Assessment of Interventions to Improve Air Quality in a Livestock Building

T. R. Anthony, A. Y. Yang, T. M. Peters

ABSTRACT. *This study examined the effectiveness of engineering controls to reduce contaminant concentrations in a swine farrowing room during winter in the U.S. Midwest. Over two winters, changes in air quality were evaluated following installation of a 1700 m^3 h^{-1} (1000 cfm) recirculating ventilation system to provide 5.4 air exchanges per hour. This system incorporated one of two readily available dust control systems, one based on filtration and the other on cyclonic treatment. A second treatment evaluated reductions in carbon dioxide (CO_2) associated with replacement of standard, unvented gas-fired heaters with new vented heaters, installed between the two winter test periods. The concentrations of carbon monoxide and hydrogen sulfide were negligible in the test room. Although concentrations of ammonia increased over each winter test period, the increase was unrelated to increased air movement from the new recirculating ventilation system. The dust concentrations were significantly reduced by the ventilation system for both inhalable dust (23% to 44% with filtration, 33% with cyclone) and respirable dust (32% with filtration, 20% with cyclone), significant ($p < 0.024$) for all except respirable dust using the cyclone ($p = 0.141$). The filtration unit is recommended to improve livestock building air quality because it was more effective than the cyclone unit at reducing respirable dust. Carbon dioxide concentrations were significantly lower with vented heaters (mean = 1400 ppm, SD = 330 ppm) compared to unvented heaters (mean = 2480 ppm, SD = 160 ppm). A 940 ppm reduction in CO_2 was attributed to the use of the vented heater, after accounting for differences in outdoor temperatures and animal housing over both test periods. The benefits of readily available technology to significantly reduce concentrations of dust and CO_2 demonstrates useful control options to improve air quality in swine buildings.*

Keywords. *Animal feeding operation, Carbon dioxide, Dust control, Gas-fired heater, Indoor air quality, Ventilation.*

An estimated 200,000 to 500,000 U.S. swine production workers are at substantial risk of adverse respiratory outcomes that include increased bronchial inflammation (Pedersen et al., 1996; Larsson et al., 1994), decreases in forced expiratory volume (FEV_1) across a work shift (Reynolds et al., 1996), accelerated FEV_1 decline (Iversen and Dahl, 2000), and bronchial hyperresponsiveness (Vogelzang et al., 2000). Corimer et al. (1991) found higher prevalence of chronic bronchitis and airflow obstruction for Canadian swine workers spending 3 h per day or more in swine confinement buildings, and Radon

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et al. (2001) found a dose-response relationship between respiratory symptoms and number of hours per day inside swine confinement buildings in Europe.

Donham et al. (1995) recommended that 8 h exposures for this workforce be maintained below 2.4 mg m^{-3} for "total dust" (as measured with a closed-face 37 mm cassette), below 0.23 mg m^{-3} for respirable dust, and below 7 ppm for ammonia (NH_3). There is currently no exposure limit for inhalable swine dust, but inhalable dust exposures maintained below the "total dust" exposure limits would be protective because inhalable dust samplers collect larger particles more efficiently than closed-face 37 mm cassettes. The recommendations by Donham et al. (1995) are all lower than regulatory limits, namely the U.S. Occupational Safety and Health Administration (OSHA) permissible exposure limits (PELs), and consensus standards, including the American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit values (TLVs) and the U.S. National Institute of Occupational Safety and Health (NIOSH) recommended exposure limits (RELs). These organizations recommend safe limits for exposure to single compounds in the workplace and are, by nature, less protective than aggregate exposure recommendations established to protect workers exposed to multiple compounds that elicit similar health outcomes.

Both animal respiration and gas-fired heaters generate carbon dioxide (CO_2), which may cause high concentrations in livestock buildings. Growing evidence provides new motivation to reduce CO_2 in livestock buildings. Significant declines in the cognitive ability of office workers were identified with CO_2 exposures in the range of 945 to 2500 ppm (Satish et al., 2012; Allen et al., 2016). For swine production workers, Donham et al. (1989) associated CO_2 concentrations above 1540 ppm with decreased lung function, specifically reduced forced expiratory volume (FEV_{50}) and forced expiratory flow (FEF_{75}). In addition, toxicological studies showed that the presence of CO_2 with swine barn dust exposures increases lung inflammation responses compared to dust-only exposures (Schneberger et al., 2015).

Studies continue to report concentrations in excess of recommended exposure limits (Predicala et al., 2001; Peters et al., 2012; Reeve et al., 2013). Exposures in production livestock buildings are often highest in the winter, when fresh air intake is restricted to minimize heating costs. Recommended ventilation rates are 34 m^3 h^{-1} (20 cfm) per head in farrowing operations during the winter to control moisture, gases, dust, and odors (Murphy et al., 1990), although these flow rates may not be sufficient to adequately reduce contaminants to safe levels. Successful ventilation systems for production livestock buildings must control hazardous dusts and gases during this high-risk season while being sensitive to heating costs that might be required to treat fresh air.

A simulation model was developed and used to examine the cost and effectiveness of a recirculating ventilation system with commercially available dust control technology in a swine farrowing room (Park et al., 2013, 2017). Anthony et al. (2014) applied the Park et al. (2013) model to simulate conditions in a farrowing barn, matching the physical parameters of the Reeve et al. (2013) test site. These previous modeling studies identified that filtration and cyclonic systems were both cost-effective dust removal options. Simulations also identified that standard, unvented, gas-fired heaters used to heat the room would increase CO_2 concentrations to hazardous levels. A potential to reduce CO_2 by 35% by replacing traditional gas-fired heaters with units that vent combustion gases to the outside was identified in the Anthony et al. (2014) simulations. The ventilation rate, treatment types, and heater replacement recommendations from these simulation studies guided the design of this field experiment.

This article describes the results of field testing of two interventions to reduce concentrations of dust and CO_2 in livestock buildings. The objectives of this study were to determine if (1) ventilation with dust control significantly and substantially reduces inhalable and respirable dust concentrations without increasing gas concentrations in swine farrowing and (2) vented heaters substantially reduce CO_2 concentrations in swine farrowing.

Methods

Test Site Description

This two-winter study (December through February of 2013-2014 and 2014-2015) was conducted in a swine farrowing room at the Kirkwood Community College Mansfield Swine Education Center in Cedar Rapids, Iowa. The 19-sow capacity farrowing room (9.2 m × 14 m) included three rows of five farrowing crates, each 1.5 m × 2.4 m, and one row of four 2 m × 2.4 m crates (fig. 1a). This room had two independent shallow plug-pull manure pits, each with a 1478 m^3 h^{-1} (870 cfm) manure pit fan discharging outside the building to the west. These fans were operated continuously during the first test period but only after January 15 in the second test period. In both test periods, the four radial exhaust fans on the north and south walls were closed, and eight pressure-activated ceiling louvers (RayDot Industries, Cokato, Minn.) located above the central aisle in the room (not shown) were locked in the closed position. Typical of this site's operation, no mechanical system was used to provide air into the room to replace the air that was exhausted from the pit by the two pit fans. Replacement air passively entered the room through the two pressure-activated louvers along the east wall (propped open approximately 2 to 5 cm) and through the two doors leading to the heated hallway. Across the hallway from the farrowing room were a nursery and a second farrowing room.

Intervention Equipment

The ventilation control intervention (fig. 1b) included installation of 20 cm (8 in.) ducts to exhaust the room air and convey it to the outside dust control unit. All ducts outside of the building were wrapped with insulation. In the first test period (2013-2014), the dust control unit was a filtration unit (shaker dust collector with standard polyester sateen filter, model SDC-140-3, United Air Specialists, Inc., Cincinnati, Ohio). In the second test period (2014-2015), the dust control unit was a cyclone (model 16, Donaldson, Inc., Minneapolis, Minn.). The treated air was returned to the room through a 25 cm (10 in.) duct that split to distribute the airflow over the two head aisles through two 25 cm (10 in.) fabric diffuser ducts suspended at the ceiling (Softflow Diffusers, Air Distribution Concepts, Delvan, Wisc.). The flow rates through both control systems was 1700 m^3 h^{-1} (1000 cfm), resulting in 5.4 air changes per hour in the farrowing room.

The second intervention involved the gas-fired heaters. In both test periods, two forced-air heaters were located above the farrowing crates near the east wall of the room (fig. 1a). The heater operation was automated with a six-stage controller (TC5-2V4SA, Airstream Ventilation Systems, Assumption, Ill.) that responded to feedback from two temperature probes suspended in each of the two the head aisles. The system set point was 21.7°C (71°F), maintaining the room temperature between 21.1°C and 22.2°C (70°F and 72°F).

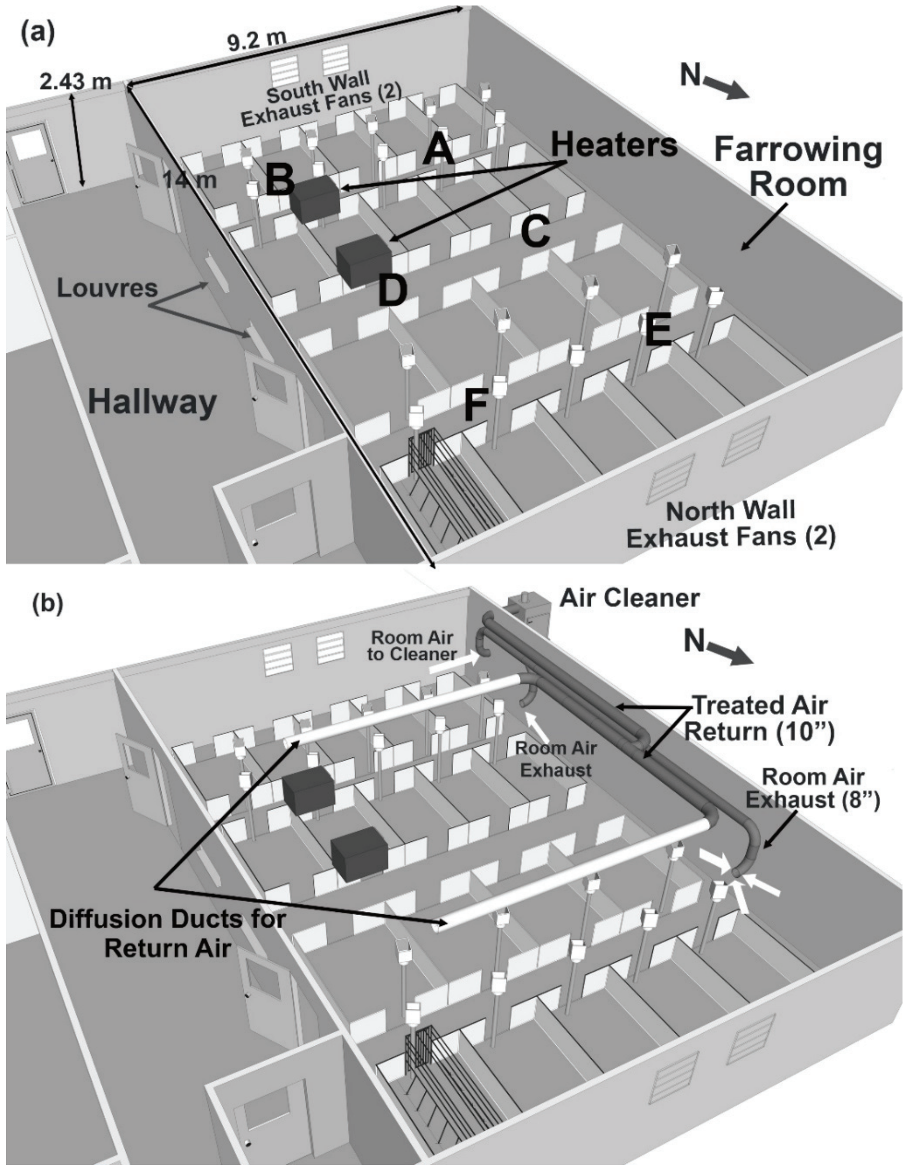

Figure 1. Farrowing room and adjoining hallway: (a) pre-intervention, with fixed area monitoring positions indicated as A-F, and (b) with recirculating ventilation system and air cleaner installed.

In the first test period, the existing unvented heaters (Guardian 60, 60,000 BTU, L.B. White Co., Onalaska, Wisc.) were in place, with only one unit in operation (south heater, fig. 1). These gas-fired heaters reflect the most commonly observed heaters in U.S. Midwest livestock production operations. The single operating heater was on for the majority of the first test period due to a particularly cold winter. Between the two test periods, the traditional unvented heaters were replaced with two new ventilated heaters (Effinity 93,

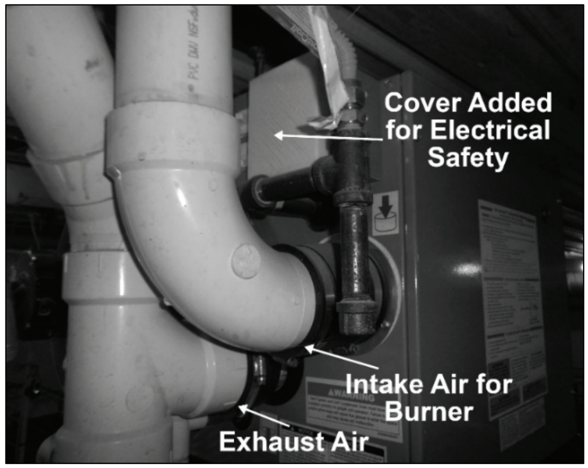

Figure 2. Back of installed vented heater, illustrating intake and exhaust ducts requiring installation.

60,000 BTU, Modine Manufacturing Co., Racine, Wisc.). These units incorporate a heat exchanger, where combustion air for the burner was brought in from the attic and combustion gases were exhausted to the outside (fig. 2). While both unvented heaters in the farrowing room were replaced for the second test period, the hallway and two additional rooms in this building relied on traditional unvented forced air heaters throughout both test periods.

Sampling Strategy

Air quality was measured for 24 h on 18 (filtration) and 19 (cyclone) randomly selected days. Because room contaminant concentrations generally increase over several months, and the actual concentrations may vary with animal housing and outdoor temperatures, sampling with the system off was required during each test period. In each test period, the "system off" days were obtained over three weeks: prior to system operation (week 1), midway through the study (week 6), and at the end of the study (week 11). A 24 h waiting period was required after any change in ventilation status prior to conducting air quality sampling.

For each 24 h sampling period, monitors were positioned at six locations (A through F in fig. 1a). In the second winter, dust monitoring occurred at only three locations (A, C, and E). Equipment was suspended from the ceiling in baskets (fig. 3), with monitor inlets positioned at worker breathing zone height (1.5 m).

Dust mass concentrations were measured using both inhalable samplers (2 Lpm, IOM, SKC, Eighty Four, Pa.) and respirable cyclones (4.2 Lpm, BGI GK2.69, Thermo-Electron Corp, Waltham, Mass.), with filters analyzed gravimetrically. Inhalable dust was sampled in lieu of "total dust" to improve the quantification of large airborne particles compared to the non-size-specific closed-face 37 mm cassette samplers. Measured inhalable dust concentrations were compared to "total dust" recommendations for swine producers (Donham et al., 1995) to assess room air quality.

Carbon dioxide was measured using ToxiRAE single-gas monitors (model PGM-1850, Rae Systems Inc., San Jose, Cal.). To address producer concerns about whether increasing air movement with a new ventilation system would bring contaminants from the manure

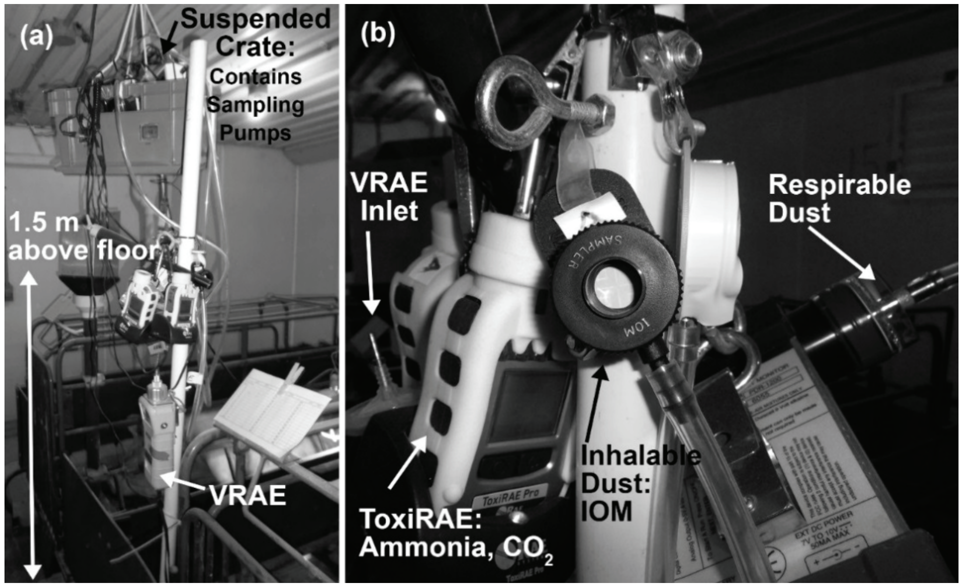

Figure 3. Samplers deployed for 24 h measurements with (a) crate with sampler pumps suspended from the ceiling and (b) sampler inlets and sensors positioned 1.5 m above the floor, as designated by eyebolts on fixed poles to ensure repeatable positioning throughout the study.

pit into the room above, NH_3, H_2S, and methane as percent lower explosive limit (%LEL) along with carbon monoxide (CO) were measured using VRAE multi-gas monitors (model 7800, Rae Systems, Inc., San Jose, Cal.). Additional ToxiRAE NH_3 monitors were deployed in the second test period. For each sampling day, 1440 one-minute averages were recorded for each gas monitoring instrument. Each gravimetric dust sampler collected one 24 h average concentration per study day.

Each instrument was calibrated in a clean laboratory before deployment in the field. Once on site, all of the direct-reading instruments were collocated in the adjacent hallway for at least 10 min prior to deployment at the fixed positions in the farrowing room. After 24 h, the direct-reading instruments were retrieved from the farrowing room and, while still logging, were again collocated in the hallway for at least 10 min. After retrieval, the instruments were returned to the laboratory for post-sampling calibration and data downloading. Filters were stabilized in an environmentally controlled laboratory for seven days prior to pre- and post-sampling weighing.

On each sample day, additional qualitative data were also collected to characterize factors that may have contributed to contaminant concentrations in the room. These factors included the farrowing room temperature, the number of heat lamps turned on, the number of sows and piglets, and the ventilation conditions of the farrowing room. For each 24 h sampling period, outside temperature was obtained from the nearest weather station, approximately 3.2 km (2 mi) to the west (KCID, Cedar Rapids Airport, http://www.wunderground.com).

Data Analysis

Concentrations measured with the collocated direct-reading instruments were analyzed to evaluate sensor drift. If differences in the 10 min averages between collocated monitors exceeded the drift criteria (200 ppm for CO_2 and 1 ppm CO, H_2S, and NH_3), the sensor data were adjusted to the mean of the collocated concentration using linear regression. One-minute concentrations for the drifted monitors were adjusted using the collocation regression equation.

Mean 24 h concentrations for each measured contaminant were computed for each test location on each sample day. The normality of concentration and log-transformed contaminant concentration data was assessed using the Shapiro-Wilk statistic. One-way ANOVA was used to test whether mean dust and gas concentrations were improved by each intervention. Multiple linear regression with backward elimination was used to attribute gas and particle concentrations to animal housing counts, outside temperature, and heat lamp use. Finally, to examine whether hallway contaminants contributed to room concentrations, Spearman correlation coefficients were computed for gases between rooms and compared between pit fan status (on, off) for the second test period.

Results

Table 1 summarizes the operational factors (outside temperatures, sow and piglet numbers) and mean 24 h concentrations measured throughout both test periods. For the filtration test, the outdoor temperatures were colder, and the room had higher mean sow and piglet counts than during the cyclone test. However, the between-year differences were not statistically significant for these parameters (ANOVA). The room-averaged concentrations were normally distributed for all contaminants tested, except NH_3. Transformed NH_3 concentration using the natural log were normally distributed and were used in subsequent ANOVA tests and linear regressions.

Air Quality Improvements

Figure 4 illustrates the 24 h mean dust concentrations throughout the study period. The room averages exceeded the recommended limit for respirable dust on only two days during the filtration test. Six of the 111 samples exceeded the 0.23 mg m^{-3} recommended limit, all on three days. None of the individual inhalable dust samples nor the room average exceeded the recommended 2.8 mg m^{-3} "total dust" exposure recommendation. Because inhalable dust samplers are capable of collecting more particle mass than "total dust" samplers, inhalable dust concentrations below a "total dust" exposure recommendation indicate low health risk. Ignoring the effect of the ventilation control device, it was clear that the dust concentrations differed between years, with significantly lower respirable dust ($p < 0.001$) identified in the second test period (table 1a).

Respirable dust concentrations were significantly reduced ($p < 0.001$) by an average of 32% (0.19 to 0.13 mg m^{-3}) with the filtration unit in the recirculating ventilation system. However, the 20% reduction (0.11 to 0.088 mg m^{-3}) in respirable dust concentration with the cyclone treatment was not statistically significant.

A 23% reduction in inhalable dust was identified with the filtration unit using only data from three positions (A, C, and E), which matched the locations in the cyclone study period. Using all six positions (A through F) in the first test period, a significant 44% reduction was identified ($p < 0.001$; Anthony et al., 2015). In the cyclone intervention year, a substantial (33%) and significant ($p = 0.024$) reduction in inhalable dust was identified with the cyclone using the three monitoring locations (A, C, and E).

Table 1. Production factors and room concentrations (a) between winters to assess production differences and heater performance and (b) within winters to assess system performance.[a]

(a) Between Test Periods	Filtration, Traditional Heater (2013-2014)				Cyclone, New Heater (2014-2015)				Between Test Period, ANOVA p
Factor	*N*	Mean	SD	Shapiro-Wilk p	*N*	Mean	SD	Shapiro-Wilk p	
Outside temp. (°C)	18	-8.77	2.57	0.189	19	-5.38	6.62	0.223	**0.05**
Sow	18	15	4.5	*<0.001*	19	12	4.7	0.089	0.058
Piglet	18	71.1	42.4	*0.017*	19	49.2	25.5	0.857	0.064
Respirable dust (mg m^{-3})	**18**	**0.15**	**0.046**	**0.231**	**19**	**0.095**	**0.025**	**0.116**	**<0.001**
Inhalable dust (mg m^{-3})	18	0.84	0.38	0.677	19	0.68	0.27	0.821	0.162
CO_2 (ppm)	**18**	**2480**	**160**	**0.4**	**19**	**1400**	**330**	**0.792**	**<0.001**
NH_3 (ppm)	18	10.1	6.5	0.09	15	11	8.7	*<0.001*	0.74
ln(NH_3)	18	1.77	1.99	*<0.001*	15	2.21	0.58	0.073	0.419
(b) Within Test Periods	Ventilation On				Ventilation Off				Between Ventilation Status, ANOVA p
Factor	*N*	Mean	SD	Shapiro-Wilk p	*N*	Mean	SD	Shapiro-Wilk p	
Filtration, traditional heater (2013-2014)									
Outside temp. (°C)	11	-9.01	2.8	0.272	7	-8.39	2.31	0.52	0.632
Sow	11	14	5.4	*0.010*	7	16.6	2.22	0.599	0.252
Piglet	11	65	44.7	0.111	7	80.5	40	0.218	0.468
Respirable dust (mg m^{-3})	11	0.13	0.03	*0.026*	7	0.19	0.035	0.738	***<0.001***
Inhalable dust (mg m^{-3})	11	0.75	0.4	0.535	7	0.98	0.33	0.347	0.236
CO_2 (ppm)	11	2460	168	0.621	7	2500	150	0.29	0.622
NH_3 (ppm)	11	11.3	7.7	0.499	7	8.3	3.8	0.068	0.35
ln(NH_3)	11	1.59	2.56	0.067	7	2.07	0.39	0.26	0.633
Cyclone, new heater (2014-2015)									
Outside temp. (°C)	12	-5.51	6.31	0.66	7	-5.16	7.65	0.306	0.915
Sow	12	10.7	5.1	0.171	7	14.28	3.02	*0.005*	0.112
Piglet	12	41	26.5	0.921	7	63.3	16.9	0.506	0.063
Respirable dust (mg m^{-3})	12	0.088	0.027	0.659	7	0.11	0.02	0.163	0.141
Inhalable dust (mg m^{-3})	12	0.578	0.248	0.498	7	0.86	0.23	0.44	**0.024**
CO_2 (ppm)	12	1280	315	0.75	7	1600	240	0.78	**0.032**
NH_3 (ppm)	8	12.2	10.6	*0.003*	7	9.8	6.4	*0.002*	*0.610*
ln(NH_3)	8	2.26	0.677	0.46	7	2.15	0.51	0.127	0.719

[a] Bold data indicate significant differences between conditions indicated. Italicized Shapiro-Wilk p-values indicate non-normally distributed data; the associated ANOVA comparison should be interpreted with caution.

Concentrations of CO, H_2S, and methane were seldom detected in both test periods, and detection limits were well below the recommended exposure limits. The frequency of non-detects was unchanged when the ventilation system was in operation. Figure 5a shows the room-averaged CO concentrations, which averaged 2.0 ppm in the filtration test with traditional heaters and 0.8 ppm in the cyclone test with the vented heaters. The heater substitution resulted in substantial (44%) and significant ($p < 0.001$) reduction of CO. However, it is important to note that the CO concentrations were well below 25 ppm exposure limits (NIOSH, 2005; ACGIH, 2017).

Daily mean NH_3 concentrations exceeded the 7 ppm recommended limit, on average (fig. 5b). While NH_3 concentrations varied throughout both test periods, they did not increase when the ventilation system was in operation ($p > 0.35$). Room concentrations exceeded the 7 ppm recommended swine production limit on 11 days in both test periods, regardless of ventilation system operation. Concentrations of NH_3 exceeded the 25 ppm exposure limits (NIOSH, 2005; ACGIH, 2017) on one day in the first test period and on two days in the second test period.

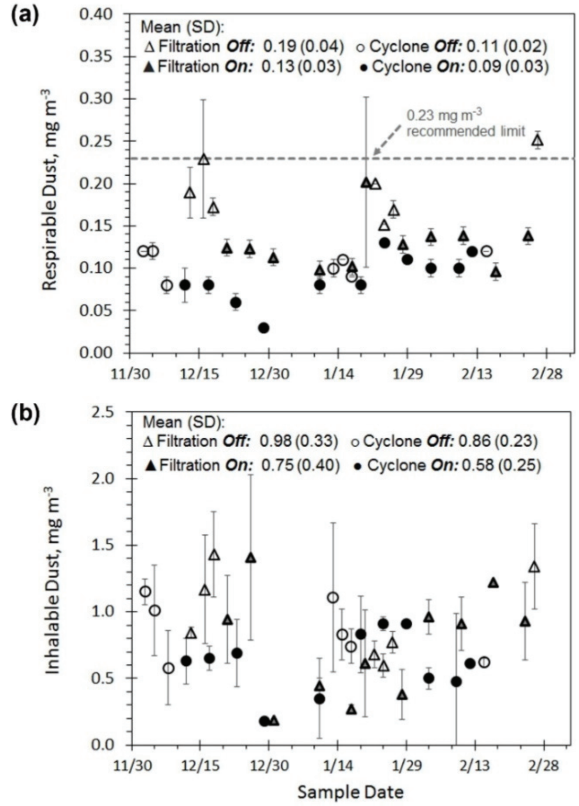

Figure 4. Room-averaged 24 h concentrations measured at locations A, C, and E for (a) respirable dust with recommended exposure limit of 0.23 mg m^{-3} and (b) inhalable dust with recommended exposure limit of 2.8 mg m^{-3}. Error bars indicate the range of concentrations measured in the room on that sample day.

Carbon dioxide concentrations were significantly ($p < 0.001$) lower with the new heaters in operation. With the traditional unvented heater, the mean CO_2 concentration was 2500 ppm (SD = 160 ppm), but the vented heater tests averaged 1400 ppm (SD = 330 ppm). In the vented heater tests, room concentrations exceeded the 1540 ppm swine production recommendation on five of 18 days (26%) (fig. 5c), compared to 100% of days exceeding this guideline with the traditional unvented heater. At no time during the vented heater tests did the room concentration exceed 2500 ppm (50% of the regulatory limit; OSHA, 1978), whereas the unvented heater tests had concentrations exceeding this value 39% of the time.

Determinants of In-Room Concentrations

Multiple linear regression was used to identify significant contributors to indoor air quality over the two test periods. Owing to production changes between years, consideration of these production factors for their effects on contaminant reduction is needed to compare results between the two interventions. The following relationships were identified:

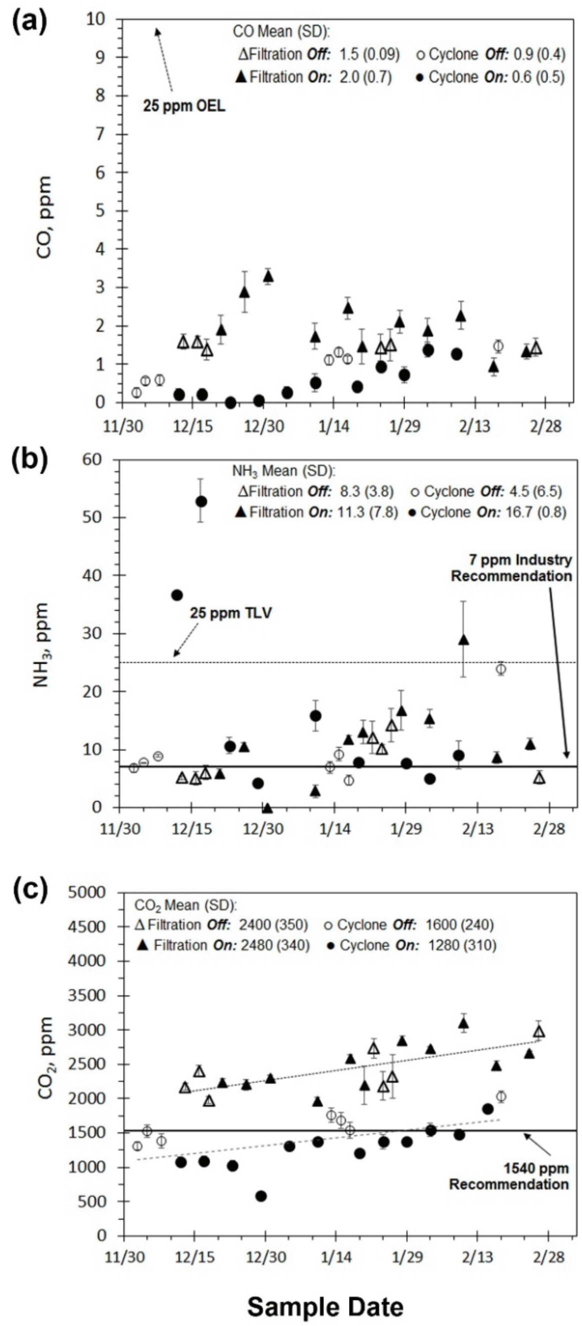

Figure 5. Room-averaged 24 h mean room concentrations of (a) CO, (b) NH_3, and (c) CO_2. Error bars indicate the minimum and maximum concentration measured on that day. Horizontal lines indicate recommended exposure limits. Dotted lines in (c) are best-fit regressions for CO_2 between the two test periods.

$$\text{Respirable dust (mg m}^{-3}) = 0.121 - 0.042\mathit{Vent} - 0.058\mathit{Year} \quad (1)$$

$$(R^2 = 0.60)$$

$$\text{Inhalable dust (mg m}^{-3}) = 0.473 - 0.156\mathit{Vent} + 0.00655\mathit{Piglet} \quad (2)$$

$$(R^2 = 0.51)$$

$$\ln(NH_3) \text{ (ppm)} = 0.193\mathit{Sow} - 0.86\mathit{Year} \quad (3)$$

$$(\text{adjusted } R^2 = 0.75)$$

$$CO_2 \text{ (ppm)} = 970 - 16.4\mathit{Temp} + 28\mathit{Sow} + 940\mathit{Heater} \quad (4)$$

$$(R^2 = 0.90)$$

where

Vent = 0 if recirculating ventilation system is off, 1 if it is on
Year = 1 for filtration system tests, 0 for cyclone system tests
Heater = 1 if unvented heater is in use, 0 if vented heater is in use
Piglet = 24 h average count of piglets in the room (range: 0 to 119)
Sow = 24 h average count of sows in the room (range: 1 to 19)
Temp = 24 h average outside temperature (°C; range: -23.9°C to 2.9°C).

Equation 4 confirmed increasing CO_2 with decreasing outdoor temperatures, consistent with the understanding of heaters as a source for CO_2 generation. The metabolic activity of sows also significantly contributed to the estimation of CO_2. Most importantly, the type of heater contributed to the estimation of room CO_2: if the heater was unvented (i.e., traditional heater), the room concentration was nearly 940 ppm higher than if a vented heater was in operation. This allowed us to partition the between-year mean 1080 ppm differences in CO_2 into production (140 ppm) and the unvented heater (940 ppm).

Contaminant Transport from Hallway

When the two manure pit fans in the test room were in operation, each exhausted 1480 $m^3\ h^{-1}$ (870 cfm). In the heater intervention test period, the hallway concentrations of CO and CO_2 were higher than and trended with those in the test room, during the second winter, with a clearer relationship when the pit fans were operating (fig. 6). When the pit fans were off, CO_2 averaged 1200 ppm in the farrowing room, but the concentrations increased to a mean of 1600 ppm with the pit fans turned on. It was hypothesized that the farrowing room air exhausted by the pit fans was replaced with air from the hallway. The ratio of room to hallway CO_2 increased from 76% with no pit fan operation (Spearman r = 0.40) to 85% with the pit fans on (Spearman r = 0.78). While well below human health concerns, CO concentrations also trended with pit fan operation, with room concentrations only 33% of that in the hallway with no pit fan operation (Spearman r = 0.38) but 60% with pit fans on (Spearman r = 0.79). The increased correlation between the hallway and farrowing room concentrations during pit fan operation indicates that some of the CO_2 and CO measured in the test room may have come from the hallway.

Discussion

Dust Reduction

A recirculating ventilation system with a filtration unit, operating at 5.4 air exchanges

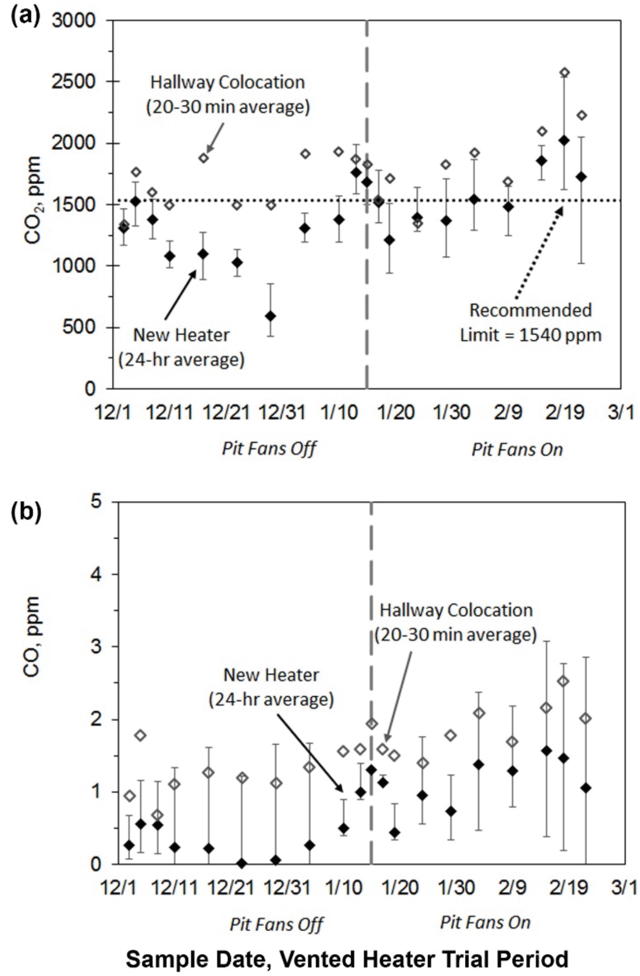

Figure 6. Average (a) CO_2 and (b) CO concentrations from the second winter (cyclone + vented heater testing), averaged over all monitors, including hallway colocation data. Error bars for 24 h data represent data ranges. Vertical dashed lines indicate the date when manure pit fans were activated.

per hour, substantially reduced dust concentrations in a 19-sow farrowing room. The filtration unit significantly reduced room concentrations of respirable dust by 32%, but the cyclone performance was not significant at 20% reduction. Reductions in inhalable dust were 23% to 44% with the filtration unit and 33% with the cyclone. For both dust hazards, the filtration unit provided better performance in removing both small (respirable) and larger (inhalable) particles in the room.

Without information on in-field performance, the selection of air pollution control technology in agriculture may focus instead on capital and maintenance costs. Typically, cyclones are less expensive to purchase and maintain (no replacement parts) compared to filtration systems, which require filter maintenance and replacement over time. For this study, both air cleaners were sized for 1000 cfm capacity: the cyclone cost $3670 and the filtration unit cost \$6700, plus \$270 for the polyester sateen filter bag. The pressure drop through a cyclone remains constant over time, whereas that of a filtration unit increases as particles deposit on the filter media inside the unit.

While the cost and convenience of cyclones may make them preferable for application in livestock production buildings, the limited improvement in respirable particle concentrations identified in this study indicates that cyclones may not provide sufficient air quality improvement in animal production buildings. Although the farrowing room had lower overall respirable dust concentrations during the cyclone test period, the filtration unit resulted in a greater reduction of respirable dust, indicating that the filtration unit may have been more effective in removing smaller particles. Cyclones operate by removing large particles more efficiently from an air stream and are typically less efficient for respirable particles in comparison to filtration systems. The study cyclone was selected to achieve a 1700 $m^3 h^{-1}$ flow rate, but other cyclones, or operating this same cyclone at higher flow rates, may improve the collection efficiencies over those found in this study.

Filtration systems may benefit from pretreatment to improve their ability to capture particles of all sizes. This study did not pre-coat the filters prior to testing in the field. Hence, the filtration unit represented the lower efficiency condition that would be expected at initial installation. As particles deposit on the surface of a filter, the collection efficiency improves, with an increased pressure drop across the system. This particular filtration unit was selected because of its "shaking" feature, which allows push-button activation of a shaker to remove the particle cake that built up on the filter. At no time during this study did the pressure drop reach the recommended upper limit of the unit (1000 Pa). The clean filter had an initial pressure drop of 124 Pa, which increased to 254 Pa over weeks 2 through 5. Prior to shutting the system down for the mid-winter background concentration measurements in week 6, the automated shaking feature was used, which reduced the pressure through the filter to 184 Pa. After the final four weeks of use, the pressure drop reached only 259 Pa. The filtration unit may have higher capital cost and maintenance than a cyclone, but the filter should provide effective control for several winters (Peters et al., 2015). However, care must be taken to secure the filter when not in use to prevent destruction by rodents.

CO_2 Reduction

In addition to dust control, this intervention showed that CO_2 concentrations were substantially lower (940 ppm) with vented heaters than with unvented heaters. Although the unvented gas-fired heaters common to this region are inexpensive (~\$1000), they contribute to in-room CO_2. The vented heater tested in this study relies on standard heat exchanger technology and was easily integrated into the existing temperature control panel. The high-end version tested had stainless-steel components and was more expensive (\$1500) than typical unvented heaters. Installation required ductwork to convey combustion air and exhaust byproducts. However, the CO_2 reduction of 940 ppm attributed to the change in heater type may be worth the incremental costs. The longevity of this heater is still under evaluation, but it continues to perform adequately after three winters. Given that clean, non-room air is used in the burner, on-going evaluations will assess the lifespan of the burner and its ability to withstand the moderately corrosive environment.

While replacing the heater in the farrowing room reduced CO_2 by 940 ppm, heater replacement may not be sufficient to reduce CO_2 in other production operations to the recommended 1540 ppm. Studies have reported room CO_2 concentrations as high as 4000 to

4500 ppm (Donham et al., 1989; Sun et al., 2008; Letourneau et al., 2010), with no indication of heater specified. Because animal respiration is the other major source of room CO_2, which cannot be controlled other than by reducing the animal numbers, the only other way to reduce CO_2 in the room is to exhaust the room air and replace it with additional fresh air. While heating the incoming fresh air would be expensive, heating with unvented heaters would generate the very compound that required the room to be purged. Early modeling simulations by Anthony et al. (2014) hypothesized this dilemma, and this field study confirmed the heater's contribution to the room CO_2.

The study design did not allow for a comprehensive assessment of the movement of contaminants from the hallway to the farrowing room. However, evidence indicated that the unvented heater in the hallway contributed to the farrowing room CO_2 concentrations. In model validation by Park et al. (2017), simulations of the fresh air needed to replace the air exhausted by the manure pit fans examined both ambient (400 ppm) and hallway (1500 ppm) CO_2 concentrations; the best performing model used estimates from the hallway. That model, combined with this field study, suggests that replacement of heaters throughout both production and non-production areas may benefit the air quality in production rooms.

Gas-fired heaters can also be a source of CO, but CO concentrations in both test periods were well below those associated with adverse health effects in humans. While the unvented heater was several years old, the 24 h room CO concentrations ranged from 0.9 to 3.3 ppm, indicating no major operating faults. Concentrations were lower (0.01 to 1.5 ppm) with the new vented heater, although in-room CO concentrations may also have been from hallway air drawn into the farrowing room to replace the manure pit exhaust, as hallway concentrations averaged 245% higher than in the test room with the pit fans off and only 65% higher with the pit fans in operation.

Factors Affecting Room Concentrations

Regression models estimated the gas and particle concentrations from production and environmental conditions. Animal counts were significant contributors to estimates of inhalable dust ($p < 0.001$, piglet), NH_3 ($p < 0.001$, sow), and CO_2 ($p < 0.001$, sow). The heat lamp counts did not contribute to the estimation of any room contaminant. Outdoor temperature was significant only for CO_2 estimation ($p = 0.023$) and had no significant effect on the determination of room NH_3. However, the significance of year as an estimator of NH_3 indicates that there may have been a change in manure management practices between years, including differences in manure pit fan operation, that was unaccounted for in the model. However, the production factors investigated only provided a moderate explanation of the 24 h variability in dust metrics ($R^2 = 0.51$ to 0.60) and only slightly more for NH_3 ($R^2 = 0.75$).

The strongest ($R^2 = 0.90$) and most relevant relationship between production factors and in-room concentrations was identified for CO_2. Equation 4 allows us to allocate room CO_2 to multiple sources. The intercept (970 ppm) indicates a background concentration above the ambient outdoor CO_2 concentration (400 ppm), perhaps due to early CO_2 buildup in the room that occurred prior to the start of air quality monitoring. In both study years, the CO_2 concentrations did not return to outdoor levels when the animals were removed from the farrowing room. The concentration dropped to only 2290 ppm with the traditional heater and to 590 ppm with the vented heater, which is closer to the ambient level with an empty room. Over the range of outdoor temperatures in this study, the estimated contribution of outdoor temperature to the CO_2 estimated with equation 4 ranged from an additional 390 ppm during the coldest day (-23.9°C) to a decrease of 50 ppm for warmer days (2.9°C), when the heating demand was lower.

Additional CO_2 reductions in production areas may be achievable by eliminating sources in adjoining rooms, with evidence provided in the second test period for the effect of manure pit fan operation. Attention to between-room contaminant transport is essential to maximize the effectiveness of air quality improvements, including gases that may be generated in non-production spaces. Production rooms with 2500 ppm or more CO_2 may require additional controls to achieve the recommended 1540 ppm, including exhausting the room air without recirculation. It is important to note that heating fresh air with traditional heaters that generate CO_2 would be counterproductive to these efforts.

Limitations

The variability in production factors between study years may affect the strength of this study's findings. During the second test period, the farrowing room never reached its full 19-sow capacity, which may have resulted in room dust and CO_2 concentrations below those of full production. However, multiple linear regression was used to account for these differences. Further, the characterization of the effect of heater type could have been strengthened by replacing all unvented heaters in the building to ensure that the replacement air from the hallway to the test room was cleaner, or by otherwise separating this room from other rooms in the building. With a complete exchange of unvented heaters to vented units, additional reductions in CO_2 within the test room might be achievable. The treatment tested here, i.e., replacing one heater at a time, may likely represent how livestock producers replace heaters in the field as individual heaters fail. Finally, the age of this production building does not represent how new farrowing buildings are constructed, which may prevent its generalizability to newly constructed buildings.

Conclusion

A recirculating ventilation system, operating at 5.4 air exchanges per hour, with filtration to remove both respirable (small particles) and inhalable (large particles) dust, performed better than the less expensive cyclone. Vented heaters can be a simple and cost-effective method to improve the air quality in indoor agricultural production buildings, reducing CO_2 concentrations by 940 ppm for a 19-sow farrowing room. These field interventions provided a valuable demonstration of the effects of control technologies to improve the air quality in an older, educational swine production building. Future work should deploy recirculating ventilation systems with filtration control technology and heater replacement to investigate and demonstrate the ability to control particle and heater gas contaminants in modern production operations, with faster sow turnover rates and larger-capacity farrowing rooms. These future studies should include demonstrations of both air quality and worker and animal health improvements from these engineering interventions.

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