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Wintertime Factors Affecting Contaminant Distribution in a Swine Farrowing Room

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Abstract

An estimated 200,000 to 500,000 U.S. workers in concentrated animal feeding operations (CAFOs) are at risk of adverse respiratory outcomes from exposures to indoor contaminants. In the wintertime, general ventilation is minimized in the Midwest due to high heating costs required to maintain indoor temperatures optimal for animal production. Pit fans typically operate to exhaust under-floor manure pits, but little other fresh air intake exists. Many operators believe that these systems are sufficient to reduce contaminant concentrations within the building during winter. Investigating whether these pit fans provide sufficient protection against classic CAFO contaminants during minimal wintertime ventilation was warranted. Direct-reading instruments were used to measure and record concentrations of multiple contaminants using both fixed-area and mobile contaminant mapping in a farrowing room during a Midwest winter. With the exception of CO, concentrations were significantly ($p < 0.001$) higher with the pit fan off compared with those with the pit fan on. Additional analyses identified that significant changes ($p < 0.001$) in mean room concentrations of respirable dust (decreased, 77% with pit fan off and 87% with pit fan on) and CO_2 (increased, 24%) over the 5-hr study periods and that multiple fixed-area monitors rather than the much-used, single center-of-room monitor provided a more conservative (e.g., protective) assessment of room concentrations. While concentrations did not exceed occupational exposure limits from OSHA or ACGIH for individual contaminants, recommended agricultural health limits from exposure-response studies suggested in the literature were exceeded for respirable dust, CO_2, and NH_3, indicating a need to consider personal exposures and control options to reduce contaminant concentrations in farrowing rooms. Pit fans reduced NH_3 and H_2S concentrations, but these fans may not be sufficient to control dust and eliminate the need for secondary exposure prevention methods.

Keywords

concentration mapping; farrowing barn; gaseous contaminants; respirable dust; swine; ventilation

Introduction

The swine industry has transformed from traditional small herd management to large-scale, confined feeding operations over the past five decades.(1) Chronic and acute respiratory diseases have been associated with work in confinement operations, indicating the need for exposure reduction to protect these workers. Studies have identified an increase in the prevalence of chronic bronchitis and airflow obstruction in swine workers,(2) a decrement in pulmonary function (FEV_1) over a work shift,(3) an increase in signs of bronchial inflammation,(4) an accelerated decline in FEV_1,(5) and bronchial hyper-responsiveness.(6)

In direct opposition to the need to increase ventilation within concentrated animal feeding operation (CAFO) rooms to reduce contaminant concentrations, ventilation is often reduced or eliminated in winter to reduce heating costs. Wall exhausts used to cool the room in the summer are typically closed, and often sealed, while manure pit fans positioned under slotted floors remain the only operable ventilation to remove contaminants generated within the room. These lower ventilation rates contribute to higher contaminant concentration in swine CAFOs during winter months, as reported by others.(7 – 12) Mean room concentrations of dust, carbon dioxide (CO_2), ammonia (NH_3), and hydrogen sulfide (H_2S) approached exposure limits (Table I) in a farrowing building, where sows give birth and nurse piglets for approximately 21 days prior to weaning.(7) Duchaine et al.(8) found increased concentrations of dust, CO_2, and NH_3 during winter compared to summer in swine finishing operations, where pigs grow to final weight. O'Shaughnessy et al.(10) found that area airborne dust and NH_3 concentrations increased during the colder months in a farrowing building. In a task-specific assessment of personal exposure to dust in gestation (where inseminated sows are housed until ready to give birth) and farrowing buildings, it was found that personal inhalable dust concentrations were also significantly higher in winter compared to spring and summer.(11)

Researchers have used a variety of sampling strategies to assess contaminant concentrations in swine rooms. Commonly, the concentrations of contaminants have been measured at only one or two locations within a CAFO building.(7, 8, 10, 13 – 15) Single fixed-area sampling may be useful if the spatial distribution of contaminants is uniform throughout the building, but studies have found significant variation in particle concentration throughout a CAFO. Jerez et al.(9) found statistically significant differences between average total suspended particulate concentrations among sampling locations within cross sections and elevations in a wean-to-finish swine building. Wang et al.(12) found that the spatial variation in total dust concentration was affected by both ventilation rate and diurnal atmospheric changes. Spatial variability of inhalable dust concentrations inside a fattening piggery by Hinz and Linke(16) identified lower concentrations in aisles compared to pens, even though an approximate uniform spatial distribution of NH_3 concentrations was found. Peters et al.(17) identified temporal and spatial variability in large gestation barns from data acquired by mobile mapping techniques, with concentrations increasing toward the exhaust. A study of particulate concentrations in swine fattening facilities(18) identified temporal variations were more significant than spatial distribution, with daily differences more significant for small particles but hourly variation for particles ranging to 10 μm. No recommendation is available to efficiently deploy monitors to assess the risk of indoor air concentrations within a CAFO.

Many production factors affect temporal concentration variability inside a swine CAFO building. Outdoor temperatures affect heater operations, as temperatures are maintained near 20°C to optimize sow health and piglet growth. Gas-fired heaters generate fine particulate matter and may generate substantial quantities of CO if not well maintained. Temperatures may also affect the release of NH_3 and H_2S from under-floor manure pits within CAFO. In addition, feeding schedules and methods affect generation of dusts and the metabolic generation of carbon dioxide from sows and piglets, which may build over the farrowing cycle with limited ventilation. Understanding how concentrations vary over a day with limited ventilation has not been assessed.

A study was undertaken to improve our understanding of factors affecting wintertime concentrations in a swine CAFO, namely the effectiveness of pit fan ventilation and temporal variation within a shift, and to examine the optimal sampler deployment to characterize room concentrations. An active swine farrowing room was available to examine these gaps.

Site Description

The survey site was the main farrowing room at the Mansfield Swine Education Center at Kirkwood Community College (Cedar Rapids, Iowa). Three rows of five smaller crates (1.5 m by 2.4 m) and one row of four larger crates (2 m by 2.4 m) ran east to west in the farrowing room (9.2 m × 14 m, Figure 1).

The site's operation followed a 21-day farrowing cycle in fall and spring. This study examined the spring cycle, which began farrowing operations on January 10. For the first four days of the study, only 14 sows were crated (Row A was empty), and on the last day all 19 crates held sows. The heads of the sows faced the aisles located between Rows A and B and Rows C and D. All crates were equipped with an automatic feed dispenser attached to the head of the sow section of the crate, but workers manually filled the dispensers. Under the four crate rows were two 0.91-m-deep pull-plug manure pits. Two manure pit exhaust plenums ran the length of the room under the floor between crate Rows A/B and C/D and connected to fixed-speed pit fans (South: $^{1}/_{8}$ HP, 60 Hz; North: $^{1}/_{4}$ HP, 28.75 Hz) that exhausted room air to the outside. For the duration of this study, only the north pit fan was operable (0.41 m^3/sec). The test site commonly turned off the pit fans during the winter, allowing the examination of wintertime concentration differences with and without the pit fans operating.

Inside the room, four radial exhaust fans were located on the north and south walls, which were not activated during winter and were wrapped in plastic to minimize heat loss. Two single-unit pressure-activated louvers lined the east wall allowing entry of temperate hallway air when exhaust fans were operated. Eight pressure activated Bi-Flo inlet vent louvers (RayDot Industries, Cokato, Minn.) lined the ceiling over the central walk alley allowing attic air to flow into the room when room pressure became negative. Ventilation surveys concurrent with the contaminant study confirmed minimal air movement through the ceiling and wall louvers, even on relatively windy days.

Operator activities within the study room were minimal on the days measurements were made. Feeding occurred in the morning between 8:00–10:00 a.m., where an operator rolled a feed tote through the aisles and scooped and dropped food into feeders. This task took approximately 20 min. Other than manually filling the feeders, workers did not spend additional time in the farrowing room during this study's monitoring periods.

Sampling Procedures

Five sampling dates, in January–February 2012 from within a 21-day farrowing period, were randomly selected for the survey. The pit fan status (on or off) was also randomly determined and was set to the study day's condition the night prior to the scheduled sampling day.

Direct-reading instruments were used to measure respirable dust, CO_2, NH_3, H_2S, and CO concentrations, with both fixed-area station sampling and mobile contaminant mapping. A photometer (pDR-1200; Thermo-Electron Corp., Waltham, Mass.) provided continuous, real-time mass concentration readings of respirable dust. The photometers were attached to sampling pumps (Model 224-PCXR4; SKC Inc., Eighty Four, Pa.) operating at 2.0 L/min, calibrated daily pre- and post-sampling, on site, using a tetraCal NIST Volumetric Air Flow Calibrator (New Star Environmental, Roswell, Ga.). Carbon dioxide and temperature were measured using VelociCalc air velocity meters (Model 9555-X; TSI Inc., Shoreview, Minn.). VRAE multi-gas meters (RAE Systems, San Jose, Calif.) were operated at 0.4 L/min to measure CO, H_2S, and NH_3.

All instruments were set to log data at 10-sec intervals, calibrated by the manufacturer, and recalibrated prior to each sample day. Direct-reading monitors were collocated in the workplace prior to and following sampling to examine concentration drift and to ensure between-monitor differences were attributable to actual concentration differences.

Seven fixed-area stations were positioned throughout the farrowing room (Figure 1), with select instruments suspended in baskets hanging from the ceiling with the equipment inlets attached to a pole approximately 1.7 m above the floor (boxed letters A through G in Figure 1), continuously measuring contaminant concentrations until the end of the sample day. All seven stations had respirable dust monitors (indicated by P in Figure 1), four had CO monitors (V), and three had multi-gas meters (M) to measure CO_2, H_2S, and NH_3. Mean concentrations were computed for each position and sample day for three sequential 90-min periods, matched in time to the mobile contaminant mapping events. Daily means were computed by averaging over all the 90-min periods.

To obtain concurrent mobile mapping data, a technician wore each of the sampling devices (pDR with sample pump, VelociCalc, VRAE) with inlets positioned in the breathing zone. The technician spent 2 min at each of the 43 mobile sampling positions (indicated by dots in Figure 1) to gather data for contaminant maps. Positions spaced along the N/S aisles were 1.5 m apart, and positions spaced along the E/W aisles were 1.2 m apart, centered on each aisle. One sample event was defined as the time to collect 2-min samples over the entire room floor, taking approximately 90 min to cover the 43 positions. Each sample day had three sequential contaminant mapping events, with each event starting at a preselected random position. Mean concentrations by position were computed over the three sequential mapping events for a given sample day (43 per day) to generate daily concentration distributions; mean room concentrations for each 90-min period were generated by averaging over the 43 positions for each sampling event (three room mean values per day).

The average farrowing room temperature over the three sample events was computed from the mobile mapping VelociCalc air velocity meter (Model 9555-X; TSI Inc.). The average outside wind condition was measured using a rotating vane anemometer (Model 5725; TSI Inc.) positioned on the exterior west side of the farrowing room approximately 3 m from the pit fan exhaust. Average daily outdoor temperatures available from the U.S. National Weather Service were used to characterize the outdoor temperature.(19) Pit fan velocity and temperature, at the exhaust, were also measured with a rotating vane anemometer three times throughout each sample day to confirm pit fan operation.

Data Analysis

Data from collocated measurements were evaluated to ensure similar instrument responses to field concentrations. When required, instrument concentrations were adjusted with linear regression to the mean responses of similar instruments during collocated periods for each sample day. The Shapiro-Wilk test was used to assess the distribution normality of the data and ln-transformed concentration measures. An adjusted Tukey (Tukey-Kramer) test of the least-square means was used to identify differences between pit fan operation status (on/off) and differences in the 90-min average concentrations over time within a sample day (SAS Version 9.2, SAS Institute Inc., Cary, N.C.). When concentration data failed both normal and ln-normal distribution criteria, nonparametric tests were performed: a Wilcoxon two-sample test was performed to analyze the 90-min average concentrations between pit fan operation status, and a Kruskal-Wallis test was performed to analyze the 90-min average concentrations over time within a sample day. All statistical tests were evaluated at $\alpha = 0.05$.

Mapping software (Surfer Version 10; Golden Software, Golden, Colo.) was used to create distribution maps of respirable dust, CO_2, NH_3, H_2S, and CO concentrations for each sample day. The average concentration over each day's three 2-min measurements was computed for each sample position for the mobile contaminant mapping. A Kriging method was first used to create a grid for each contaminant for both mapping and fixed-area station measurements. The gridded data were plotted to map the farrowing room contaminant distribution to identify areas of high concentrations.

To evaluate risk interpretation differences between using single-point, multiple-point, or mobile contaminant mapping estimates of room concentration, three estimates of average room concentrations were generated for each sample day. The comparison relied on respirable dust concentration measures, as this was the most robust data set for fixed monitors (seven stations). For each day's set of three 90-min event averages, means were computed for: (A) the single location in the middle of the room; (B) the seven fixed sampling locations; and (C) each mapping position. Average daily concentrations were ranked in descending order for each data collection method to determine if using one long-term (90-min), seven long-term (90-min), or 43 short-term (2-min) sampling positions produced similar results when ranking overall daily average respirable dust concentrations. Room concentration estimates from each method were compared to occupational exposure limits to assess whether hazard decisions depended on the method used to characterize the concentration.

Results

Table II characterizes the environmental and production conditions over the 5 sample days. Average daily outside temperatures ranged from –0.6°C to 10.6°C, proving to be a mild winter season for the Midwest, while indoor farrowing room temperature remained relatively stable (22.9°C to 26.9°C). Outside wind speed varied between sample days with the highest wind speeds on Day 4 (4.2 m/sec) and the lowest wind speeds on Day 5 (0.8 m/sec).

Respirable dust and CO_2 fixed station and mapping concentrations were the highest during Day 2 when the pit fan was turned off. Minimum respirable dust fixed station and mapping concentrations were identified on the first sample day, and minimum CO_2 concentrations for both fixed station and mapping were identified on Day 5 (both with pit fan on). The daily mean concentration of NH_3 was highest (10.8 ppm) on Day 5, which was the warmest day with the pit fan turned on and was also the day when the test site had a full complement of sows. Ammonia concentrations were lowest on Day 3 (0.03 ppm), which also had the pit fan on but was colder than Day 5. Hydrogen sulfide concentrations were highest on Day 4 when the pit fan was off and lowest on Day 1 when the pit fan was on, but concentrations ranged from non-detect (<0.01 ppm) to 0.67 ppm. Carbon monoxide concentrations were highest on Day 1, the coldest day when the heaters operated more frequently in the farrowing room, and were lowest on Day 5, a warmer day when the heaters never cycled on. While this resulted in a maximum difference of 68% change between study days, CO concentrations were relatively low, ranging from 0.91 ppm to 1.53 ppm.

Both fixed-area and mapping concentrations on a given day were similar for each contaminant except NH_3. Fixed-area NH_3 mean concentrations were noticeably higher than the mapping mean for Days 2, 4, and 5, leading to concerns that the mapping instrument's NH_3 sensor may not have been functioning properly.

Table III provides mean contaminant concentrations by pit fan operation, illustrating that when the pit fan was turned off, all concentrations were significantly higher than when the pit fan was turned on, except for CO. This result was apparent when using parametric ($p < 0.001$) and nonparametric tests on non-transformed ($p < 0.001$) and ln-transformed data ($p < 0.001$). When the pit fan was turned off, daily fixed-area respirable dust concentrations were, on average, 41% higher and CO_2 concentrations were 28% higher (see online supplemental materials for additional details).

The significantly higher contaminant concentration when the pit fan was turned off was apparent when comparing contaminant mapping contours for respirable dust (Figure 2) and CO_2 (Figure 3). With the pit fans on (Figure 2a), slightly lower respirable mass concentrations were identified near the east hallway, where doors and louvers allowed relatively clean air into the room. With the pit fans off (Figure 2b), concentrations were noticeably higher with a slight gradient from low near the east hallway to high near the northwest corner. For CO_2, concentration varied little across the room with the pit fan on (Figure 3a), but it was highest in the aisle between crate Rows C and D (10.5 m from the south wall), where the heads of crated sows in these rows faced. With the pit fan off (Figure

3b), again this aisle contained the largest concentrations, with a noticeable low concentration in the center aisle (7.5 m from the south wall), where the tails of crated sows from Rows B and C faced.

To examine the extent to which concentrations changed throughout the 5-hr sample period, the 90-min average data, at each fixed sample position, were compared between three sequential 90-min mapping event periods. Adjusted Tukey analysis and nonparametric Kruskal-Wallis tests were performed, as these data were neither normally nor ln-normally distributed. Both tests yielded the same results. Respirable dust concentrations were significantly higher in the first two 90-min periods ($p < 0.001$, both tests, both fan conditions), when early morning swine activity and feeding tasks occurred, compared to the third 90-min period. This trend occurred for both fan operation conditions: when the pit fan was turned on, the largest decrease in respirable dust concentration from the beginning to the end of the sample day was by 87%, and when the pit fan was turned off, there was a 77% decrease in respirable dust concentration. Concentrations of CO_2 were significantly lower in the first 90-min period compared to the second and third (p < 0.011 Tukey and < 0.027 Kruskal-Willis), a trend that was again apparent for both fan operation conditions. Concentrations increased an average of 24% over these periods. No other temporal differences were observed between the event means for NH_3, H_2S, and CO during sample days when the pit fan was off or on, although the sample sizes for these measurements (nine for fan on, six fan off) may have limited our ability to detect differences.

For each sample day, three estimates of the room mean concentrations were computed for respirable dust based on data from (A) the single center-of-room fixed monitor, (B) all seven fixed monitors, and (C) mobile mapping (Table IV). The three methods identically ranked the daily average concentrations from high to low, with the exception of using one centrally located fixed-area station that inversely ranked sample Days 3 and 5 compared to the other two methods. Estimates of mean respirable dust concentrations were compared to one-tenth of the occupational exposure limit (OEL) values,(20) namely, 0.3 mg/m^3 ($^1/_{10}$ ACGIH® threshold limit value, TLV®(21)). Using multiple fixed-area stations and mobile contaminant mapping, measured concentrations exceeded this target respirable dust concentration on 4 and 3 days, respectively. However, using one representative fixed-area station in the middle of the room, only 2 of 5 days had measured daily average concentrations means above 0.3 mg/m^3. One centrally located monitor underestimated mean room concentrations, which may affect interpretation of exposure risk.

Discussion

Impact of Pit Fan on Contaminant Concentration

Operation of the manure pit fan significantly reduced contaminant concentrations, with the exception of CO. An increase in contaminant concentration during the colder months when ventilation rates were low has already been reported. Inherently, when ventilation rates decrease, as in our case when the pit fan was not operating, concentrations will experience a further increase throughout the day. A statistically significant difference was found between mean respirable dust concentrations during days when the pit fan was turned off compared to when it was turned on, which resulted in an average of 41% higher dust concentration when the pit fan was turned off. However, in reality, the dust control provided may not be sufficient to eliminate the need for secondary exposure prevention methods (i.e., respiratory protection) (maximum area concentration with fan off: 0.54 mg/m^3, minimum area concentration with fan on: 0.30 mg/m^3).

A statistically significant difference was found in CO_2 concentration when the pit fan was turned off, with a 25% increase compared to concentrations when the pit fan was turned on. Clark and McQuitty(7) found daily CO_2 averages of 2570 ppm and 2765 ppm in farrowing rooms that maintained a minimal ventilation rate, comparable to the daily average area concentrations measured when the pit fan was on in the current study. The current and previous studies measured CO_2 concentrations above ASHRAE indoor air quality recommended levels (1000 ppm) indicating potential worker discomfort,(22) but note that this limit is not a guideline based on preventing a human health response. These concentrations also exceeded the Donham et al.(13) recommendation of 1540 ppm.

A statistically significant difference in NH_3 and H_2S concentrations between pit fan settings was observed, although concentrations remained below the 25 and 1 ppm TLVs, respectively. Mean daily NH_3concentration of 3.9 ppm when pit fan was turned on was similar to the area mean concentration of 3.64 ppm (standard deviation = 2.57 ppm) obtained by O'Shaughnessy et al.(10) in a farrowing building with minimal ventilation in winter. Mean NH_3 concentration measured with the pit fan off (Days 2 and 4) and on one day with the pit fan on (Day 5) exceeded the 7 ppm limit recommended by Donham et al.(13) Heightened wintertime levels of NH_3 were found in previous studies,(7, 8, 23) which could be due to differences in the swine operation, the warmer temperatures, and wind conditions during the current study. Farrowing barns with both deep and shallow manure pits were present in the study conducted by Clark and McQuitty,(7) who reported that pits were filled to overflowing in one of the barns and a continuous flow gutter was used in another, both of which may account for the higher NH_3 concentrations than in the current study, where the manure pits did not overflow. Duchaine et al.(8) found higher NH_3 concentrations in swine fattening (finishing) operations that housed larger and more swine in buildings, having a smaller room volume per pig ratio compared to the current farrowing study.

Temporal Factors Affecting Concentration

Over the 5-hr sample period, significant decreases in respirable dust and increases in CO_2 concentrations were identified, both with and without the pit fan on. This change in respirable dust concentration could be related to the feeding that occurred over the time period during events one and two, which agrees with results of previous studies identifying feed contributions to higher dust concentrations.(9, 15, 18) In addition, more sow activity in the farrowing room occurred during feeding, which also contributes to an increase in concentration.(7, 9, 12) While feeding occurred in the late portion of the first 90-min or the early portion of the second 90-min sampling round, concentrations were reduced by the third 90-min period within each day's sampling event.

However, temporal changes in CO_2 exhibited opposite trends. When the pit fan was not running, the room was found to have a significant (24%) increase in area CO_2 concentration during the middle and end of the 5-hr sample period. Carbon dioxide is exhaled continuously by swine. Limited air exchange with the pit fan off resulted in increased CO_2 concentrations throughout the day. Mean concentrations of CO_2 did not increase as much over the day when the pit fan was compared to when the pit fan was turned off (maximum 15% increase).

Assessment of Air Quality

Across all of the contaminants, area concentrations did not surpass individual regulatory or international consensus occupational exposure limits (Table I). However, respirable dust, CO_2, and NH_3 exceeded recommendations for agricultural health limits suggested in the literature. Specifically, for non-smokers, Donham et al.(3) identified that exposure to 2.8 mg/m^3 as total dust for 2 or more hours per day for 6 years was associated with a 10% decline in FEV_1. In addition, Donham et al.(13) identified that respirable dust of 0.23 (area) and 0.28 (personal) mg/m^3 along with personal carbon dioxide exposures exceeding 1540 ppm was associated with a significant decrease in baseline pulmonary function (FEV_{50} and FEF_{75}) in swine workers.

Measured area mean respirable dust concentrations were above the recommended area limit of 0.23 mg/m^3 for all sample days and exceeded the $^1/_{10}$ TLV (0.3 mg/m^3, indicative of "low risk" exposure category) for 2 to 4 of the sample days, depending on method used to sample and quantify mean exposures. Mean CO_2 concentrations ranged from 2821 ppm to 3804 ppm over all sample days, remaining above the ASHRAE(22) recommendation of approximately 1000 ppm and the Donham et al.(13) recommendation of 1540 ppm to prevent a decrease in pulmonary function; however, the average daily mean concentrations did not surpass the ACGIH TLV (5000 ppm). Mean area NH_3 concentrations were higher than the recommended 7 ppm limit(13) for three of the five sample days but were well below the ACGIH TLV (25 ppm). In this work site, the time workers spent in this single-room farrowing facility was shorter than what is observed in larger production facilities where workers often have to perform tasks in multiple farrowing rooms across a shift.

Averaging concentration measurements using multiple data collection methods (one representative fixed-area station, multiple fixed-area stations, and contaminant mapping) produced similar rankings of average daily concentrations; however, a difference in the concentrations was noticed between the three data collection methods when comparing daily concentrations to the target concentration of 0.3 mg/m^3 ($^1/_{10}$ TLV). Using multiple fixed-area stations resulted in the highest daily average concentration measurements for four out of the five sample days, followed by mapping, with using one representative fixed-area station in the middle of the room yielding the lowest room concentration estimate. This suggests that using multiple fixed stations may capture sufficient variability and quantify higher concentrations that would help make more conservative health protection decisions to control potential worker exposure. The area sampling methods did not assess personal exposure, which has the potential to underestimate worker exposure. Therefore, the most conservative approach should be strongly considered: using multiple fixed-station monitors to characterize the air quality within swine farrowing barns is recommended. Although more equipment-intensive, the multiple fixed-station monitoring method requires less personnel resources than mobile contaminant mapping.

Obtaining repeated measurements and analyzing a larger sample size may improve spatial and temporal contaminant resolution of contaminant concentrations within a farrowing barn. When examining NH_3 concentrations, there was no statistical difference between pit fan settings when using daily average concentrations ($N = 15$, $p = 0.06$) but when using three 90-min average concentration data ($N = 45$), significant differences in room concentration by pit fan setting was identified ($p = 0.001$). The larger sample size provided a better understanding of contaminant distribution in the farrowing room.

Relevance of Test Site to Production Farrowing Barn Rooms

To understand the relevance of the results from this study of an educational swine production building, comparison of the test facility to local swine farrowing operations is necessary. Three local farrowing barns were visited to examine layout, ventilation, and operational practices (Table V). The test site was a farrowing facility with similarities in the operation, physical layout, and ventilation practices to three other farrowing facilities in Iowa. The test site did possess characteristics that differed from the other farrowing rooms that may affect contaminant distribution. Three out of the four walls of the test site farrowing room had direct contact with the outside, where inherent leaks in the building could dilute indoor concentrations more than in typical production barns that have only one wall (or two walls for the end units) in contact with the outside. Another important difference is the larger room volume-to-sow ratio in the test site, which may have resulted in lower contaminant concentrations at the test site compared to what may be found at production farrowing facilities. The test site was a smaller operation with fewer crates per room and deeper manure pits than more recently constructed farrowing barns. However, the test site exhibited ventilation, thermal regulation, and feed distribution characteristics typical in larger production farrowing rooms that will allow the results to be generalizable to farrowing facilities, but actual concentrations in longer rooms with more crates may not be represented by those measured here.

Limitations

The generalizability of findings in this study is limited by several factors, including: the examination of only a single geometry farrowing room, occupancy less than full sow occupancy during four of five sampling days, one of two manure pit fans was inoperable during this study, and winter temperatures were warmer than usual during this 2012 sample period. While these factors affected the concentrations measured during this study, they reflect conditions that existed during the randomly selected sampling days during one farrowing cycle. In addition, while no personal exposure monitoring for swine farrowing operators was included in this study, thereby preventing our ability to fully characterize risk of working within this swine barn, the examination of mean and spatial and temporal variation of concentration throughout the room allowed understanding of relative performance of pit fans as room ventilation and identified risk factors associated with increased contaminant concentrations.

Conclusions

Respirable dust, CO_2, NH_3, H_2S, and CO concentrations were measured at fixed-area stations and mapped in a 19-crate farrowing room in winter. Concentrations of H_2S and CO were well below occupational exposure limits, both regulatory and industry recommendations. However, respirable dust, CO_2, and NH_3 concentrations exceeded industry recommendations within the room, indicating exposure risk to workers who would be in the room for a full shift. The effectiveness of the pit ventilation, even with only one of the two fans operational, was demonstrated by significant reductions in concentrations of all contaminants except CO, for which concentrations were related to ambient temperature and room heater operation. Respirable dust concentrations were significantly higher in the beginning of the day, regardless of pit fan operation, due to the feeding operations and sow activity, but declined later in the day. Alternatively, swine respiration resulted in increased CO_2 concentrations over monitoring days when the pit fan was off. Pit fans were not always able to reduce respirable dust concentrations and NH_3 below industry-recommended limits (0.23 mg/m^3 and 7 ppm, respectively). Finally, of the three methods used to estimate daily room concentrations of respirable dust, the method that included multiple (seven) fixed-area monitors resulted in the highest concentration estimate, indicating a need for more than one centrally located fixed sampler to adequately characterize room concentrations. Using information from multiple monitors provides a more conservative estimate of exposure risk and is recommended for future studies examining air quality in a swine CAFO.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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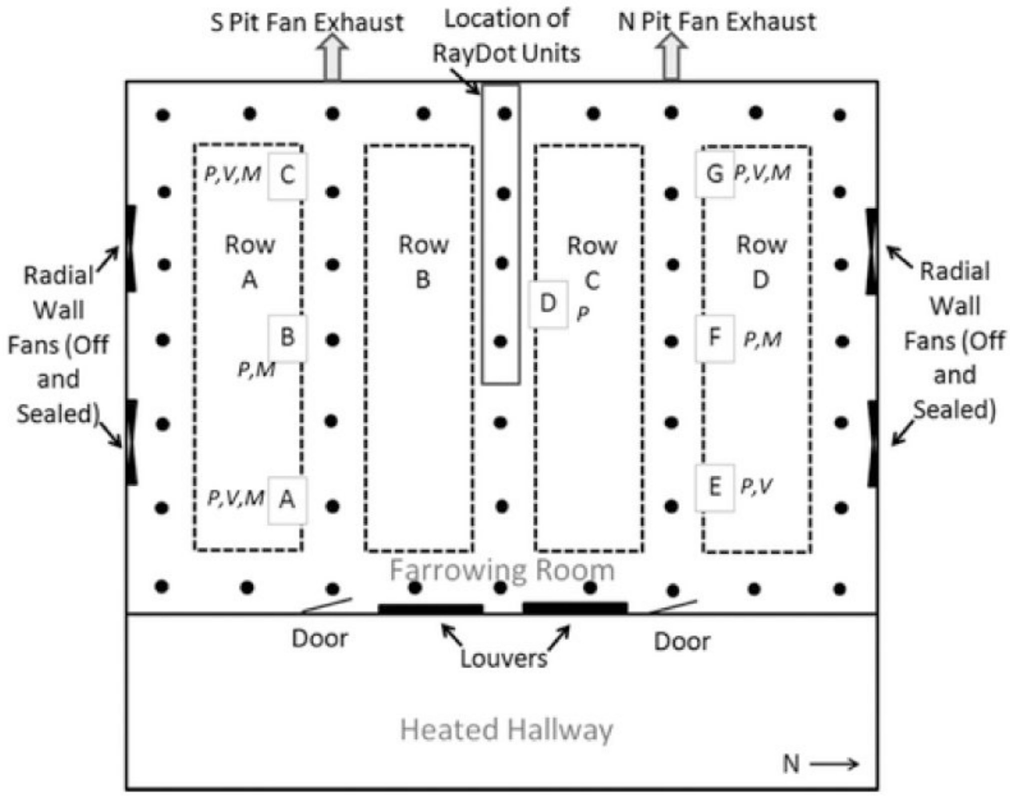

Figure 1.
Schematic diagram of the swine farrowing room and attached hallway. Boxed letters A–G indicate fixed sampling positions. Letters by the sampling positions indicate the equipment deployed at that position: P = photometer (respirable dust); V = VelociCalc (CO_2), M = multi-gas (CO, H_2S, NH_3). All three devices were used at the 43 mobile monitoring positions, indicated by the dots in the aisles.

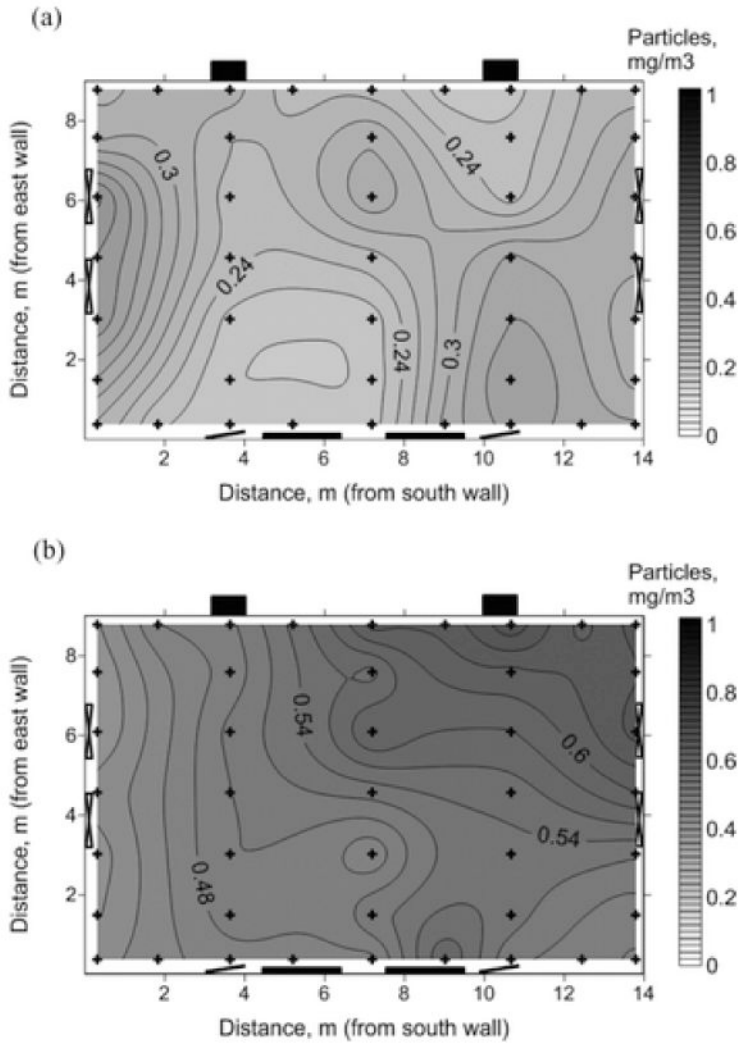

Figure 2.

Respirable dust concentration contour for (a) Day 1 with pit fan on, and (b) Day 2 with pit fan off

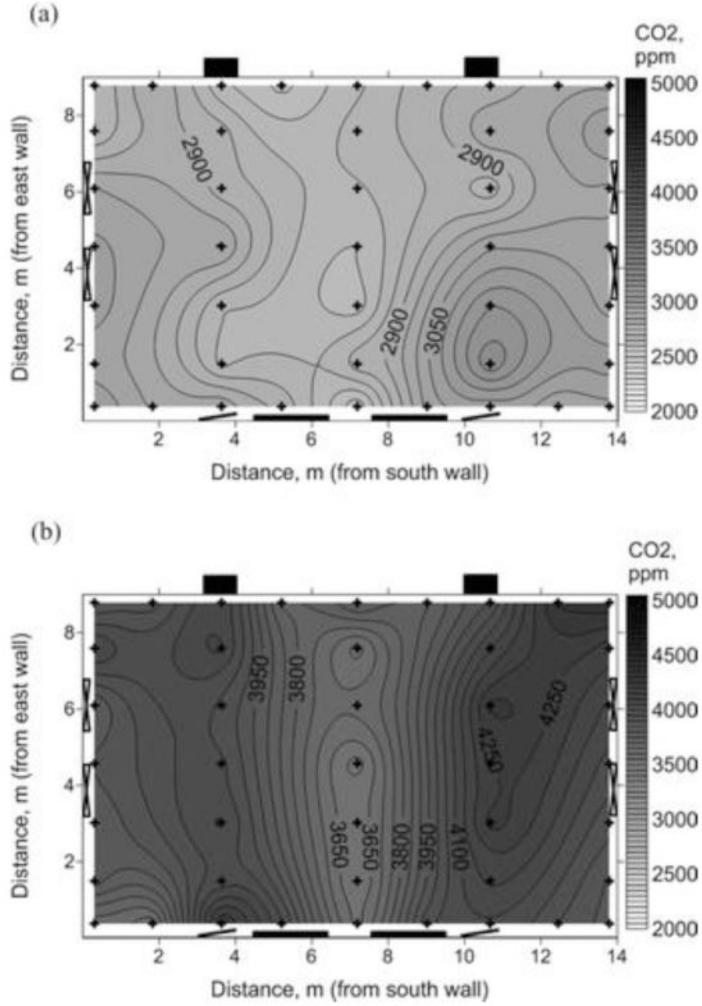

Figure 3.

Carbon dioxide concentration contour for (a) Day 1 with pit fan on, and (b) Day 2 with pit fan off

Table I

OELs for Common Swine CAFO Contaminants

Contaminant	OSHA PEL [A]	ACGIH® TLV®	Industry Recommendations
Dust (respirable)	5 *mg/m*^{3}	3 *mg/m*^{3}	0.23 mg/m^3 [B]
CO_2	5000 *ppm*	5000 *ppm*	1540 ppm [B]
NH_3	50 *ppm*	25 *ppm*	7 *ppm* [B]
H_2S	10 *ppm*	1 *ppm*	—
CO	50 *ppm*	25 *ppm*	—

[A] Permissible exposure limit.

[B] Source: Reference 3.

Table II

Environmental and Operating Conditions Recorded for Each Sample Day

Conditions	Day 1	Day 2	Day 3	Day 4	Day 5 [A]
Manure pit fan setting	On	Off	On	Off	On
Outside temperature °C (°F)	–0.6 (31)	3.3 (38)	0 (32)	10.6 (51)	7.2 (45)
Farrowing room temperature °C (°F)	25.1 (77.2)	24.4 (75.9)	26.9 (80.5)	24.7 (76.5)	22.9 (73.3)
Mean outside wind conditions (Airflow in m/sec)	3.2	2.4	2.1	4.2	0.8
Number of pigs (sows + piglets)	115	115	115	115	120
Range of piglet age (days)	2–1	5–14	8–17	9–18	11–20

[A] The room heaters did not turn on during Day 5.

Table III

Concentrations by Pit Fan Operation (Fixed Area)

Contaminant	Sampling Method	Sample Size, Fan On/Fan Off [A]	Mean Concentration [B] Fan On	Fan Off	Increase with Fan Off,%	Significance Test,[C] p
Dust	Fixed station	63 / 42	0.33	0.46	41	<0.001
	Mapping	129 / 86	0.31	0.46	50	
CO_2	Fixed station	36 / 24	2920	3660	28	<0.001
	Mapping	129 / 86	2910	3690	26	
NH_3	Fixed station	27 / 18	3.9	8.4	113	0.011
	Mapping	129 / 86	1.2	0.76	-37	
H_2S	Fixed station	27 / 18	0.11	0.48	332	<0.001
	Mapping	129 / 86	0.09	0.40	342	
CO	Fixed station	27 / 18	1.16	1.12	-4	0.991
	Mapping	129 / 86	1.14	1.12	-2	

[A] Calculations for fixed area sampling used 90-min average concentrations, three per sample day, 3 days with fans on, 2 off. Calculations for mapping used three 2-min average concentrations at 43 positions per day, 3 days with fans on, 2 off.

[B] Concentrations in ppm for all but dust, which is in mg/m^3.

[C] Wilcoxon two-sample (non-parametric) test comparing fixed area concentrations between fan settings. Same interpretation for parametric tests (non-transformed and ln-transformed data analyzed with adjusted Tukey).

Table IV
Comparison of Daily Mean (SD) Respirable Dust Concentrations (mg/m^3)

Sample Day (Fan Setting)	Central Fixed-Area Station (1 Station, 3 Events)	Multiple Fixed-Area Stations (7 Stations, 3 Events)	Contaminant Mapping (43 Locations, 3 Events)
1 (On)	0.263 (0.110)^5	0.296 (0.120)^5	0.271 (0.086)^5
2 (Off)	**0.470** (0.152)^1	**0.539** (0.186)^1	**0.520** (0.162)^1
3 (On)	0.271 (0.091)^4	**0.345** (0.134)^3	**0.337** (0.127)^3
4 (Off)	**0.371** (0.113)^2	**0.394** (0.116)^2	**0.398** (0.116)^2
5 (On)	0.287 (0.092)^3	**0.340** (0.110)^4	0.298 (0.085)^4

Notes: Superscripted numbers 1–5 represent the rank in dust concentration in descending order for each data collection method. Bolded numbers indicate mean concentrations exceeded the 0.3 mg/m^3 ($^1/_{10}$ TLV) criteria.

Table V
Farrowing Room Comparison—Survey Site and Additional Rooms Visited

Characteristic	Producer 1	Producer 2	Producer 3	Survey Site
Annual production	31,000	62,000	27,000	1200–1500
Number of rooms	8	9	14	1
Number of crates per room	26	1 room @ 28 8 rooms @ 58	4 rooms @ 6 4 rooms @ 10 5 rooms @ 20 1 room @ 30	19
Crate size	2.1 m × 1.5 m	2.1 m × 1.5 m	2.1 m × 1.5 m	15@ 2.4 m × 1.5 m 4@ 2.4 m × 2.0 m
Farrowing cycle	3 Weeks	3 Weeks	3 Weeks	3 Weeks
Employee schedule	Full shift	Full shift	Full shift	Sporadic
Feeding	Manual	Pneumatic	Manual	Manual
Target litter size	10.5	10–10.5	11–13	8
Manure pit depth	0.61 m	0.46 m	0.76 m-0.91 m (shallow); 2.4 m (deep)	0.91 m
Temperature Regulation	Space heaters; evaporative cooling	Space heaters; evaporative cooling	Space heaters; evaporative cooling	Space heaters
Ventilation practices				
Primary	Manure pit fan	Manure pit fan	Manure pit fan	Manure pit fan
Exhaust fan control	Thermal sensor	Thermal sensor	Thermal sensor	Thermal sensor
Exhaust fan position, relative to main hallway	Opposite	Opposite	Opposite	Adjacent
Ceiling inlets	None	Above aisles	Above aisles	Above one central aisle