2012. Accessed 5 March 2015. Available at http://www.epa.gov.libproxy.lib.unc.edu/agriculture/ag101/printpoultry.html.
30 Lemon J. Plotrix: a package in the red light district of R. *R-News* 2006; **6**(4): 8–12.
31 Carslaw D, Ropkins K2015 openair: open-source tools for the analysis of air pollution data. R package version 1.5. Available at http://CRAN.R-project.org/package=openair.

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32 Greenland S. Randomization, statistics, and causal inference. *Epidemiology* 1990; **1**(6): 421–429.
33 Rothman KJ. Statistics in nonrandomized studies. *Epidemiology* 1990; **1**(6): 417–418.
34 Wing S, Horton RA, Marshall SW, Thu K, Tajik M, Schinasi L *et al.* Air pollution and odor in communities near industrial swine operations. *Environ Health Perspect* 2008; **116**(10): 1362–1368.
35 Schwartz J. Air pollution and children's health. *Pediatrics* 2004; **113**(4 Suppl): 1037–1043.
36 Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological profile for Hydrogen Sulfide/Carbonyl Sulfide (Draft for Public Comment) 2014.
37 Schinasi L, Horton RA, Guidry VT, Wing S, Marshall SW, Morland KB. Air pollution, lung function, and physical symptoms in communities near concentrated Swine feeding operations. *Epidemiology* 2011; **22**(2): 208–215.
38 Schiffman SS, Studwell CE, Landerman LR, Berman K, Sundy JS. Symptomatic effects of exposure to diluted air sampled from a swine confinement atmosphere on healthy human subjects. *Environ Health Perspect* 2005; **113**(5): 567–576.
39 Horton RA, Wing S, Marshall SW, Brownley KA. Malodor as a trigger of stress and negative mood in neighbors of industrial hog operations. *Am J Public Health* 2009; **99**(Suppl 3): S610–S615.
40 Wing S, Horton RA, Rose KM. Air pollution from industrial swine operations and blood pressure of neighboring residents. *Environ Health Perspect* 2013; **121**(1): 92–96.
41 Smit LA, Hooiveld M, van der Sman-de Beer F, Opstal-van Winden AW, Beekhuizen J, Wouters IM *et al.* Air pollution from livestock farms, and asthma, allergic rhinitis and COPD among neighbouring residents. *Occup Environ Med* 2014; **71**(2): 134–140.
42 Borlee F, Yzermans CJ, van Dijk CE, Heederik D, Smit LA. Increased respiratory symptoms in COPD patients living in the vicinity of livestock farms. *Eur Respir J* 2015; **46**(6): 1605–1614.
43 U.S. Environmental Protection Agency (EPA). Air trends: particulate matter. 2015. Accessed 10 November 2015. Available at http://www3.epa.gov/airtrends/pm.html.

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