Air Pollution and Odor in Communities Near Industrial Swine Operations

Steve Wing,¹ Rachel Avery Horton,¹ Stephen W. Marshall,¹ Kendall Thu,² Mansoureh Tajik,³ Leah Schinasi,¹ Susan S. Schiffman⁴

¹Department of Epidemiology
School of Public Health
University of North Carolina

²Department of Anthropology
Northern Illinois University

³Department of Health and Sustainability
University of Massachusetts Lowell

⁴Department of Psychiatry
Duke University

Corresponding author:

Steve Wing
2101F McGavran-Greenberg Hall
Department of Epidemiology
School of Public Health, CB# 7435
University of North Carolina
Chapel Hill, NC 27599-7435
Phone: 919-966-7416
Fax: 919-966-2089
steve_wing@unc.edu
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Abbreviations:

CAFO: concentrated animal feeding operation
H2S: hydrogen sulfide
mph: miles per hour
PM: particulate matter
ppm: parts per million
ppb: parts per billion
SAS: Statistical Analysis System
Section Headers:

Abstract

Introduction

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Abstract

Background: Odors can affect health and quality of life. Industrialized animal agriculture creates odorant compounds that are components of a mixture of agents which could trigger symptoms reported by neighbors of livestock operations.

Objective: We quantified swine odor episodes reported by neighbors and their relationships with environmental measurements.

Methods: Between September 2003 and September 2005 101 non-smoking volunteers living within 1.5 miles of industrial swine operations in 16 neighborhoods in eastern North Carolina completed twice-daily odor diaries for approximately two weeks. Meteorological conditions, hydrogen sulfide, and PM$_{10}$ were monitored in each neighborhood. Mixed models were used to partition odor variance within and between people and between neighborhoods, and to quantify relationships between environmental factors and odor.

Results: Participants reported 1,655 episodes of swine odor. In 9 neighborhoods odor was reported on more than half of study-days. Odor ratings were related to temperature, PM$_{10}$, and semi-volatile PM$_{10}$ in standard but not mixed models. In mixed models odor increased an average of 0.15 (standard error $\pm$ 0.05) units for one ppb increase in hydrogen sulfide, and 0.45 ($\pm$0.14) units for 10 $\mu$g/m$^3$ increase in PM$_{10}$ at wind speeds above 6.75 mph. The odds of reporting a change in daily activities due to odor increased 62% for each unit increase in average odor during the prior 12 hours (t-value=7.17).

Conclusions: This study indicates that malodor from swine operations is commonly present in these communities and that the odors reported by neighbors are related to objective environmental measurements and interruption of activities of daily life.
Introduction

There is a long history of medical interest in the health impacts of environmental malodor, from Hippocrates to William Farr, England’s first Registrar General. In recent decades, scientific consideration of the health consequences of malodors has increased in the context of residential exposures to malodors from municipal solid waste landfills, waste water treatment, land application of treated sewage sludge, industrialized animal operations, and the production, storage and transport of industrial chemicals (Schiffman et al. 2000). Environmental malodors may prompt reports of annoyance, worry, and physical symptoms (Shusterman 2001). The extent to which malodor is an aesthetic issue vs. a threat to health is a subject of scientific investigation and litigation that has important implications for environmental regulation, public health, and environmental justice (Thu 1998).

Odorant compounds can impact human health via several mechanisms (Schiffman et al. 2000; Shusterman 1992). First, at concentrations high enough to stimulate the trigeminal nerve, odorant chemicals may produce irritation of the eyes, nose, and throat, or other toxicological effects. In this case, the toxicological properties of the odorous molecules, rather than odor, produce symptoms. Second, via innate aversion, conditioning, or stress responses, odorant compounds can induce symptoms such as nausea, vomiting, headaches, stress, negative mood, and a stinging sensation at concentrations higher than the olfactory nerve threshold but below the trigeminal nerve threshold (Schiffman et al. 2000; Schiffman 1998; Shusterman 1992; Shusterman 2001; Shusterman et al. 1991). Third, symptoms occurring in response to odorant mixtures may be due to a non-odorant component such as endotoxin, which can induce inflammation and airflow obstruction (Kline et al. 1999).
Odors may be quantified in natural settings or by laboratory analysis of ambient air samples using trained odor panels, scentometers, olfactometers, or electronic noses (Schiffman et al. 2001; Schiffman et al. 2005); however, transient and unpredictable odors are difficult to quantify. Although spontaneous reports of malodor may be quantified (e.g., Aitken and Okun 1992; Drew et al. 2007), this approach mixes variation in odor with variation in people’s propensities to report odors and the limited availability of public agencies or researchers to track reports.

Research on malodors from concentrated animal feeding operations (CAFOs) and their consequences for the health and quality of life of nearby neighbors has increased with expansion of industrial animal agriculture. Recent studies report that CAFO neighbors experience elevated levels of gastrointestinal and respiratory tract symptoms (Thu et al. 1997; Wing and Wolf 2000), wheezing and asthma (Merchant et al. 2005; Mirabelli et al. 2006; Radon et al. 2007), and decreased secretion of salivary immunoglobulin A during episodes of high odor (Avery et al. 2004). Research on malodor is of interest in the context of broader impacts of industrial livestock production on energy use, diet, air and water pollution, and occupational health and safety (Donham et al. 2007; Thu 2002).

The purpose of this paper is to quantify reports of hog odors made by neighbors of swine CAFOs. To address a common limitation of research into connections between odor and health based on self-report without objective measures, we measured hydrogen sulfide, a product of anaerobic decomposition of hog waste, and PM$_{10}$, which can transport odorant chemicals (Bottcher 2001), while participants rated odor levels. Swine CAFOs are located disproportionately in low income communities of color (Wilson et al. 2002; Wing et al. 2000) where fear of reprisals and community discord may discourage residents from reporting
malodors and health concerns to health or environmental officials (Wing 2002), limiting the possibility of obtaining data about odor from public records. The Community Health Effects of Industrial Hog Operations study used community-based participatory research methods to increase the completeness and quality of data collection while promoting community organizing for environmental justice (Wing et al. 2007).

**Materials and Methods**

*Setting and data collection.* From September 2003 through September 2005 we collected data in eastern North Carolina, an area with one of the world’s highest densities of swine production. Volunteers were recruited through community based organizations. Non-smoking adults aged 18+ who lived within 1.5 miles of at least one swine CAFO and had a freezer in their home (for storage of saliva samples) were eligible to be enrolled. Participants in each neighborhood attended a structured training session at which they practiced data collection activities. Odor sensitivity threshold was evaluated by asking participants to choose which of two vials had an odor; one vial was distilled water and the other contained butanol. Participants were presented up to 12 pairs of vials in series. The concentration of butanol increased two-fold with each successive pair, beginning with 10 ppm. Odor sensitivity was defined as the lowest concentration of a series of five correct choices.

Twice daily for two weeks (three neighborhoods chose to continue up to seven additional days) participants sat outside their homes for 10 minutes at times agreed upon during the training session, usually morning and evening. They used a structured diary to report levels of hog odor and information about health and quality of life. During their 10 minutes outside participants were asked to recall levels of hog odor inside at home, outside at home, and away from home for each hour of the day since their last diary entry. In this paper we examine ratings of *hourly*
outdoor odor and hourly indoor odor reported in this portion of the diary. Participants also rated the current strength of hog odor at the end of the 10-minute period. We analyze these twice-daily odor ratings, which were made in the same locations at pre-selected times of day, in relation to odor sensitivity and environmental variables. Odor was rated on a 9-point scale from 0 (none) to 8 (very strong). Participants also indicated whether they had changed activities or decided not to do something because of hog odor.

We placed a small farm trailer with air monitoring equipment in each neighborhood. Locations were chosen to be as inconspicuous as possible but free from trees or structures that could affect air flow. A Rupprecht & Patashnick Tapered Element Oscillating Microbalance Series 1400a Ambient Particulate Monitor (TEOM) with a Series 8500 FDMS Filter Dynamics Measurement System (Rupprecht and Patashnick Co, Inc., East Greenbush, NY) was used to record hourly values of PM$_{10}$ and semi-volatile PM$_{10}$. These were updated every 6 minutes. An MDA Scientific Single Point Monitor (Zellweger Analytics, Inc., North America, Lincolnshire, IL) provided concentrations of hydrogen sulfide (ppb) averaged over 15 minute intervals. Temperature, humidity, wind speed and wind direction were recorded every 10 minutes with a Vantage Pro Weather Station (Davis Instruments, Hayward, CA), and every 30 minutes with a Young Model 05103VM-42 Wind Monitor (R.M. Young Company, Traverse City, MI). The Davis wind speed data were more complete but the instrument was less sensitive, with values about 2 mph lower than the Young monitor. To fill in missing data from each machine, values from the two machines were collectively categorized as low ($\leq$0.57 mph), medium (0.58 – 6.75 mph), or high (>6.75 mph). In about three percent of records weather parameter values were missing for both instruments, and data were obtained from the nearest airport weather station.
In each neighborhood a local "community monitor" was shown how to check the operation status of the monitoring equipment and was asked to call research staff on a toll-free line to report any outage or error message. In 12 neighborhoods a study participant served in this capacity.

The number of swine CAFOs within two miles of the monitoring platform was calculated using latitude and longitude coordinates derived from on-line satellite imagery and operating permits issued by the NC Division of Water Quality. We counted operations within two miles because odor reports are made from that far away and because that distance has been used in previous research (Thu et al. 1997; Wing and Wolf 2000). Coordinates for the monitoring trailer and each participant’s home were determined using a hand-held global positioning system device.

The study protocol and survey instruments were approved by the University of North Carolina’s Institutional Review Board for research involving human subjects following input and approval from the Concerned Citizens of Tillery’s Community Research Advisory Board. We obtained a Certificate of Confidentiality from the National Institutes of Health because of legal measures taken by the NC Pork Council to obtain identifiable participant information from a prior study.

Statistical analysis. Relationships between environmental measurements and twice-daily odor were evaluated by stratification, standard linear regression, and linear mixed models. The sample sizes for these analyses varied based on the numbers of missing values for environmental measurements. Although hog odor ratings were highly right-skewed, the number of observations was adequate to produce normal sampling distributions for the regression coefficients (Lumley et al. 2002); therefore untransformed odor was considered as a continuous dependent variable in
our linear regression models. Hourly average hydrogen sulfide, temperature, humidity, and wind speed for hours centered at the time of sitting outside were considered as predictors of odor.

Mixed models with twice-daily odor as the dependent variable and environmental measures as independent variables were fit using the SAS MIXED procedure to account for variance within people, between people, and between neighborhoods. Akaike Information Criterion (AIC) statistics for fixed-slope and random-slope models were compared, and models with lower AIC statistics were chosen for presentation. We fit models with intercepts when the only predictor of odor is coded as an indicator variable, providing a test of the difference between the omitted category and the other category or categories. For models with the interaction of a variable coded as continuous and one coded as an indicator, we fit models with no intercept in order to provide an estimate of the effect of the continuous variable, its standard error, and a test of difference from zero, at each level of the indicator variable.

For analyses of activity limitation as the dependent variable we used mixed logistic regression. Average hourly outdoor odor since the previous diary entry was the independent variable. Models were fitted using the SAS GLIMMIX procedure. Random intercepts and fixed effects of average odor ratings of 1 to <2, 2 to <3, 3 to <5, and 5 or higher, compared to no odor, were estimated as predictors of activity limitation due to odor, coded as a 0/1 variable. A model was also fit with average hourly odor as a continuous variable.

Standard errors of regression coefficients are presented as measures of precision. Contributions of predictors to the fit of models were assessed by t-tests. Test statistics are presented instead of p-values because this is not a randomized study (Greenland 1990).

**Results**
Neighborhood and participant characteristics. 102 volunteers from 16 neighborhoods enrolled in the study. One person who had difficulty with the study protocol was excluded from analyses. Analyses here include 84 people who collected data for two weeks, 15 (from three neighborhoods) who chose to continue an additional four to seven days, and two who stopped before two weeks. Sixty-six women and 35 men participated. Age ranged from 19 to 89 years; mean age was 53. Eighty-four participants identified themselves as Black, 15 as White, one as Black/Native American, and one as Latino.

Characteristics of study neighborhoods, labeled A through P, are given in Table 1. Two neighborhoods had one swine CAFO within two miles of the monitoring trailer while six neighborhoods had 10 or more within two miles. Approximately two-thirds of participants lived in neighborhoods within two miles of five or more swine CAFOs. In nine neighborhoods participants reported outdoor swine odor on more than half the study days. Mean temperature on study days ranged from 47°F in neighborhood A to 82°F in neighborhood K; no neighborhoods participated during January. Mean hydrogen sulfide was 0.004 ppb in neighborhood E, where 99.8% of readings were below the detection limit (2 ppb) and 99.8% of values were below detection. Neighborhoods O and C had the highest mean values, 1.02 and 1.48 ppb, respectively, and the highest values recorded in neighborhood O were at the upper limit of detection, 90 ppb. Average PM$_{10}$ varied from 10.8 $\mu$g/m$^3$ in neighborhood A to 28.7 $\mu$g/m$^3$ in neighborhoods C and E, whereas semi-volatile PM$_{10}$ was highest, 9.2 $\mu$g/m$^3$ in neighborhood O and lowest in H, where it was -3.2 $\mu$g/m$^3$, indicating the high degree of measurement error when using the microbalance to characterize semi-volatile particle levels over short time periods.

Frequency, magnitude and duration of odor episodes. We calculated the average daily odor that participants reported following the twice-daily pre-selected 10-minute periods of sitting
outdoors, and the average hourly outdoor odor reported each day. Study participants collected data on 1,495 days although twice-daily odor was missing for 39 of these days. Results for the 1,456 days with twice-daily odor information are reported here (Table 2). Average twice-daily odor was zero for 563 days (38.7%), and greater than 5 on 51 days (3.5%). Average hourly outdoor odor was zero for 591 days (40.6%) and greater than 5 on 33 days (2.3%). Average twice-daily odor was zero on fewer days than average hourly odor. This is possible because participants could report non-zero odor during twice-daily times sitting outdoors when there was no odor at other times during the hour.

Reported hourly outdoor odor was highest in the mornings and evenings and lowest in the middle of the day and night (Figure 1). Morning odor was highest during the 3 AM hour (mean=1.7) when 12.2% of ratings were five or greater. Mean odor was 2.1 during the 8 PM hour, when 19.2% of odor ratings were five or greater.

Based on hourly outdoor odor ratings, participants reported 1,655 odor episodes (Table 3). The duration of an episode is the number of consecutive hours that swine odor was reported to be above zero. The majority of episodes (62.1%) lasted one hour, whereas 9 episodes (0.5%) lasted 9 hours or longer. Average odor was less than 2 for about 39% and greater than 5 for about 16% of odor episodes lasting one or two hours. Average strength was 5 or greater for more than 21% of odor episodes of three hours or more.

Hog odor was reported inside homes on 185 of 1,456 person-days of follow-up (12.5%). There were 500 episodes of indoor hourly odor, of which 233 (46.6%) lasted one hour, 179 (35.8%) lasted two to three hours, and 88 (17.6%) lasted four or more hours. Three of the one-hour indoor odor episodes, with odor levels of 3, 6 and 8, were reported in the middle of time
periods when consistent sleep was indicated, suggesting that odor interrupted participants’ sleep in the middle of the night.

Butanol odor sensitivity threshold was estimated for 98 participants, of whom 39 had a threshold of 10 or 20 ppm (Table 4). Most odor ratings were provided by people with butanol detection thresholds between 10 and 160 ppm. Average reported odor declined with sensitivity from 20 to 160 ppm. Among the 12 participants with odor thresholds of 320 and above there was not a clear relationship between odor sensitivity and average odor.

Environmental correlates of odor. Analyses of environmental correlates were based on the twice-daily odor ratings reported at pre-selected times of day when participants sat outdoors for 10-minutes. Table 5 provides results of bivariate simple linear regression models for each environmental variable as a predictor of 10-minute odor ratings. Odor ratings increase, on average, 0.26 (±0.02) for every 10°F increase in temperature; the t-test value is large (11.65). Odor ratings increased 0.17 (±0.02) for every ppb increase in hydrogen sulfide, 0.04 (±0.02) for a 10 µg/m³ increment in PM_{10}, 0.03 (±0.01) per µg/m³ of semi-volatile PM_{10}, and 0.06 (±0.02) for a 10% increase in relative humidity. Average odor at moderate wind speeds was 1.02. Compared to moderate wind speeds, odor was higher by 0.43 (±0.08) at low wind speeds, and higher by 0.72 (±0.15) at high wind speeds.

Temperature and semi-volatile PM_{10} showed little association with 10-minute odor ratings as main effects in mixed models (data not shown). Table 6 presents effect parameters from mixed models with other environmental variables. The relationship between hydrogen sulfide and odor was best fit with a random intercept, random slope model, in which odor increased an average of 0.15 (±0.05) for every 1 ppb increase in hydrogen sulfide (t-value for hydrogen sulfide=3.10).
Because there is a strong main effect for hydrogen sulfide, we considered odor sensitivity as a modifier of its association with odor. Hydrogen sulfide was positively related to odor among participants with detection thresholds of 160 ppm and lower (0.17±0.06/ppb), but not among participants with thresholds of 320 ppm and greater (0.02±0.14/ppb).

The relationship between wind speed and odor was adequately fit with a random intercept, fixed slope model. Parameters for low and high wind speeds were estimated in mixed models with medium wind speed as the referent (Table 6). Average odor was lowest at medium wind speed (1.23±0.20). Compared to the odor at medium wind speed, odor was higher by 0.18 (±0.07) units at low wind speeds and by 0.38 (±0.13) units at high wind speeds.

Relationships between odor, hydrogen sulfide and PM$_{10}$ depended on wind speed (Table 6). A mixed model with fixed effects for wind speed and random effects for hydrogen sulfide showed that hydrogen sulfide and odor were not associated at medium wind speed (-0.09±0.10/ppb). At low wind speeds odor increased an average of 0.28 (±0.11)/ppb (t=2.49), and at high wind speed there was an increase of 0.77(±0.44) (t=1.75). In contrast, PM$_{10}$ was associated with odor at high wind speeds (0.45±0.14/10 µg/m$^3$, t=3.14), but not at low or medium wind speeds.

Activity limitation. On 118 occasions 34 participants reported that they cancelled or changed an activity because of hog odor. Typical changes included closing windows, avoiding sitting in the yard and socializing with friends, halting plans to barbecue, not putting clothes out to dry, declining exercise via outdoor walks, not putting up Christmas lights, not being able to garden or mow the lawn, not washing the car, or not being able to sit on the porch. One participant reported on two occasions that odor made it difficult to sleep. Whereas in other records this participant reported 6 to 8 hours of sleep during the previous night, on these 2
occasions he or she indicated having slept either 0 or 4 hours. The common theme in these disruptions was the adverse impact of odor on people’s social and personal space. There was an association between activity change and average outdoor odor intensity during the 12 hours prior to a diary record, with odor grouped into several levels (Table 7). Participants noted changes in activity due to odor from 1.4% of occasions when average odor was below 1.0 up to 16.2% when average odor was greater than or equal to 5.0. Estimates from logistic mixed models with random intercepts and a fixed slope for odor show a similar relationship; all model coefficients are substantially larger than their standard errors, and t-values are large. A separate model was estimated for odor as a continuous variable; the log odds ratio of activity change for a one-unit increase in odor is 0.48±0.07, a 62% increase in the odds of activity change per odor unit (t=7.17).

Discussion

In this study 101 participants from 16 neighborhoods in eastern North Carolina reported on levels of hog odor inside and outside their homes for approximately two weeks while temperature, humidity, wind speed, hydrogen sulfide, and PM10 were monitored nearby. The number of swine CAFOs within two miles of the location of the monitoring platform in each neighborhood ranged from 1 to 16. Odor was reported outside on more than half the study days in nine neighborhoods. Odor ratings made during 10-minute periods of sitting outside twice a day were associated with weather conditions, hydrogen sulfide, and PM10. One third of participants reported ceasing or changing their activities due to malodor, and the intensity of odors reported between diary entries was strongly associated with these reports. This study indicates that malodor from swine operations is commonly present in these communities and that the odors reported by neighbors are related to objective environmental measurements.
Neighborhoods were included in the study if at least several members were interested in participating in a two-week study that required a three-hour training session and a twice daily routine of reporting and measurement. Neither the neighborhoods nor participants are a representative or systematic sample of the region. We relied on local knowledge to select neighborhoods where hog odor had been reported to community organizers and where individuals might be interested in participating. However, there are more than 2,000 swine CAFOs in the region, and we had no way to identify those CAFOs with higher releases of odorant chemicals. Therefore, it is unlikely that neighborhoods with the highest exposures were included in this study. Furthermore, participants in several neighborhoods reported cessation or relocation of hog waste sprayers, and reduced odor, during their period of study participation.

Other analyses indicated that the completeness and consistency of data in this study were high (Schinasi 2007). Participants reported twice-daily odor ratings in 94% of 2,949 total journal entries and at least 1 such rating on 97% of 1,495 study days. On the 1,456 study days with at least 1 twice-daily odor rating, the mean and median percentages of hours of the day for which hourly odor ratings were provided were 96% and 100%, respectively. On 95% of study days, participants reported information on whether hog odor had altered their daily activities.

We evaluated the hypothetical possibility that, due to their access to the hydrogen sulfide monitor, odor ratings of 12 study participants who were asked to check for malfunctions with the environmental monitoring equipment could have been influenced by the value on the display screen; in this case the relationship between hydrogen sulfide and odor might be overestimated. We re-fit the random intercept, random slope model for hydrogen sulfide and odor excluding these 12 participants; the beta coefficient and its standard error rounded to the same values reported in Table 6.
Although the structured reporting of odor by neighbors of swine CAFOs is a strength of our study, the frequency, duration and intensity of reported hog odor episodes must be interpreted in the context of participants’ daily activity patterns. Participants reported being indoors at home 30.0%, outdoors at home 17.1%, away from home 25.5%, and sleeping 27.4% of hours in the study. The large proportion of time spent indoors and away from home limits information on outdoor odor episodes. The duration of outdoor odor episodes is also truncated by going indoors or away from home to avoid odor; this may contribute to the shorter duration of reported outdoor hourly odor episodes (62.1% lasted one hour) compared to indoor hourly odor (46.6% lasted one hour).

With the exception of PM\textsubscript{10} in higher wind conditions, temperature, PM\textsubscript{2.5}, and semivolatile PM\textsubscript{10} were correlated with hog odor ratings only if the within-person, between-person, and between-neighborhood structure of the data was ignored. This might reflect the lack of seasonal variation of these variables within neighborhoods sampled for only about two weeks. Hydrogen sulfide, in contrast, was strongly related to odor in mixed models. Unlike the weather variables, hydrogen sulfide levels varied markedly within neighborhoods. In a recent chamber experiment, naïve volunteers exposed to swine CAFO air with a 24 ppb concentration of hydrogen sulfide reported an average odor of 5.29 on a 0-8 scale (Schiffman et al. 2005). The predicted odor at 24 ppb in our study, based on the linear regression function from Table 4, odor=1.25+0.17*H\textsubscript{2}S(ppb), produces a similar value of 5.33.

In theory, a stronger relationship between odor ratings and the concentration of odorant compounds should have been observed among people with a better sense of smell. We considered butanol detection threshold as a modifier of the hydrogen sulfide effect because, unlike PM\textsubscript{10}, it was strongly associated with odor even without taking into account the modifying
effect of wind speed. The observation that this association was restricted to people with
detection thresholds below 320 ppm suggests that this simple threshold test distinguishes a
subgroup of participants (87.8%) who are more responsive to hydrogen sulfide.

The microbalance produced many negative values for semi-volatile PM$_{10}$, indicating
large measurement error relative to the semi-volatile particle signal. This reduced the power of
the study to detect associations between reported odor and semi-volatile compounds in particle
phase, including ammonia, an important odorant chemical emitted by swine CAFOs (Lim et al.
2003; Reynolds et al. 1997; Wilson and Serre 2007). We did not have the capacity to directly
measure ammonia or other odorant compounds for this study.

The presence of air pollution from swine CAFOs in neighboring communities depends on
wind direction and speed. We did not evaluate wind direction because there were at least several
CAFOs in different directions near most neighborhoods in the study. Wind speed was related to
odor and was also a modifier of relationships between air pollution levels and odor levels
reported by neighbors. Although odor was highest at high wind speeds, mean hydrogen sulfide
levels were lowest at high wind speeds (0.05 ppb) compared to medium (0.09 ppb) and low (0.45
ppb) wind speeds. Hydrogen sulfide was strongly related to odor at low wind speeds
(0.28±0.11/ppb). Although the point estimate of the odor-hydrogen sulfide relationship at high
wind speeds was very large (0.77), its standard error was also large (0.44), reflecting the limited
range of hydrogen sulfide values and smaller sample size at higher wind speeds.

In contrast, PM$_{10}$ was related to odor in mixed models only during periods of higher wind
speed. This observation is consistent with the greater capacity of stronger winds to transport
PM, and provides evidence that organic dusts from swine CAFOs may be inhaled by CAFO
neighbors during higher wind conditions. Although PM$_{10}$ is associated with a variety of health
outcomes, most studies have been conducted among populations where the composition of PM is largely affected by combustion by-products and urban dusts. Although PM from animal dander, dried feces, feed, pharmaceuticals, and micro-organisms is known to affect occupational health of workers in swine confinement buildings (Donham 1993; Donham et al. 2000; Donham et al. 1995; Donham 1990), its effect at lower levels and among non-worker populations is poorly understood.

Among the 98 participants who answered questions about residential history, 76 grew up on farms where they had experience with animal odors, and 82 had lived in their homes for more than five years. Thus, adaptation and loss of sensitivity to malodors from swine operations could have occurred. On the other hand, the study protocol prompted participants to pay attention to swine odors, thus, physiological adaptation or reduced attention to odor as a means of coping may have been offset by the odor reporting protocol. In considering the effects of odor, it is important to note that adaptation occurs most readily when there is little variation in the concentration of odorant chemicals, whereas swine odors are transient. Like other environmental agents that act as stressors, unpredictable acute odor episodes may cause more of a stress response in susceptible persons than non-episodic stressors.

The health significance of malodorous compounds is due, in part, to diseases related to pollutants such as PM that would occur even among persons with no sense of smell. However, malodor also should be considered in the context of scientific interest in endpoints that are not specific diseases. For example, biological markers of exposure to or effects of toxicants, genetic markers of susceptibility, and physiological states associated with increased risk of disease, are widely recognized as relevant to understanding and improving environmental health, even though they are not specific diseases. Similarly, environmental malodor is an important subject
for inquiry, not only because it may be involved in causation of specific diseases, but because of its potential to affect health, considered as not merely the absence of disease, but as a state of physical, mental and social well-being. Environmental malodors may be markers of agents that can produce inflammatory, immunological, infectious, or toxicological responses; additionally they may affect physical, mental and social well-being due to their psychological and cultural meaning (Schiffman et al. 2000). Odors that are viewed as unpleasant, embarrassing, or sickening, may interfere with mood, beneficial uses of property, and social activities that are central to quality of life.

We found that average odor over a 12-hour period relates strongly to changes in activities because of hog odor, and that odor may interrupt or limit sleep. Other studies have shown that the odor of feces and urine from liquid waste management systems can negatively impact neighbors’ quality of life. Among a subsample of participants in this study, odor was found to be related to levels of stress reported in daily diaries (Horton 2007). However, numerical relationships between hog odor and disrupted activity are insufficient to capture the full impacts of quality of life disruptions. Ethnographic interviews conducted with a sub-sample of study participants demonstrate that malodor, when present, limited many daily physical and social activities that have been shown to reduce stress and promote health. Even when odor is not present, anticipation of the potential impact of irregular and unpredictable odor events may create stress and anxiety about daily routines and about social events that could cause embarrassment if odor occurs when relatives, friends, or out-of-town guests are present (Tajik et al. 2008).

Previous studies indicate that NC swine CAFOs are located disproportionately in low income communities of color (Edwards and Ladd 2000; Ladd and Edwards 2000; Wing et al.
2000). These communities may be more adversely affected by CAFOs because of their limited resources, higher disease rates, poor food supplies, poor housing, and unprotected sources of groundwater for drinking. Lower levels of formal schooling and less access to legal and political resources make it more difficult for such communities to bring about more protective environmental policies and enforcement. The present study adds to a growing body of literature suggesting that malodor from swine CAFOs, and the physical and chemical agents with which it is associated, have the potential to negatively impact public health, especially in communities that are already vulnerable (Donham et al. 2007).

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Table 1. Characteristics of Neighborhoods and CAFOs within 2 Miles of the Monitoring Platform.

<table>
<thead>
<tr>
<th>Site</th>
<th>Swine CAFOs (no.)</th>
<th>Participating (no.)</th>
<th>Mean 10-minute odor</th>
<th>Days with any odor outdoors (%)</th>
<th>Days with any odor indoors (%)</th>
<th>Mean Temp (F)</th>
<th>Mean H₂S (ppb)</th>
<th>H₂S values &lt;2 (ppb) (%)</th>
<th>Highest H₂S (ppb)</th>
<th>Mean PM₁₀ PM₁₀ (µg/m³)</th>
<th>Mean semi-volatile PM₁₀ (µg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>7</td>
<td>0.4</td>
<td>26</td>
<td>2</td>
<td>47</td>
<td>0.01</td>
<td>99.7</td>
<td>4</td>
<td>10.8</td>
<td>1.1</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>6</td>
<td>0.7</td>
<td>48</td>
<td>10</td>
<td>50</td>
<td>0.09</td>
<td>97.0</td>
<td>9</td>
<td>13.6</td>
<td>1.8</td>
</tr>
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<td>C</td>
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<td>5</td>
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<td>70</td>
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<td>60</td>
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</tr>
<tr>
<td>D</td>
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<td>6</td>
<td>0.8</td>
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<td>9</td>
<td>59</td>
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<td>90.7</td>
<td>20</td>
<td>13.7</td>
<td>1.4</td>
</tr>
<tr>
<td>E</td>
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<td>7</td>
<td>0.5</td>
<td>20</td>
<td>15</td>
<td>77</td>
<td>&gt;0.00</td>
<td>99.8</td>
<td>2</td>
<td>28.7</td>
<td>5.9</td>
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<tr>
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<td>94.2</td>
<td>10</td>
<td>28.4</td>
<td>3.9</td>
</tr>
<tr>
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<td>4</td>
<td>0.6</td>
<td>41</td>
<td>2</td>
<td>51</td>
<td>0.07</td>
<td>96.7</td>
<td>3</td>
<td>17.5</td>
<td>5.0</td>
</tr>
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<td>-3.2</td>
</tr>
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<td>2.9</td>
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<td>79</td>
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<td>3.5</td>
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<td>K</td>
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<td>8</td>
<td>1.3</td>
<td>73</td>
<td>12</td>
<td>82</td>
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<td>93.3</td>
<td>21</td>
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<td>8.6</td>
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<td>0.8</td>
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<td>3</td>
<td>71</td>
<td>0.05</td>
<td>97.6</td>
<td>4</td>
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<td>4.6</td>
</tr>
<tr>
<td>M</td>
<td>12</td>
<td>10</td>
<td>2.1</td>
<td>73</td>
<td>11</td>
<td>75</td>
<td>0.05</td>
<td>98.6</td>
<td>27</td>
<td>17.1</td>
<td>1.6</td>
</tr>
<tr>
<td>N</td>
<td>15</td>
<td>5</td>
<td>0.9</td>
<td>49</td>
<td>13</td>
<td>59</td>
<td>0.01</td>
<td>99.5</td>
<td>4</td>
<td>27.3</td>
<td>4.6</td>
</tr>
<tr>
<td>O</td>
<td>15</td>
<td>5</td>
<td>1.8</td>
<td>68</td>
<td>26</td>
<td>77</td>
<td>1.02</td>
<td>91.1</td>
<td>90</td>
<td>18.7</td>
<td>9.2</td>
</tr>
<tr>
<td>P</td>
<td>16</td>
<td>8</td>
<td>1.2</td>
<td>66</td>
<td>10</td>
<td>59</td>
<td>0.08</td>
<td>97.3</td>
<td>9</td>
<td>19.1</td>
<td>6.5</td>
</tr>
</tbody>
</table>

1Based on 15-minute average values
Table 2. Daily Averages of Twice-Daily and Hourly Outdoor Odor Ratings.

<table>
<thead>
<tr>
<th>Mean Odor Rating</th>
<th>Twice-Daily Odor</th>
<th>Hourly Outdoor Odor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>%</td>
</tr>
<tr>
<td>0</td>
<td>563</td>
<td>38.7</td>
</tr>
<tr>
<td>&gt; 0</td>
<td>541</td>
<td>37.2</td>
</tr>
<tr>
<td>&gt; 2</td>
<td>301</td>
<td>20.7</td>
</tr>
<tr>
<td>&gt; 5</td>
<td>51</td>
<td>3.5</td>
</tr>
<tr>
<td>Total</td>
<td>1456</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Table 3. Duration and Strength of Reported Outdoor Odor Episodes.

<table>
<thead>
<tr>
<th>Mean odor</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4-8</th>
<th>9+</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N (%)</td>
<td>N (%)</td>
<td>N (%)</td>
<td>N (%)</td>
<td>N (%)</td>
<td>N (%)</td>
</tr>
<tr>
<td>1 – 1.99</td>
<td>398 (38.8)</td>
<td>126 (38.5)</td>
<td>30 (18.9)</td>
<td>29 (21.8)</td>
<td>3 (33.3)</td>
<td>586 (35.4)</td>
</tr>
<tr>
<td>2 – 4.99</td>
<td>462 (45.0)</td>
<td>152 (46.5)</td>
<td>89 (56.0)</td>
<td>76 (57.1)</td>
<td>4 (44.4)</td>
<td>783 (47.3)</td>
</tr>
<tr>
<td>5 – (value)</td>
<td>167 (16.3)</td>
<td>49 (15.0)</td>
<td>40 (25.2)</td>
<td>28 (21.1)</td>
<td>2 (22.2)</td>
<td>286 (17.3)</td>
</tr>
<tr>
<td>Total</td>
<td>1027 (100.0)</td>
<td>327 (100.0)</td>
<td>159 (100.0)</td>
<td>133 (100.0)</td>
<td>9 (100.0)</td>
<td>1655 (100.0)</td>
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</tbody>
</table>
Table 4: Simple linear regression coefficients for environmental predictors of odor

<table>
<thead>
<tr>
<th>Predictors</th>
<th>No. records</th>
<th>Coefficient</th>
<th>Standard error</th>
<th>t-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (x10)</td>
<td>2772</td>
<td>0.26</td>
<td>0.02</td>
<td>11.42</td>
</tr>
<tr>
<td>Hydrogen sulfide (ppb)</td>
<td>2701</td>
<td>0.17</td>
<td>0.02</td>
<td>8.73</td>
</tr>
<tr>
<td>PM₁₀ (10 µg/m³)</td>
<td>2005</td>
<td>0.03</td>
<td>0.02</td>
<td>1.89</td>
</tr>
<tr>
<td>Semi-volatile PM₁₀ (µg/m³)</td>
<td>2005</td>
<td>0.03</td>
<td>0.01</td>
<td>2.90</td>
</tr>
<tr>
<td>Humidity (10%)</td>
<td>2772</td>
<td>0.05</td>
<td>0.02</td>
<td>2.91</td>
</tr>
<tr>
<td>Low Wind</td>
<td>1617</td>
<td>0.43</td>
<td>0.08</td>
<td>5.73</td>
</tr>
<tr>
<td>Medium Wind (intercept)</td>
<td>972</td>
<td>1.02</td>
<td>0.06</td>
<td>16.96</td>
</tr>
<tr>
<td>High Wind</td>
<td>183</td>
<td>0.73</td>
<td>0.15</td>
<td>4.87</td>
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</table>
Table 5: Butanol Odor Sensitivity Threshold and Mean Twice-Daily Odor

<table>
<thead>
<tr>
<th>Butanol (ppm)</th>
<th>No. of participants</th>
<th>No. of twice-daily odor ratings</th>
<th>Mean odor</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>18</td>
<td>503</td>
<td>1.51</td>
</tr>
<tr>
<td>20</td>
<td>21</td>
<td>575</td>
<td>1.64</td>
</tr>
<tr>
<td>40</td>
<td>15</td>
<td>405</td>
<td>1.32</td>
</tr>
<tr>
<td>80</td>
<td>14</td>
<td>396</td>
<td>1.08</td>
</tr>
<tr>
<td>160</td>
<td>17</td>
<td>479</td>
<td>0.85</td>
</tr>
<tr>
<td>320</td>
<td>4</td>
<td>97</td>
<td>1.39</td>
</tr>
<tr>
<td>640</td>
<td>5</td>
<td>125</td>
<td>1.25</td>
</tr>
<tr>
<td>1280</td>
<td>1</td>
<td>20</td>
<td>1.55</td>
</tr>
<tr>
<td>2560</td>
<td>1</td>
<td>27</td>
<td>4.89</td>
</tr>
<tr>
<td>5120</td>
<td>1</td>
<td>28</td>
<td>2.07</td>
</tr>
<tr>
<td>20480</td>
<td>1</td>
<td>28</td>
<td>1.00</td>
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</table>
Table 6: Mixed model coefficients for environmental predictors of odor

<table>
<thead>
<tr>
<th>Effect</th>
<th>SE</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed(^1,^2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>0.18</td>
<td>2.62</td>
</tr>
<tr>
<td>Medium (intercept)</td>
<td>1.23</td>
<td>6.03</td>
</tr>
<tr>
<td>High</td>
<td>0.38</td>
<td>2.91</td>
</tr>
<tr>
<td>Relative humidity(\geq 50%)(^1)</td>
<td>0.29</td>
<td>2.59</td>
</tr>
<tr>
<td>Hydrogen sulfide (ppb)(^3)</td>
<td>0.15</td>
<td>3.10</td>
</tr>
<tr>
<td>Hydrogen sulfide x wind speed(^4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>0.28</td>
<td>2.49</td>
</tr>
<tr>
<td>Medium</td>
<td>-0.09</td>
<td>-0.83</td>
</tr>
<tr>
<td>High</td>
<td>0.77</td>
<td>1.75</td>
</tr>
<tr>
<td>PM(_{10}) (10 (\mu g/m^3)) x wind speed(^5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>-0.01</td>
<td>-0.23</td>
</tr>
<tr>
<td>Medium</td>
<td>0.00</td>
<td>0.25</td>
</tr>
<tr>
<td>High</td>
<td>0.45</td>
<td>3.14</td>
</tr>
</tbody>
</table>

\(^1\) random intercepts, fixed slope model
\(^2\) low \(\leq 0.57\) mph; 0.57<medium \(\leq 6.75\); high>6.75
\(^3\) random intercepts, random slopes
\(^4\) random intercept, random slope for hydrogen sulfide, random intercept, fixed slope for wind
\(^5\) random intercept, fixed slope for wind and PM\(_{10}\)
Table 7: Reports of change in activities due to odor in relation to average odor during the previous 12 hours

<table>
<thead>
<tr>
<th>12-hour average</th>
<th>Number of change in activity reports</th>
<th>Percentage of times with change in activity</th>
<th>Rate Ratio</th>
<th>loge odds ratio&lt;sup&gt;1&lt;/sup&gt;</th>
<th>SE</th>
<th>t-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Odor &lt; 1</td>
<td>22</td>
<td>1.4</td>
<td>1.0</td>
<td>referent</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1≤Odor &lt; 2</td>
<td>23</td>
<td>5.1</td>
<td>3.6</td>
<td>1.32</td>
<td>0.38</td>
<td>3.46</td>
</tr>
<tr>
<td>2≤ Odor &lt; 3</td>
<td>19</td>
<td>7.1</td>
<td>5.0</td>
<td>1.56</td>
<td>0.40</td>
<td>3.93</td>
</tr>
<tr>
<td>3≤Odor &lt; 5</td>
<td>30</td>
<td>11.0</td>
<td>7.7</td>
<td>2.12</td>
<td>0.39</td>
<td>5.46</td>
</tr>
<tr>
<td>Odor ≥5</td>
<td>24</td>
<td>16.2</td>
<td>11.3</td>
<td>2.78</td>
<td>0.43</td>
<td>6.39</td>
</tr>
</tbody>
</table>

<sup>1</sup>From mixed model with random intercepts and fixed slope for odor terms
Figure Legend: Time of Day and Odor
Figure 1

Time of Day and Odor

- Mean Hourly Odor
- Percent Hourly Odor >= 5