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Measurement and analysis of ammonia and hydrogen sulfide emissions from a mechanically ventilated swine confinement building in North Carolina

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Abstract

Emissions of atmospheric ammonia–nitrogen (NH_3–N, where NH_3–N $= (\frac{14}{17})NH_3$) and hydrogen sulfide (H_2S) were measured from a finishing swine confinement house at a commercial pig farm in eastern North Carolina. Continuous simultaneous NH_3–N and H_2S emissions were made for ~1-week period during four different seasons. The number of pigs contained in the house varied from ~850 to 900 with average weights ranging from ~38 to 88 kg. Average NH_3–N concentrations were highest during the winter and spring sampling periods, 8.91 ± 4.61 and 8.44 ± 2.40 ppm, respectively, and lower during the summer and fall, 2.45 ± 1.14 and 4.27 ± 0.71 ppm, respectively. Measured average H_2S concentrations were 673 ± 282, 429 ± 223, 47 ± 18, and 304 ± 88 ppb during winter, spring, summer, and fall, respectively. Generally, the H_2S concentrations were approximately an order of magnitude less than NH_3–N during winter, spring, and fall, and two orders of magnitude smaller during the summer season.

The average ambient temperature ranged from 5.5 to 22.3 °C while the average barn temperature measured at the outlet fans ranged from 19.0 to 26.0 °C in the winter and summer, respectively. The average fan ventilation rates varied from $253\,m^3\,min^{-1}$ during the fall sampling period to $1024\,m^3\,min^{-1}$ during summer.

Calculated total emission rates for both NH_3–N and H_2S were highest during the spring, $4519 \pm 1639\,g\,N\,day^{-1}$ and $481 \pm 142\,g\,day^{-1}$, respectively. Emissions were lowest during the fall season for NH_3–N ($904 \pm 568\,g\,N\,day^{-1}$) and the summer season for H_2S ($82 \pm 49\,g\,day^{-1}$). Normalized NH_3–N emission rates were highest in winter and spring (33.6 ± 21.9 and $30.6 \pm 11.1\,g\,N\,day^{-1}\,AU^{-1}$, where 1 AU (animal unit) = 500 kg) and lowest during summer and fall (24.3 ± 12.4 and $11.8 \pm 7.4\,g\,N\,day^{-1}\,AU^{-1}$). Normalized H_2S emissions were highest during the winter and spring seasons (4.2 ± 2.1 and $3.3 \pm 1.0\,g\,day^{-1}\,AU^{-1}$) and were lowest in summer and fall (1.2 ± 0.7 and $1.7 \pm 0.5\,g\,day^{-1}\,AU^{-1}$).

Keywords: Ammonia; Hydrogen sulfide; Swine barns; CAFOs

1. Introduction

Changes in livestock production methods in the US are in turn changing emissions of trace gases (e.g., sulfur, carbon, and nitrogen species) into the

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atmosphere (Aneja et al., 2006). Large-scale commercial operations have emerged over the last few years, dramatically increasing the number of pigs in geographically concentrated areas. In North Carolina, for example, the swine industry has grown significantly since the early 1990s, with an increase in inventory from 2.5 to ~10 million animals. As the pig population increased over time, the number of pig operations decreased in parallel, from 18,000 in 1985 to 2600 by 2004. The shift in the pig farming industry over the past two decades is illustrated in Fig. 1. (The pig growth ceased in 1997, due to a moratorium imposed on any new or existing pig farms in the state by a the North Carolina State Legislator (House Bill 515; S.L.1997-458).) Currently, there are more than 1400 operations with more than 1000 head, accounting for almost 99% of the state inventory (http://www.nass.usda.gov/QuickStats/), with the vast majority of the pig farms in North Carolina clustered in the southeastern coastal plain region of the state.

Subsequently, emissions of potentially harmful gases such as ammonia (NH_3) and hydrogen sulfide (H_2S) from confined animal feeding operations (CAFOs) have become a major concern in recent years (Aneja et al., 2001). Public concerns about potential environmental and health effects of air emissions from CAFOs have increased along with the growth and consolidation of this industry.

Ammonia is a by-product of microbial decomposition of the organic compounds in manure and nitrogen occurs as both unabsorbed nutrients in manure and as urea in urine (US EPA, 2001). Ammonia released from near-surface sources (i.e., confinement houses and waste treatment lagoons) into the atmosphere generally has a relatively short lifetime of ~1–5 days (Warneck, 2000) and may deposit near the source through dry or wet deposition processes. However, ammonia can also participate in atmospheric reactions (e.g., gas-to-particle conversion) once airborne, forming ammonium aerosols such as ammonium sulfate, -nitrate, -chloride, which tend to have longer atmospheric residence lifetimes (~1–15 days) due to a decrease in dry deposition velocity (Aneja et al., 1998) and therefore may be transported and deposited further downwind from the source. An environmental hazard in eastern North Carolina that has been associated with ammonium aerosols is deposition into sensitive coastal river systems where nitrogen loading may lead to enhanced eutrophication and soil acidification, which may in turn upset plant nutrient balances near sources (Paerl, 1997).

Hydrogen sulfide is a colorless, potentially harmful gas released from swine manure (US EPA, 2003).

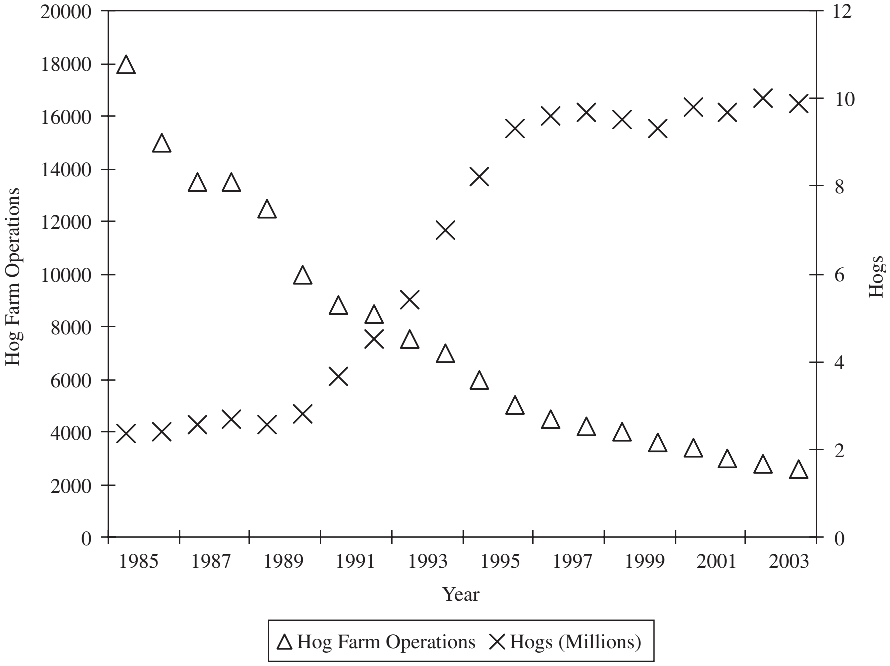


Fig. 1. Number of North Carolina pig farming operations and pigs from 1985 to 2004.

It is produced as manure decomposes anaerobically, resulting from the mineralization of organic sulfur compounds as well as the reduction of oxidized inorganic sulfur compounds such as sulfate by sulfur-reducing bacteria (US EPA, 2001). With a low odor threshold ranging from 0.0005 to 0.3 ppm (ATSDR, 2004), it is one of the primary gases released from swine facilities that is associated with odor complaints due to its characteristic "rotten egg" smell. However, it is noted that H_2S is just one component of many odorous gases that have been identified in pig farm emissions. Potential negative health effects of overall emissions from pig farms have been identified in production workers and neighboring residents that include respiratory illnesses such as bronchitis and asthma, and increased psychological stress (Schiffman, 1998).

Hoff et al. (2004) reviewed various ventilation measurement methodologies to estimate emission rates from mechanically ventilated CAFOs and Arogo et al. (2003) reviewed several studies, both in Europe and the US, undertaken to estimate NH_3 emissions from animal confinement houses. Emissions of ammonia (Zhu et al., 2000; Heber et al., 2000; Schmidt et al., 2002; Jacobson et al., 2005) and hydrogen sulfide (Heber et al., 1997; Zhu et al., 2000; Ni et al., 2002; Schmidt et al., 2002; Jacobson et al., 2005) from swine confinement houses in the Midwestern US have been estimated. It is noted that none of the studies were conducted on farms in the Southeastern US. Various factors, such as farming activities (i.e., feed composition, animal density) and regional climates, may affect the emissions of gases into the atmosphere. Emissions estimates generated for one set of conditions or for one type of CAFO may not translate readily to others. It is therefore important for comprehensive emission measurements to be made from different types of operations in order for accurate emission factors to be estimated.

The primary objective of this research initiative was to investigate and evaluate the variability of ammonia and hydrogen sulfide emissions with respect to diurnal and seasonal variations for four seasons as well as the influence of meteorological factors on the emission processes. Data presented here was collected continuously for a 1-week period during each season (i.e., fall, winter, spring, and summer) from a finishing swine confinement house at a commercial pig farm in eastern North Carolina.

2. Methods and materials

2.1. Physiographic location and farm description

The experimental site is an operational commercial swine finishing farm located in Jones County, NC in the southeastern coastal plain region of the state, where the majority of pig farming operations are located. The on-site waste storage treatment lagoon is ~17,150 m^2 (1.715 ha) at the normal liquid level and the farm maintains eight fan-ventilated confinement houses, long axis oriented east–west (the exhaust fans face west), with each barn measuring 61×12.2 m. Generally, the pigs are rotated out of each house approximately every 18 weeks, weighing ~22–24 kg upon arrival and gaining an average of 5 kg per week. The weight gain is assumed to be linear and the weekly animal mortality rate was documented and taken into account for total weight estimations. Each house is cleaned and sanitized between rotations. There are 800–900 animals housed in each barn and rotations are staggered for each house. The pigs are placed in the barns approximately one week apart, starting with the barn located at the south end. A full description of the pig numbers, weights, and number of weeks in rotation for each season during the initiative is provided in Table 1. Each barn has a shallow manure collection pit which is emptied once

Table 1

Sampling periods for NH_3–N and H_2S barn emission measurements and information for pigs housed inside the barns

Season	Sample dates	Number of pigs	Number of weeks in rotation	Average weight[a,b]	Total weight[a]
Winter	Feb. 22–27, 2005	851	8	57.6	48,963
Spring	Apr. 07–14, 2005	842	14	87.8	73,895
Summer	Jun. 19–24, 2005	896	4	37.9	33,952
Fall	Oct. 26–31, 2005	889	5	43.2	38,390

[a] Measured in units of kg.

[b] Weighted average for pigs of different weights brought into the barn on different dates.

a week. The farm utilizes a conventional ''lagoon and spray'' technology as its primary means of handling effluent. The pits are recharged with lagoon liquid that has a total ammoniacal nitrogen (TAN) content of 360–590 mg L^{-1} and a total sulfide content of 0.1–13.0 mg L^{-1} (range is based on samples collected from the lagoon during all four experimental periods). Effluent is flushed directly from the pig barns into the storage lagoon where it is treated via natural microbial processes. The stored wastewater is used to recharge the barn pits, and also periodically irrigated over on-site agricultural crops for nutrient enrichment purposes.

2.2. Experimental procedure

One barn, located furthest north on the property, was selected for measurements. Five AAA Associates Inc. Maxi-Brute^{TM} fans with plastic shutters (Niles, MI), two 91 cm diameter direct-driven and three 122 cm diameter belt-driven, were located at the west end of the building (see Fig. 2). The fans were staged to operate as temperature increased inside the building.

In order to determine fans revolutions per minute (rpm), a Mabuchi VDC motor (Santa Clara, CA) was either: (1) mounted to a stainless-steel plate configured to fit over the front of the 91 cm fan plate or (2) attached to a cylinder sleeve which fit over the fan shaft of the 122 cm fans. Single analog output wires were connected from each motor to a Campbell Scientific CR10X data logger (Logan, UT) which continuously recorded the measured voltage output every second and averaged the data over a 15 min timeframe. Prior to the experiment, each motor was calibrated in the laboratory to obtain voltage outputs at a specific rpm. For this process, each VDC motor was attached to the shaft of a Dayton SCR Controlled DC Motor (Model # 2M168C). A Shimpo DT-725 Stroboscopic Digital Tachometer and Shimpo DT-207B Direct Contact Digital Tachometer (Itasca, IL) were used to determine rpm and a Micronta Digital Multimeter (Model # 22-185) was used to simultaneously determine voltage output at the respective rpm. The rpm for each fan as well as ''on/off'' times could then be determined and flow rates subsequently calculated. According to manufacturer specifications the direct drive motor on the 91 cm fans is rated at 850 rpm and the 122 cm fan motor is rated at 1725 rpm. We estimated the ''pulley ratio'' for the 122 cm fans to be 2.9:1; therefore, the fans should be rotating at ~595 rpm. However, fan belts may become loose over time and the rpm decrease, thus

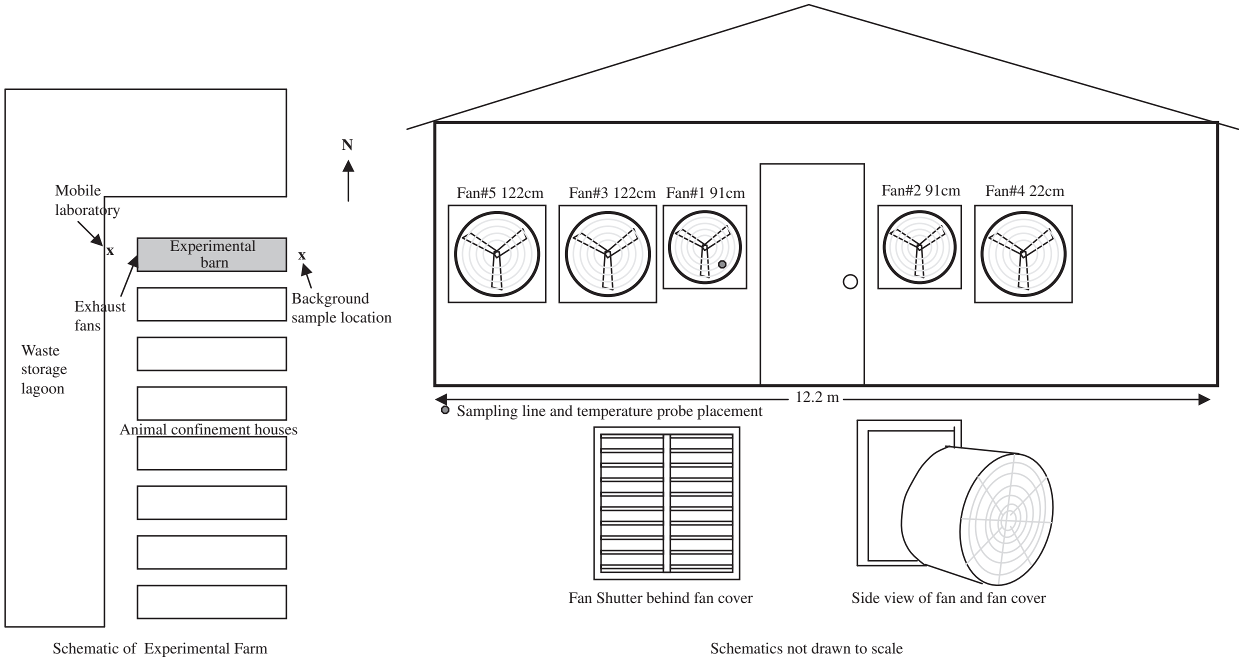


Fig. 2. Schematic of experimental site and mechanically ventilated fan exhaust system at experimental site. Fans are numbered in the order in which they are staged to turn on.

affecting the flow rate. Broken shutters and excess dirt on fan blades may also reduce air flow rates through the exhaust systems. Janni et al. (2005) conducted a study to test fan flow rates and found that 122 cm diameter belt-driven fans with 1-hp motor and plastic shutters was 58–65% of laboratory airflow rate (Bioenvironmental Engineering Structure Systems (BESS) Lab, University of Illinois at Urbana-Champaign) and that fans with loose belts had airflow rates that were 72–74% of fans with tight belts.

The static pressure inside the building was monitored during the spring season using a Model PX655 Omega pressure transducer to measure the pressure difference between the inside of the barn (placed away from any wind currents) and the outside ambient air (tubing housed inside the mobile laboratory). The pressure sensor did not work properly during the other seasons. However, during the spring initiative the full range of ventilation rates was recorded (i.e., all five fans turned on at some point) and the static pressure was found to vary from 0.08 to 0.13 inches of water (21–31 Pa), with an average and median value of 0.11 inches of water. This value was subsequently used for further emission rate calculations. Based on data from the fan manufacturer, the difference between the highest and lowest measured pressures can result in a ~6% and 10% change in flow rate for the 91 cm and 122 cm fans, respectively, with higher flow rates for lower pressure difference. The flow rates for each fan size were calculated using the following calculation:

$$\text{Calculated flow rate} = \left(\frac{\text{Manufacturer fan flow rate}}{\text{Specified rpms}}\right) \times (\text{Measured rpms}),$$

where the manufacturer fan flow rate was adjusted to the average static pressure measurements. For example, given a static pressure of 0.11 inches of water, manufacturer fan flow rates for the 91 cm fan with shutter and 122 cm fan are ~269 and ~640 $m^3\,min^{-1}$, respectively.

A $\frac{1}{4}''$ o.d., $\frac{5}{32}''$ i.d. 20′ length Teflon sample line was inserted inside the chimney of the first 91 cm fan to turn on, between the shutter and fan blade, at roughly half the fan radial distance (see Fig. 2). Due to the nature of the airflow through the building, it is assumed that the gaseous concentrations are uniformly distributed at each fan outlet. The air is drawn through the system and is then split using a Swagelok® stainless steel Union Tee in order to deliver the sample simultaneously to the different analysis instruments: a thermo environmental instruments (TEI) Model 450C pulsed fluorescence H_2S/SO_2 analyzer and a Model 17C chemiluminescence NH_3 analyzer (Thermo Environmental Corporation, Mountain View, CA). The Model 450C analyzer draws in sample air at ~1.0–1.2 $L\,min^{-1}$ through an internal vacuum pump and the Model 17C analyzer draws in sample air at ~0.5 $L\,min^{-1}$ via an external vacuum pump (KNF Neuberger, Inc., Trenton, NJ); therefore the sample entering each analyzer is free of contamination. Due to the air flow rate and sample line size, the residence time of an air mass inside the sample line is small (~3 s), thus limiting condensation.

Multipoint calibrations (80%, 60%, 40%, and 20% of full-range scale) for the Model 450C and Model 17C analyzers were conducted according to the TEI Model 450C and Model 17C instruction manuals prior to each sampling campaign using a TEI Model 146 dilution-titration system (Thermo Environmental Corporation, Mountain View, CA). During the field study, zero and span checks for H_2S and NH_3 concentration were conducted daily and results added to the calibration curve.

Discrete 5-min integrated background samples were collected daily using an SKC Vac-U-Chamber system and 10-L Tedlar® bags (Fullerton, CA). A vacuum collection box (SKC_West Inc., Fullerton, CA) was used to draw air into the bags, thus allowing air to enter the collection bag free of any contamination. The sample was drawn through a Teflon tube which was split using a Swagelok® stainless steel Union Tee and delivered to the respective H_2S and NH_3 analyzers (temporarily disconnected from the fan outlet sample line). There was a 5–10 min gap between the time the barn sample line was disconnected and replaced by the background sample line. Data were recorded from the background samples after 3 min, allowing the instruments to stabilize.

Concentration levels were subsequently recorded from each analyzer. The background samples collected were on average 0–4% of the concentration values measured for both NH_3 and H_2S at the fan ventilation exhaust and were therefore not considered during emission calculations. It is noted that the background samples were collected during the daytime. Variations in the concentration may occur. Additionally, background concentrations may be higher during stable nighttime conditions.

2.3. Meteorological and lagoon parameters instrumentation

A 10 m meteorological tower was erected to measure ambient air temperature and relative humidity (RH). Air temperature and RH measurements were made at 2 m height with a Model CS500-L Vaisala 50Y temperature and RH probe (Campbell Scientific, Inc., Logan, UT) housed in a Model 41303 RM Young 6-plate gill solar radiation shield (Campbell Scientific, Inc., Logan, UT). Additionally, a CS107 temperature probe (Campbell Scientific Inc., Logan, UT) was placed next to the sample line in order to measure the temperature at the fan exhaust.

A Model CR10X data logger equipped with a Model AM 16/32 Channel Relay Multiplexer (Campbell Scientific, Inc., Logan, UT) was used to collect all meteorological, fan voltage, and gas measurement data. A Dell Inspiron 600m laptop computer was used to download the data, which was collected every second, and averaged and recorded over a 15 min timeframe. The data loggers and gas analyzers were housed inside a temperature-controlled mobile laboratory (N.C. State University Air Quality Ford Aerostar Mini-Van), maintained at ~21 °C (~70 °F).

3. Results

3.1. Ammonia and hydrogen sulfide concentrations

All results for ammonia are presented as ammonia–nitrogen (NH_3–N). To convert to NH_3, multiply the value by 1.214. Table 2 gives mean seasonal concentration values for NH_3–N and H_2S measured at the first 91 cm diameter exhaust fan to turn on in series as well as total fan ventilation rates, temperature measured at the fan exhaust, and ambient temperature and relative humidity measurements. Average NH_3–N concentrations were highest during the winter and spring sampling periods, 8.9 and 8.4 ppm, respectively. Maximum values of ~14 ppm were measured during both seasons. The higher concentration values during the winter may be attributed to less airflow through the building since the ambient and barn temperatures are generally cooler and the fans are staged to turn on at predetermined temperature set points. A buildup of the gas therefore occurred with fewer fans operating. Although the spring ventilation rates are more than double the rates during the winter time, it is likely that the large concentrations measured in the spring are due to the age and weights of the animals housed in the barn (see Table 1). During the spring, the average pig weight was ~88 kg (see Table 1) as compared to 38–58 kg

Table 2
Simple statistics for barn measurements made for experimental periods during four different seasons

	H_2S concentration[a] (ppb)	NH_3–N concentration[a] (ppm)	Ventilation rate[b,c] ($m^3\,min^{-1}$)	Fan outlet temperature[a] (°C)	Ambient temperature (°C)	Ambient relative humidity (%)
Winter 2005						
Average (Std. Dev.)	673 (282)	8.91 (4.61)	328 (170)	19.7 (2.5)	5.5 (4.8)	83 (17)
Range	0–982	0.65–14.55	87–778	13.1–24.0	−3.4–16.2	38–100
Spring 2005						
Average (Std. Dev.)	429 (223)	8.43 (2.40)	726 (380)	22.3 (2.8)	13.7 (5.8)	75 (24)
Range	55–996	3.14–14.14	251–1996	14.6–27.9	3.7–26.9	22–98
Summer 2005						
Average (Std. Dev.)	47 (18)	2.45 (1.14)	1024 (684)	26.0 (2.6)	22.3 (4.9)	73 (19)
Range	2–113	0.58–6.59	248–2273	12.4–31.4	12.1–32.3	36–97
Fall 2005						
Average (Std. Dev.)	304 (88)	4.27 (0.71)	253 (119)	19.0 (2.8)	9.1 (5.1)	76 (23)
Range	6–527	3.27–7.63	101–491	14.0–25.8	1.0–21.5	20–96

[a] Measured at 91 cm fan outlet.

[b] Flow from two 91 cm fans and three 122 cm fans summed together.

[c] Multiply by 35.31 to obtain cfm ($ft^3\,min^{-1}$).

during the other seasons when measurements were made.

The lowest concentrations measured at the fan exhaust occurred during the summer experimental period. At least two 91 cm fans were almost always operational and usually four or five were turned on during the daytime. The buildup of gas inside the barn is minimized because the ventilation rates are continuously higher than during the cooler seasons. Another contributing factor may also be that the animals are in week # 4 of the rotation, weighing an average of 38 kg.

The daily averaged H_2S concentrations were approximately an order of magnitude less than NH_3–N during winter, spring, and fall, and two orders of magnitude smaller during the summer season. Similar to NH_3–N, measured H_2S concentrations were highest during the winter and lowest during the summer, 673 and 47 ppb, respectively. The average H_2S concentration was 6–14 times less during the summer sampling period as opposed to the other seasons.

Since temperature normally increases during the daytime and the fan operating system is temperature dependent, it is expected that the concentration measured at the first staged fan should be highest during the nighttime when fewer fans are running and lower during the daytime when more fans are usually turned on and ventilation rates are higher. Fig. 3 depicts the hourly averaged diurnal profile for H_2S and NH_3–N during each season. The diurnal H_2S concentration patterns generally show a decrease during the early to mid-morning hours and an increase as temperatures begin to fall in the late afternoon. During the summer, the pattern is less defined during the afternoon and the concentration remains relatively steady during the daytime.

During the winter and fall sampling periods, the NH_3–N concentrations actually begin to increase in the mid-morning and continue until early afternoon. Jacobson et al. (2005) measured ammonia at the exhaust of two mechanically ventilated swine buildings and the diurnal profiles for the warm months at a gestation house and cool months at a breeding house also indicated a slight increase in concentration during the midday. Possibly, gas accumulation inside the barn during cooler temperatures (i.e., lower fan flow rate) or animal activity in the barn may affect the emissions; however, it is unclear why this pattern does not also exist for H_2S.

3.2. Ammonia and hydrogen sulfide emission rates

Total and normalized emission rates (500 kg per AU where AU = animal unit) for both NH_3–N and H_2S are given in Table 3. Calculated total emission rates for both NH_3–N and H_2S were highest during the spring, 4519 and 481 g day^{-1}, respectively. Emissions were lowest during the fall season for NH_3–N (904 g N day^{-1}) and the summer season for H_2S (82 g day^{-1}). It is important to bear in mind that the actual fan flow rates may be lower than the calculated flow rates due to the accumulation of dirt/dust on the fan blades.

The average emission rate for each season was further normalized, thus removing the total live mass as a variable to explain emission rates. The normalized value is obtained by dividing the total emission rate by total live mass and then multiplying by 500 kg (1 AU). The normalized emission rates ranged from 11.8 to 33.6 g N day^{-1} AU^{-1} for NH_3–N and 1.2–4.2 g day^{-1} AU^{-1} for H_2S. The normalized emission rate for H_2S from the barn was ~3.5 times higher during the winter season compared to summer and the normalized emission rate for NH_3–N was almost three times higher in winter than fall, thus indicating that emissions may not increase linearly with animal mass.

Normalizing the data provides an effective means to compare emission rates between studies. Tables 4 and 5 compare estimated emission rates of NH_3–N and H_2S, respectively, from this study with previous studies. Normalized NH_3–N emission rates measured during April and June (30.6 and 24.3 g day^{-1} AU^{-1}) are higher than rates reported by Lim et al. (2004) from May to July for 1-week pit recharge (8.2 g day^{-1} AU^{-1}). However, that study was conducted inside a building at the Purdue University Swine Research Center as opposed to an operational farm. Emission rates were lower than Heber et al. (2000) during the summer, June–September (120 and 78 g day^{-1} AU^{-1}, measured from two barns). On the other hand, calculated emission rates from this study during the winter sampling period (33.6 g day^{-1} AU^{-1}) are higher than those reported by Schmidt et al. (2002) from a mechanically ventilated barn from February to March (6.6 g day^{-1} AU^{-1}). It is noted that both Heber et al. (2000) and Schmidt et al. (2002) made measurements from barns containing deep pits for manure storage.

The measured normalized emission rates of H_2S compare well with those in the literature; however, Schmidt et al. (2002) reported a much lower rate of

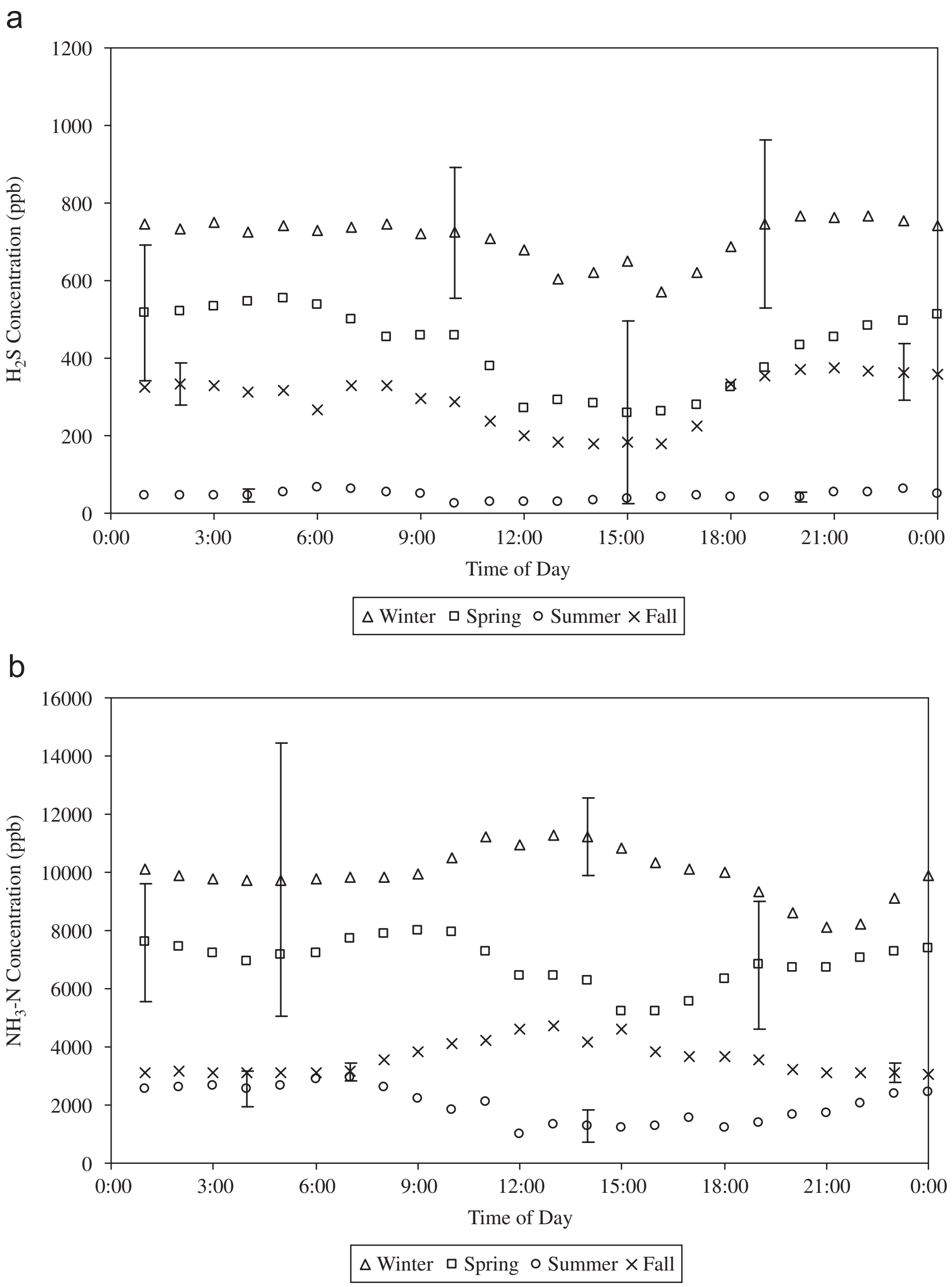


Fig. 3. Seasonally averaged diurnal variations for: (a) H_2S and (b) NH_3–N concentrations measured at fan ventilation exhaust.

0.0007 g day^{-1} AU^{-1} during the winter. Although normalizing the calculated emissions by the weight of the animals is helpful for comparison, it does not take into account factors such as animal age, length of time in rotation, length of time since the house has been cleaned and/or waste removal, temperatures, and ventilation rates, all of which may also play a role in emissions.

Hourly averaged normalized NH_3–N and H_2S emissions were graphed in Fig. 4 to show the diurnal profiles for each season. It would be expected that the emission rates remain relatively steady throughout the profile since gas concentrations decrease as ventilation rates increase. However, the emission rates for NH_3–N increased during the warmer daytime hours and decreased during the night for

Table 3
Statistical summary table of total and normalized average daily NH_3–N and H_2S barn emission rates for each season

Season	Total emission rate[a]			Normalized emission rate[a,b]		
	Mean[c]	Minimum	Maximum	Mean[c]	Minimum	Maximum
NH_3–N						
Winter 2005	3290 (2143)	54	8930	33.6 (21.9)	0.5	91.2
Spring 2005	4519 (1639)	1550	14514	30.6 (11.1)	10.5	98.2
Summer 2005	1653 (840)	626	8935	24.3 (12.4)	9.2	131.6
Fall 2005	904 (568)	299	3027	11.8 (7.4)	3.9	39.4
H_2S						
Winter 2005	412 (208)	0	887	4.2 (2.1)	0	9.1
Spring 2005	481 (142)	113	859	3.3 (1.0)	0.8	5.8
Summer 2005	82 (49)	2	287	1.2 (0.7)	0	4.2
Fall 2005	133 (42)	0	252	1.7 (0.5)	0	3.3

NH_3–N flux $= \left(\frac{14}{17}\right)$ NH_3 flux.

[a] Units of flux are $g\,day^{-1}$.

[b] AU (animal units) = 500 kg live animal weight.

[c] Numbers in parenthesis represent one standard deviation.

Table 4
Normalized NH_3–N confinement house emission rates from previous studies compared with this study

Study	Season	Facility type	Manure pit type	Ventilation type	Normalized NH_3–N[a] emission rate[b]
Heber et al. (1997)	Jan.–Mar.	Finish	Deep pit	Natural	34
Heber et al. (2000)	Mar.–May	Finish	Deep pit	Mechanical	54
Heber et al. (2000)	Mar.–May	Finish	Deep pit	Mechanical	54
Heber et al. (2000)	Jun.–Sept.	Finish	Deep pit	Mechanical	120
Heber et al. (2000)	Jun.–Sept.	Finish	Deep pit	Mechanical	78
Schmidt et al. (2002)	Feb.–Mar.	Finish	Deep pit	Mechanical	6.6
Schmidt et al. (2002)	Jun.–July	Finish	Deep pit	Natural	66.0
Lim et al. (2004)	May-July	Finish	Pit recharge, 1 week	Mechanical	8.2
Lim et al. (2004)	May-July	Finish	Pit recharge, 2 week	Mechanical	9.9
Lim et al. (2004)	Mar.-May	Finish	Pit recharge, 6 week	Mechanical	9.1
This study	Feb.	Finish	Pit recharge, 1 week	Mechanical	33.6
This study	Apr.	Finish	Pit recharge, 1 week	Mechanical	30.6
This study	Jun.	Finish	Pit recharge, 1 week	Mechanical	24.3
This study	Oct.	Finish	Pit recharge, 1 week	Mechanical	11.8

[a] Multiply by 1.214 to obtain NH_3 emission rate.

[b] Measured in $g\,day^{-1}$ 500 kg live animal weight $(LAW)^{-1}$.

all seasons. The warmer temperatures during the daytime likely enhance the volatilization of the gas from the animal waste.

The H_2S spring diurnal profile exhibits a slight decrease in emission rates during the late morning to early afternoon while the remainder of the day remains fairly stable. The emission rates increase more dramatically during the daytime in the winter. During two days of the measurements, all fans turned off during much of the overnight hours and emissions were negligible, influencing those night-time average emission rates.

4. Discussion

There are several parameters that may affect gaseous concentrations inside the barns as well as the emission rates via mechanically ventilated fan exhaust systems, including age and weight of the animals housed inside the barn, waste storage and/or flushing frequency, amount of time since the inside of the barn was cleaned and sanitized, fan ventilation rates, barn temperatures, which influence ventilation rates as well as gas volatilization, and meteorological parameters (i.e., ambient temperature, relative humidity).

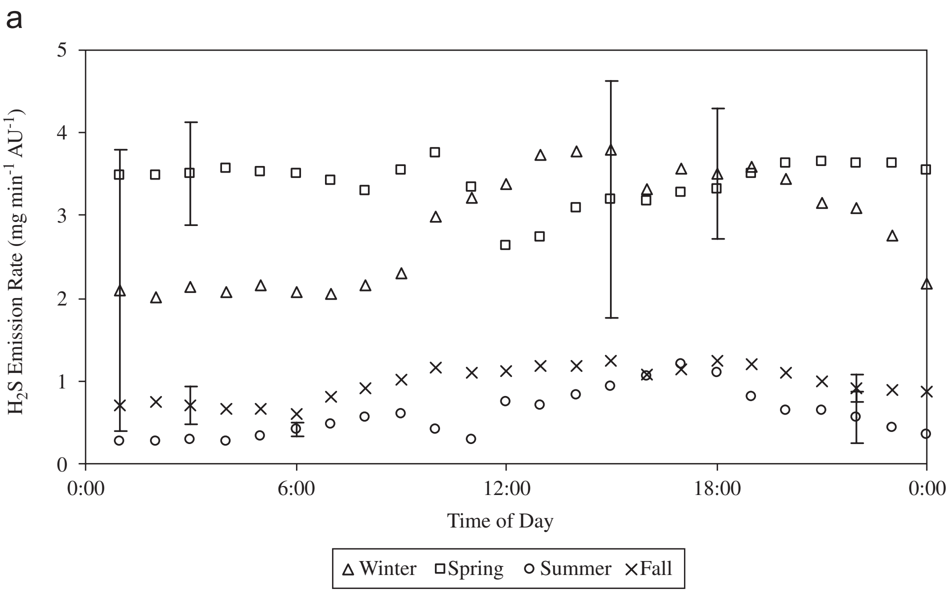
The amount of time the animals and/or animal waste have been housed inside the confinement structure may play a large role in the gas emission rates from the barns. In houses with deep pits, the waste may be stored beneath the floor for months and the normalized emission rates would not necessarily be reflected by the animal weights alone as waste accumulates. Similarly, in a house with shallow pits, although the pits are recharged frequently (i.e., daily or weekly), the houses are only cleaned and sanitized between animal rotations and so a buildup of waste may occur over time as well. For example, during the summer experimental period it was roughly one month since the house was cleaned as opposed to more than three months for the spring sampling period and the normalized emission rates for H_2S were three times higher during the spring season. For this study design, it was not possible to investigate this possible influence and other parameters may certainly have influenced the emissions as well. In a previous study, Lim et al. (2004) determined that weekly or bi-weekly pit recharge with recycled secondary lagoon effluent reduced NH_3 and H_2S emissions by 51–62% and 18–40%, respectively. Daily flushing was even more effective, reducing NH_3 emissions by 45% and H_2S emissions by 58% than the weekly cycles. It should be considered that the concentration of TAN and total sulfide in the recharge may influence barn emission rates.

Pearson's correlation coefficients were calculated to examine the individual relationships between total fan flow rates, gas concentrations, normalized gas emission rates, ambient and fan exhaust temperature and ambient relative humidity using a statistical software package (SAS Institute Inc., Cary, NC). The results are presented in Table 6. Ventilation fans are used to create airflow in the pig barns in order to remove warm, concentrated air, thereby maintaining relatively steady temperatures and good indoor air quality. It is therefore expected that concentration levels will decrease as ventilation rates and both ambient and barn temperatures increase (ambient and barn temperatures were positively and strongly correlated, $r^2 = 0.88$, $p < 0.0001$). The barn exhaust temperatures for all seasons were plotted against

Table 5
Concentrations of hydrogen sulfide at barn exhaust systems from previous studies compared with this study

Study	Season	Facility type	Manure pit type[a]	Total live animal weight[b]	Ventilation type	Ventilation rate[c]	Number of samples	Average daily mean concentration[d]	Normalized H_2S emission rate[e]
Zhu et al. (2000)	Sept.	Finish	Full	44,990	Mechanical	218	7	414	2.00[f]
Zhu et al. (2000)	Sept.	Finish	Full	43, 640	Natural	501	7	271	3.11[f]
Heber et al. (1997)	Jan.–Mar.	Finish	Full	–	Natural	–	1500	180	0.84
Ni et al. (2002)	June–Sept.	Finish	Full	48,783	Mechanical	2637	529	173	7.0[f]
Schmidt et al. (2002)	Winter	Finish	Full	102,058	Mechanical	–	–	6	0.007[f]
This study	Feb.	Finish	Shallow	48,963	Mechanical	328	385	632	4.2
This study	Apr.	Finish	Shallow	73,895	Mechanical	726	617	441	3.3
This study	Jun.	Finish	Shallow	33,952	Mechanical	1024	415	47	1.2
This study	Oct.	Finish	Shallow	38,390	Mechanical	253	432	304	1.7

[a] Full = deep pit; Shallow = pit recharge (1 per week).
[b] Measured in kg.
[c] Measured in $m^3\ min^{-1}$ (multiply by 35.31 to obtain cfm ($ft^3\ min^{-1}$)).
[d] Measured in ppb.
[e] Measured in $g\ day^{-1}\ 500\ kg$ live animal weight $(LAW)^{-1}$.
[f] Calculated based on data available in literature.



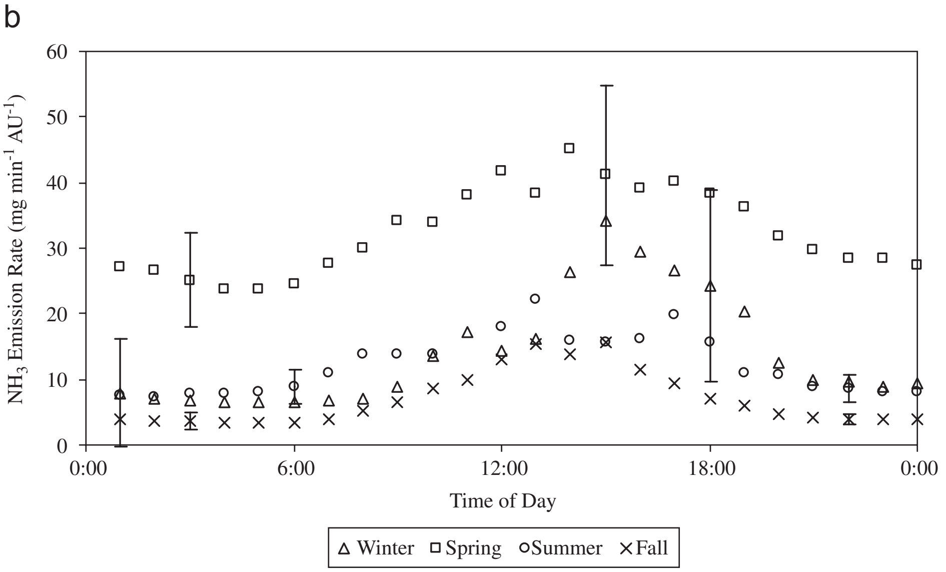


Fig. 4. Seasonally averaged diurnal variations for (a) H_2S and (b) NH_3–N normalized emission rates from pig barn.

the corresponding ventilation rates (Fig. 5). Generally, greater temperature ranges tend to occur at ventilation rates between 500 and 1000 $m^3 min^{-1}$ but overall there was a fairly strong positive correlation ($r^2 = 0.65$, $p < 0.0001$), meaning that 65% of the variation in ventilation rates can be explained by the exhaust temperature. It is noted that the temperature at the fan exhaust may differ from the location in the barn where the fan stage control operates. Although not plotted, ambient temperature had an even higher correlation with total ventilation rate ($r^2 = 0.70$, $p < 0.0001$). Relative humidity was negatively correlated with ventilation rate as well but with a much smaller r^2 value of 0.32 ($p < 0.0001$), meaning that little of the variation is explained by this parameter.

The NH_3–N and H_2S normalized emission rates showed low correlation to one another ($r^2 = 0.20$, $p < 0.0001$). The normalized H_2S emission rate was well correlated with the measured gas concentration ($r^2 = 0.55$, $p < 0.0001$) and showed almost no dependence on the total ventilation rate ($r^2 = {\sim}0$, $p = 0.72$). On the other hand, normalized NH_3–N emissions showed a higher correlation with the total

Table 6
Pearson's correlation coefficients calculated to show relationships between gas concentrations, normalized gas emission rates, fan flow rate, and meteorological parameters

	H_2S concentration	H_2S normalized emissions	NH_3–N concentration	NH_3–N normalized emissions	Total ventilation rate	Air temperature	Barn temperature
H_2S normalized emission	0.74[a] 0.55[b] <0.0001[c] 1817[d]						
NH_3–N concentration	0.67 0.45 <0.0001 1575	0.68 0.46 <0.0001 1577					
NH_3–N normalized emission	−0.15 0.02 <0.0001 1687	0.45 0.20 <0.0001 1577	0.41 0.17 <0.0001 1577				
Total ventilation rate	−0.46 0.21 <0.0001 1818	−0.01 ~0 0.72 1819	−0.29 0.08 <0.0001 1577	0.58 0.33 <0.0001 1577			
Air temperature	−0.66 0.44 <0.0001 1818	−0.18 0.03 <0.0001 1819	−0.34 0.12 <0.0001 1577	0.56 0.31 <0.0001 1577	0.84 0.70 <0.0001 1995		
Barn temperature	−0.41 0.17 <0.0001 1657	0.09 0.01 0.0003 1658	−0.09 0.01 0.0013 1416	0.64 0.41 <0.0001 1416	0.81 0.65 <0.0001 1827	0.94 0.88 <0.0001 1827	
Relative humidity	0.33 0.11 <0.0001 1818	−0.03 ~0 0.2797 1819	0.07 0.0035 0.0121 1577	−0.54 0.29 <0.0001 1577	−0.56 0.32 <0.0001 1995	−0.59 0.35 <0.0001 1995	−0.56 0.32 <0.0001 1827

[a] Correlation coefficient (r): measure of the strength of the relationship between two variables.

[b] Coefficient of determination (r^2): percent of variation that can be explained by the predictor variable.

[c] p-value: measure of probability that result occurred strictly by chance.

[d] Number of observations for comparison (n).

ventilation rate ($r^2 = 0.33$, $p < 0.0001$) than the measured gas concentration ($r^2 = 0.17$, $p < 0.0001$). These correlations, along with the diurnal profiles shown in Fig. 4, indicate that the H_2S concentration inside the barn does not tend to buildup when fewer fans are running while the NH_3–N concentration may accumulate. Relative humidity and barn temperatures were not correlated at all with either normalized H_2S emission rate ($r^2 = 0.01$ and $r^2 = \sim 0$, respectively.

Time series graphs (Fig. 6) were created in order to further examine the relationship between ventilation rates and barn temperature as well as gaseous concentration levels. The spring experimental period was chosen due to the large variation in flow rates during the measurement period. The ventilation rates (sum of all flow rates for the fans in operation) during this period ranged from 251 to 1996 $\mathrm{m^3\,min^{-1}}$. The ventilation rates change in accordance with the temperature, lagging slightly.

As indicated by Pearson's correlation coefficients, the measured NH_3–N and H_2S gas concentrations are both inversely related to the ventilation rates. Data gaps in the measured H_2S and NH_3–N occurred when the analysis instruments were being

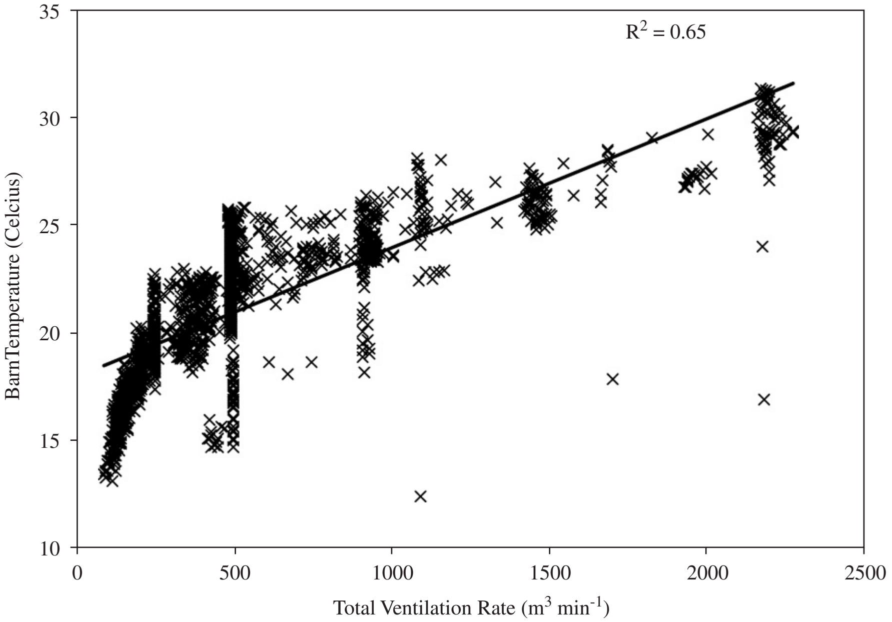


Fig. 5. Measured barn exhaust temperature plotted against total fan exhaust ventilation rate.

spanned and/or background samples were being measured. Toward the end of the graph, for approximately a 24-h period (April 12–13), the ventilation rate remains constant. During this period, the H_2S concentration levels fluctuate slightly but remain relatively steady; however, the NH_3–N concentration decreases from ~10 to ~6 ppm around 02:30 and remains near this level throughout the remainder of this 24-h period. Examining the data, no significant changes were recorded for static pressure, ambient temperature, barn temperature, or relative humidity. The instrument span checks indicated no errors in the analyzer. The reason for the change in concentration is unknown.

Total fan ventilation rates were also plotted against NH_3–N and H_2S emission rates in Figs. 7 and 8, respectively, to determine possible variations from the ventilation rates. During the winter and fall, when ventilation rates were on average lower than spring and summer (Table 2), emission rates for both NH_3–N and H_2S increase linearly until both 91 cm fans are running steadily ($\leqslant 500\,\mathrm{m^3\,min^{-1}}$) and then stabilize at higher ventilations. During the spring, NH_3–N emissions increase linearly as ventilation increases up to $\sim 1000\,\mathrm{m^3\,min^{-1}}$ (three fans running) and then stabilizes. The H_2S emission rates during spring do not exhibit this pattern. There is little difference between emission rates at various ventilation rates. During the summer, when ventilation rates were highest and usually two or more fans were running, NH_3–N emission rates remained steady while H_2S increased slightly. As shown in Figs. 7 and 8, the correlation between total fan ventilation rates and normalized emission rates for each gas varies by season. When seasonal variation is not considered (Table 6), there is almost no correlation between the ventilation rates and H_2S normalized emission rates ($r^2 = \sim 0$, $p = 0.72$). The correlation is higher for NH_3–N normalized emission rates for all four seasons ($r^2 = 0.33$, $p < 0.0001$).

5. Conclusions

Data were collected continuously for a 1-week period during each season (i.e., fall, winter, spring, and summer) for one year from a finishing swine confinement house at a commercial pig farm in eastern North Carolina. The primary objective of this research initiative was to investigate and evaluate the variability of ammonia and hydrogen sulfide emissions with respect to diurnal and seasonal variations as well as the influence of meteorological factors.

Average NH_3–N concentrations were highest during the winter and spring sampling periods, 8.9 and 8.4 ppm, respectively. The higher concentration

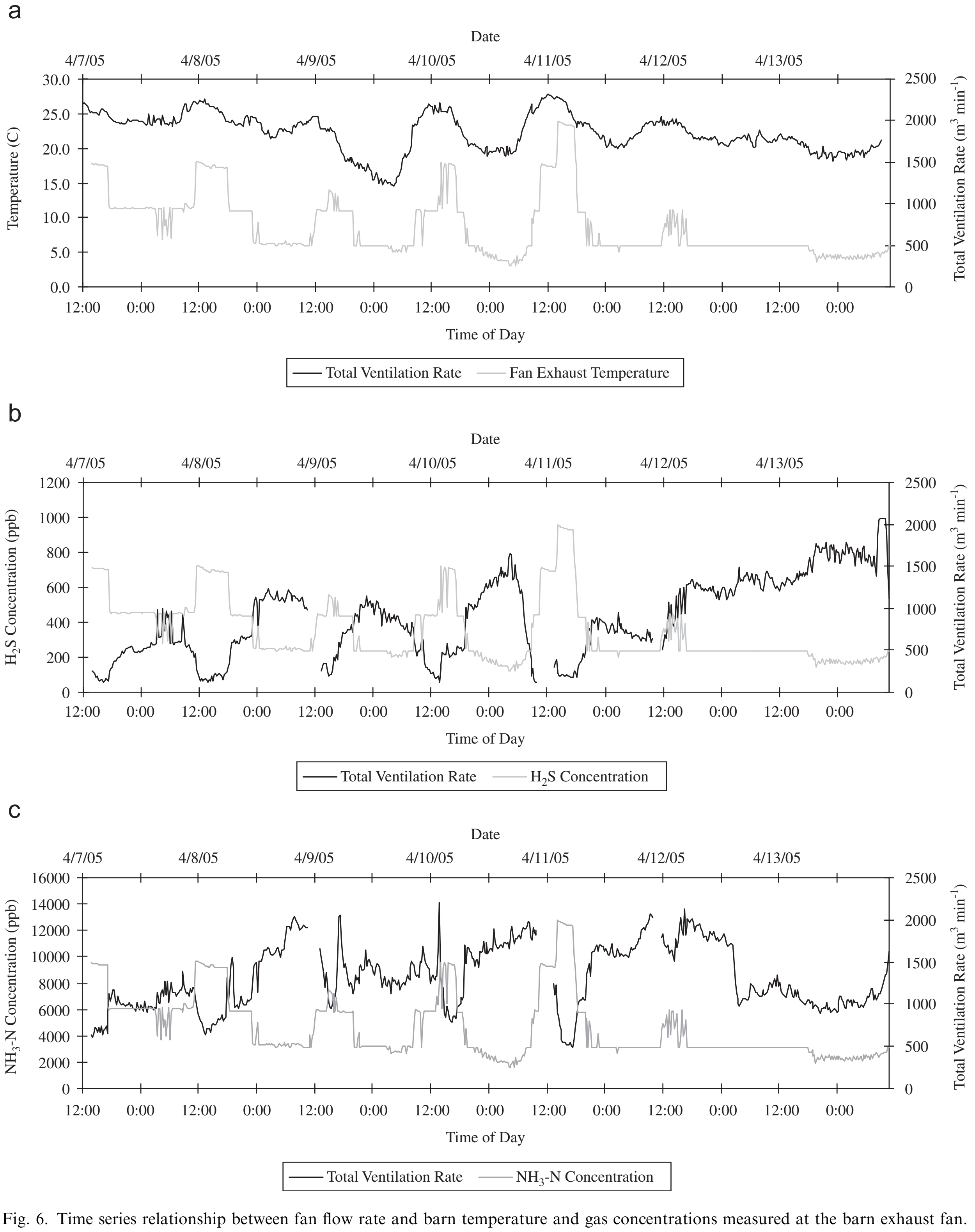


Fig. 6. Time series relationship between fan flow rate and barn temperature and gas concentrations measured at the barn exhaust fan.

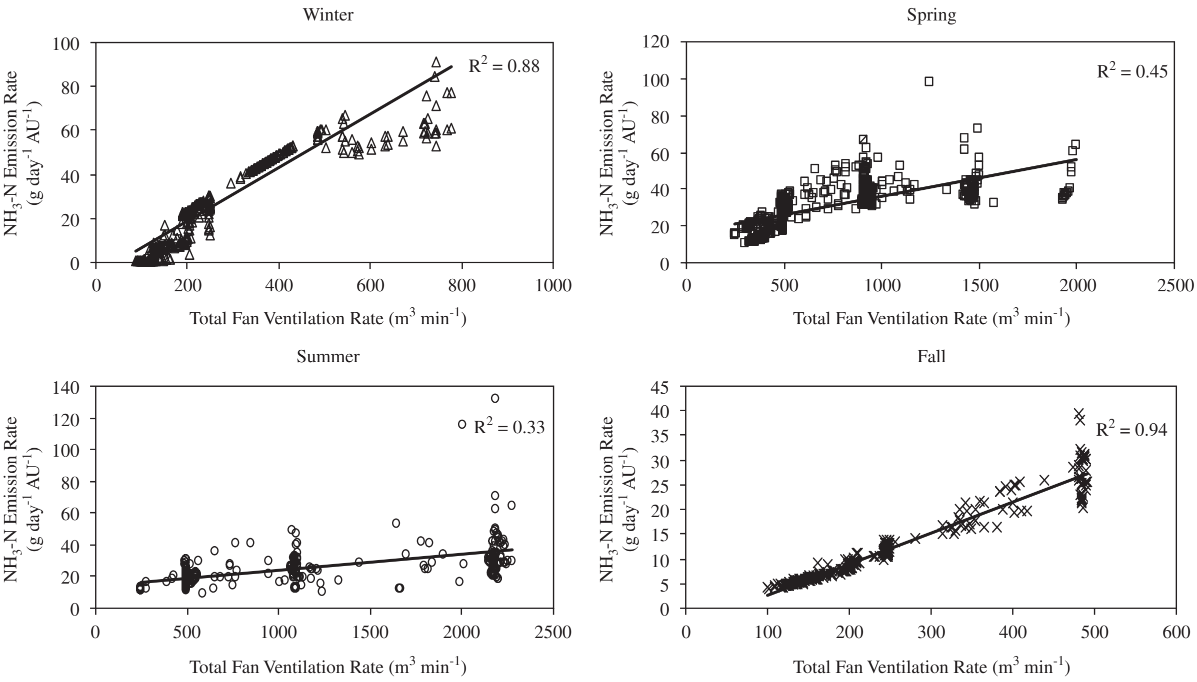


Fig. 7. Emission rates of NH_3–N plotted against total fan ventilation rates for each season.

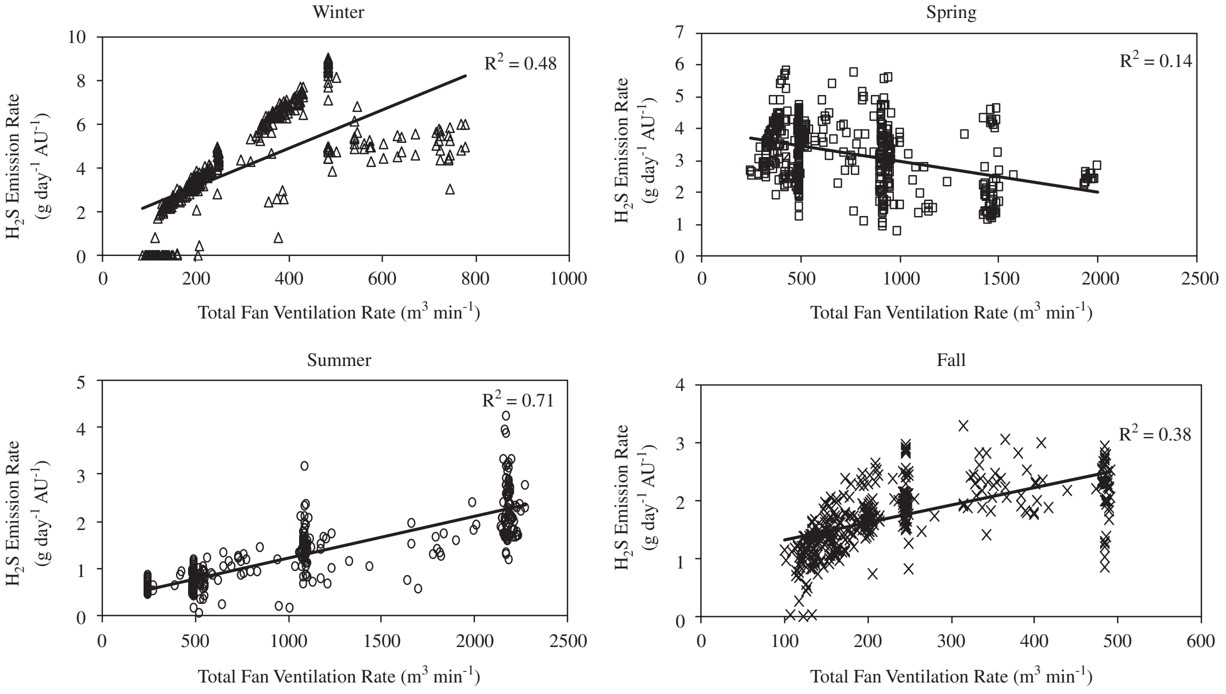


Fig. 8. Emission rates of hydrogen sulfide plotted against total fan ventilation rates for each season.

values during the winter may be attributed to less airflow through the building compared to other seasons, causing a buildup of the gas to occur. It is likely that the large concentrations measured in the spring are due to the age and weights of the animals housed in the barn.

The lowest concentrations measured at the fan exhaust occurred during the summer experimental period, when ventilation rates were higher. Measured H_2S concentrations were highest during the winter and lowest during the summer, 673 and 47 ppb, respectively. The average H_2S concentration was 6–14 times less during the summer sampling period as opposed to the other seasons. Generally, the H_2S concentrations were approximately an order of magnitude less than NH_3–N during winter, spring, and fall, and two orders of magnitude smaller during the summer season.

Calculated normalized emission rates for both NH_3–N and H_2S were highest during the winter, 33.6 and 4.2 g day^{-1}, respectively. Normalized emissions were lowest during the fall season for NH_3–N (24.3 g day^{-1} AU$^{-1)}$ and the summer season for H_2S (1.2 g day^{-1} AU^{-1}). The normalized emission rate for H_2S from the barn was ~3.5 times higher during the winter season than summer and the normalized emission rate for NH_3–N was almost three times higher in winter than fall, indicating that emissions may not increase linearly with animal mass.

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References

Agency for Toxic Substances and Disease Registry (ATSDR), Center for Disease Control, 2004. Public Health Statement for Hydrogen Sulfide, Draft for Public Comment, CAS # 7783-06-4 (January 13, 2006). 〈http://www.atsdr.cdc.gov/toxprofiles/phs114.html〉.

Aneja, V.P., Murray, G.C., Southerland, J., 1998. Atmospheric nitrogen compounds: emissions, transport, deposition, and assessment. Environmental Manager.

Aneja, V.P., Roelle, P.A., Murray, G.C., Southerland, J., Erisman, J.W., Fowler, D., Asman, W.A.H., Patni, N., 2001. Atmospheric nitrogen compounds II: emissions, transport, transformation, deposition and assessment. Atmospheric Environment 35, 1903–1911.

Aneja, V.P., Schlesinger, W.H., Niyogi, D., Jennings, G., Gilliam, W., Knighton, R.E., Duke, C.S., Blunden, J., Krishnan, S., 2006. Emerging national research needs for agricultural air quality. Eos, Transactions, American Geophysical Union 87 (3), 25, 29.

Arogo, J., Westerman, P.W., Heber, A.J., 2003. A review of ammonia emissions from confined animal feeding operations. Transactions of the ASAE 46 (3), 805–817.

Heber, A.J., Ni, J.Q., Duggerirala, R.K., Spence, M.L., Haymore, B.L., Adamchuk, V.I., Bundy, D.S., Sutton, A.L., Keely, D.T., Keener, K.M., 1997. Manure treatment to reduce gas emissions from large swine houses. In: Proceedings of the International Symposium on Ammonia and Odour Control from Animal Production Facilities. Dutch Society of Agricultural Engineering, The Netherlands, Wageningen, pp. 449–457.

Heber, A.J., Ni, J.Q., Lim, T.T., Diehl, C.A., Sutton, A.L., Duggirala, R.K., Haymore, B.L., Kelly, D.T., Adamchuk, V.A., 2000. Effect of a manure additive on ammonia emission from swine finishing buildings. Transactions of the ASAE 43 (6), 1895–1902.

Hoff, S.J., Bundy, D.S., Huebner, M.A., Zelle, B.C., Jacobson, L.D., Hetchler, B.P., Johnson, V.J., Nicolai, R.E., Schmist, D.R., Goodrich, P.R., Heber, A.J., Ni, J.Q., Lim, T.T., Tao, P.C., Zhang, Y., McClure, J., Jerez, S., Roberts, M., Koziel, J.A., Baek, B.H., Balota, A., Spinhirne, J.P., Sweeten, J.M., Beasley, D.B., Baughman, G.R., Munilla, R., 2004. Real-time ventilation measurements from mechanically ventilated livestock buildings for emission rate estimations. ASAE Meeting Paper No. 044178. St. Joseph, MI.

Jacobson, L.D., Hetchler, B.P., Johnson, V.J., 2005. Spatial, diurnal, and seasonal variations of temperature, ammonia, and hydrogen sulfide concentrations in two tunnel ventilated sow gestation buildings in Minnesota. In: Livestock Environment VII, Proceedings of the Seventh International Symposium, May, 2005, Beijing, China, pp. 18–20. ASAE Publication No. 701P0205. St. Joseph, MI.

Janni, K.A., Jacobson, L.D., Nicolai, R.E., Hetchler, B., Johnson, V.J., 2005. Airflow reduction of large belt-driven exhaust ventilation fans with shutters and loose belts. In: Livestock Environment VII, Proceedings of the Seventh International Symposium, May, 2005, Beijing China, pp. 18–20. ASAE Publication No. 701P0205, St. Joseph, MI.

Lim, T.T., Heber, A.J., Ni, J.-Q., Kendall, D.C., Reichert, B.T., 2004. Effects of manure removal strategies on odor and gas emissions from swine finishing. Transactions of the ASAE 47 (6), 2041–2050.

Ni, J.Q., Heber, A.J., Diehl, C.A., Lim, T.T., Duggirala, R.K., Haymore, B.L., 2002. Summertime concentrations and emissions of hydrogen sulfide at a mechanically ventilated swine finishing building. Transactions of the ASAE 45, 193–199.

Paerl, H.W., 1997. Coastal eutrophication and harmful algal blooms: importance of atmospheric deposition and groundwater as "new" nitrogen and other nutrient sources. Limnology and Oceanography 42, 1154–1165.

Schiffman, S.S., 1998. Livestock odors-implications for human health and well-being. Journal of Animal Science 76, 1343–1455.

Schmidt, D.R., Jacobson, L.D., Janni, K.A., 2002. Continuous monitoring of ammonia, hydrogen sulfide and dust emissions from swine, dairy and poultry barns. ASAE Meeting Paper No. 024060. St. Joseph, MI.

US Environmental Protection Agency (US EPA), 2001. Emissions from Animal Feeding Operations. EPA Contract No. 68-D6-0011. Emissions Standards Division, Office of Air Quality Planning and Standards, Research Triangle Park, 27711.

US Environmental Protection Agency (US EPA), 2003. Toxicological Review of Hydrogen Sulfide (CAS No. 7783-06-4). EPA/635/R-03/005. US Environmental Protection Agency, Washington, DC.

Warneck, P., 2000. Chemistry of the Natural Atmosphere. Academic Press, San Diego, 757pp.

Zhu, J., Jacobson, L., Schmidt, D., Nicolai, R., 2000. Daily variations in odor and gas emissions from animal facilities. Applied Engineering in Agriculture 16 (2), 153–158.