SEMI-CONTINUOUS AIR SAMPLING VERSUS 24-HOUR BAG SAMPLES TO EVALUATE BIOFILTERS ON A SWINE NURSERY IN WARM WEATHER

K. A. Janni, L. D. Jacobson, B. P. Hetchler, J. P. Oliver, L. J. Johnston

ABSTRACT. *Economical and effective methods are needed to assess practices that reduce gas emissions. This project compared gas concentrations measured using semi-continuous sampling with dedicated gas analyzers versus concentrations obtained using 50 L FlexFoil bags filled over 24 h. Sampling was done over four months in summer and early fall of 2010 and 2011 from four biofilters (flat-bed with old media, A-frame, and two flat beds with either 10 cm or 5 cm screen birch mulch) treating air from deep manure pits below swine nurseries. Concentration ratios and percent reductions were calculated and compared using both sampling methods. The NH_3, H_2S, CO_2, CH_4, and N_2O concentration data indicated that the 24 h bag sampling concentrations and percent reductions tracked the semi-continuous sampling concentrations and percent reductions well. Most (77%) of the NH_3 concentrations differences (24 h bag sample minus semi-continuous) were within ±2 ppm of the semi-continuous concentrations, 78% of the H_2S concentration differences were within ±200 ppb, 87% of the CH_4 concentration differences were within ±10 ppm, and 88% of the N_2O concentration differences were within ±75 ppb. Ratio means for NH_3, CO_2, and N_2O were close to one (between 0.95 and 1.09). H_2S ratio means varied from 0.61 in 2010 to 1.68 in 2011. Semi-continuous percent reduction results indicated that the four biofilters reduced NH_3, H_2S, and CH_4 emissions. For three of the four biofilters, mean percent NH_3 reductions ranged from 53% to 86%, mean percent H_2S reductions ranged from 41% to 74%, and mean percent CH_4 reductions ranged from 8% to 39%. One biofilter reduced N_2O concentrations by 17% to 22%, while three biofilters generated N_2O by 8% to 81%. The 24 h bag sampling system tested was an effective method for measuring gas concentrations and percent reductions of an air treatment system in the field based on NH_3, CH_4, and N_2O.*

Keywords. *24 h sampling, Ammonia, Biofilters, Hydrogen sulfide, Nitrous oxide, Reduction efficiency, Semi-continuous sampling.*

There is a need for effective and low-cost methods for assessing new techniques purported to reduce gas emissions from mechanically ventilated livestock and poultry facilities and manure storage units. Concerns about odors and the role of ammonia emissions from animal feeding operations in fine particulate formation are expected to lead to a need for additional effective and economical mitigation practices that reduce gas emissions. As this demand for effective mitigation practices increases, entrepreneurs will be encouraged to develop new practices. As new mitigation practices are developed it will be necessary to have economical and standardized methods to measure and verify their effectiveness in the field. Without affordable standardized testing protocols, the adoption of new, effective, and economical mitigation practices may be slowed.

Research in the 1990s aimed at reducing odor and ammonia emissions from livestock systems in the Netherlands led to the development of a measurement and evaluation protocol called Green Label (Groen Label, 1996). The Green Label protocol specified evaluation at one farm location under real farm conditions, long measurement periods during winter and summer, continuous high-frequency sampling, and standard management practices during measurement periods. Analysis of three variance sources (i.e., between farm, within farm, and instrument measurement) led to development of an updated Green Label protocol (Mosquera and Ogink, 2005). The updated protocol for assessing farm emissions specified sampling at four representative farm locations, 24 h cumulative sampling, six independent sampling events, and documentation of standard farm practices (Ogink et al., 2008).

Schmidt et al. (2008) described a draft protocol for conducting standardized tests of mitigation technologies. The protocol recommended sampling technologies operating on farms after acclimation over a range of standard operating conditions. Semi-continuous sampling, 24 h sampling, and pre- and post-treatment sampling were acceptable for evaluating technologies.

Submitted for review in March 2014 as manuscript number SE 10653; approved for publication by the Structures & Environment Division of ASABE in July 2014. Presented at the 2013 ASABE Annual Meeting as Paper No. 1605534.

The authors are **Kevin A. Janni, ASABE Fellow,** Professor and Extension Engineer, **Larry D. Jacobson, ASABE Fellow,** Professor and Extension Engineer, **Brian P. Hetchler,** Research Fellow, and **Jason P. Oliver, ASABE Member,** Graduate Student, Department of Bioproducts and Biosystems Engineering, University of Minnesota, St. Paul, Minnesota; **Lee J. Johnston,** Professor, West Central Research and Outreach Center, University of Minnesota, Morris, Minnesota. **Corresponding author:** Kevin A. Janni, 1390 Eckles Avenue, St. Paul, MN 55108; phone: 612-625-3108; e-mail: kjanni@umn.edu.

Researchers have tested various semi-continuous sampling systems and schedules to monitor gas concentrations in animal barns. Xin et al. (2003) tested portable monitoring units (PMU) that measured carbon dioxide (CO_2) and ammonia (NH_3) concentrations, both ambient and inside animal barns. The PMU used 12 min purging and 8 min sampling cycles and registered data every 30 s. Maximum NH_3 concentrations in a laying hen house measured with the PMU were the only measurements that did not show a difference compared to ammonia concentrations measured using a chemiluminescence NH_3 analyzer in an on-site trailer (Xin et al., 2003). Gay et al. (2006) used PMU to measure NH_3 concentrations in turkey barns. The PMU used 24 min purging and 6 min sampling cycles, measured the concentration every second, and recorded an average every minute. Zhao et al. (2013) used PMU to measure NH_3 and CO_2 concentrations in laying hen barns. For the study by Zhao et al. (2013), PMU were programmed to sample ambient air for 20 min and barn air for 10 min. Because of the sampling system response time, only the last 2 min of data of each sampling period were used to determine NH_3 and CO_2 concentrations (Zhao et al., 2013).

Hayes et al. (2013) used a multi-gas analyzer plumbed to four composited sample lines to measure NH_3, CO_2, nitrous oxide (NO_2), and methane (CH_4) concentrations in two side-by-side aviary layer houses. Each composite sample line combined air from two filtered sample lines taking air near continuously running exhaust fans. The multi-gas analyzer was housed in an enclosure in one of the layer houses. Sample pumps cycled on and off as needed. Each composite sample line was sampled for 6 min, with the first 5.5 min for stabilization and the last 0.5 min for measurement (Hayes et al., 2013).

The National Air Emission Monitoring Study (NAEMS) used on-site semi-continuous gas emissions monitoring with multiple gas analyzers in environmentally controlled trailers to measure concentrations and airflow rates at 14 sites (Heber et al., 2008). Concentrations were measured using between 6 to 17 sample lines depending on the site. Sample pumps ran continuously and purged air not sent to the analyzers. The sample lines were sampled for either 10 or 15 min, depending on sample line length, and the last 5 min of data were averaged.

Semi-continuous sampling is labor-intensive and expensive, which limits its use for verifying the effectiveness of innovative mitigation technologies. Studies have commonly used different purge air sampling, indoor air sampling and sensor stabilization times as part of their semi-continuous monitoring schedules (Xin et al., 2003; Gay et al., 2006; Heber et al., 2008; Zhao et al., 2013; Hayes et al., 2013). There is a need for economical techniques to assess mitigation technologies in the field.

The purpose of this project was to compare gas concentrations measured using semi-continuous sampling versus gas concentrations obtained using bags filled over 24 h. In addition, percent gas concentration reductions through biofilters were calculated and compared using the inlet and outlet concentrations determined with both sampling methods.

MATERIALS AND METHODS

Data to compare semi-continuous sampling versus 24 h bag sampling were collected from air entering and exiting biofilters nine times each summer between June 15 and October 15 in 2010 and between June 25 and October 15 in 2011. The biofilters treated air from three swine nursery rooms with separate deep manure storage pits at the University of Minnesota West Central Research and Outreach Center (WCROC). Pigs were in the nurseries during each sampling.

Pigs entered the nursery on the day of weaning between 18 and 20 days of age and remained in the nursery rooms for five to six weeks. The environment in each room was controlled with a computerized controller (Phason Omni, Phason, Winnipeg, Manitoba, Canada). All ventilation air was drawn from the outside through the attic, distributed through inlets, and exhausted through the manure pits under each room in winter or with a combination of pit and wall fans in spring, summer, and fall. All of the exhausted air was treated with biofilters. Supplemental heat was provided by two natural gas direct-fired heaters in each room. The heaters were used to warm up the nursery rooms before pigs were added for all groups. In warm weather, the heaters typically cycle on and off both day and night for the first week. As pigs grow in warm weather, the heaters typically cycle on and off only at night. In cooler weather, the heaters typically cycle on and off both day and night throughout the nursery period. Heater usage was not monitored.

BIOFILTER DESCRIPTIONS

In 2010, the two sampled biofilters treated 100% of the ventilation air through pit and wall fans exhausting from two nursery rooms on the south side of the barn. The rooms were labeled southeast (SE) and southwest (SW). Each room was capable of housing 288 nursery-age pigs under conditions simulating commercial production. One biofilter was a flat-bed biofilter that treated air from the SE nursery, and the other was an A-frame vertical biofilter treating air from the SW nursery. The flat-bed biofilter was originally built in 2002 following design guidelines that were incorporated into an online design guide (Schmidt et al., 2004). The flat-bed media was a mixture of wood chips and compost. In late 2006, the original media was replaced with new wood chips and compost, so the flat-bed media was more than 3.5 years old during the 2010 monitoring.

The A-frame biofilter used wood chip media and was put into operation in 2009. A-frame biofilter design and performance information was reported by Akdeniz and Janni (2012). Figure 1 is a schematic of the A-frame biofilter. The flat-bed biofilter media moisture was managed using sprinklers connected to garden hoses. Water was added to the A-frame biofilter using soaker hoses on top of the A-frame biofilter connected to garden hoses (fig. 1). Timers were used to add water daily.

In 2011, the two sampled biofilters were rejuvenated flat-bed biofilters treating 100% of the ventilation air through pit and wall fans exhausting from two nursery rooms labeled southeast (SE) and northeast (NE). The

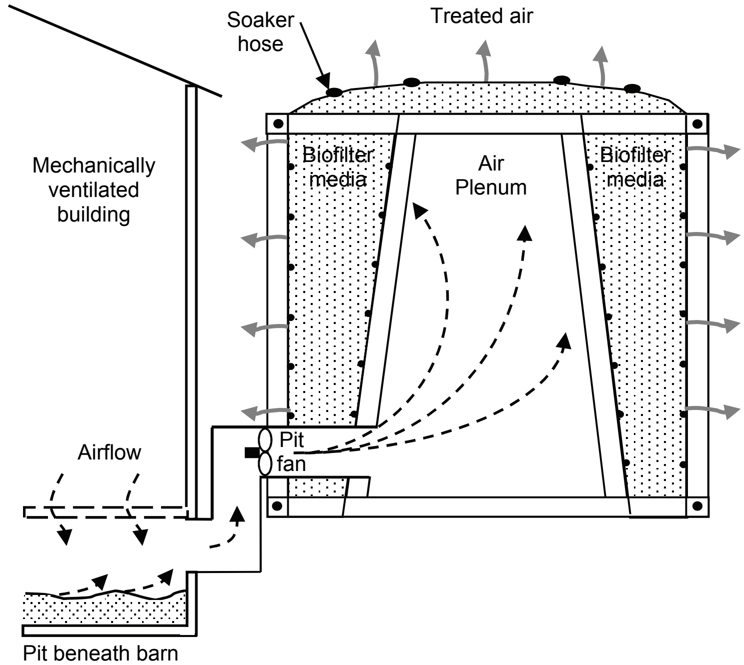

Figure 1. Schematic of the A-frame biofilter (not to scale) (Akdeniz and Janni, 2012).

nursery room capacities and production conditions were similar to those in 2010. The ducts connecting the pit and wall fans to the plenum beneath the flat-bed biofilters were rebuilt, and the media was completely replaced before sampling began in 2011.

Prior to 2011, the ducts connecting the pit and wall fans to the flat-bed biofilter plenums were common ducts. All pit and wall fans exhausted into the common duct and fed the plenum beneath the flat-bed biofilters. All of the fans, except one continuously running pit fan, had closable shutters to reduce backdrafting when the fans were turned off. Ventilation problems were observed in the nursery rooms that indicated that the shutters were not sealing tightly, and there was significant backdrafting from the common duct into the nursery rooms through the closed shutters on fans that were not running. It was decided to add dividers to the duct so that each pit and wall fan would supply a separate biofilter. Figure 2 illustrates the new biofilter layout and ducting. The plenum under the media was created using wooden pallets and plastic bird netting (Schmidt et al., 2004). Plastic sheeting (4 mil) was placed vertically between the pallets to create the separate biofilters in figure 2. Air sampling for this project was done on the biofilters treating air from the continuously running fans (fan 1) of the southeast (SE) and northeast (NE) flat-bed biofilters.

Fan 1 was a continuously running pit fan that had a reported airflow rate of approximately 0.3 $m^3 s^{-1}$. Fan 2 was a variable-speed pit fan that moved approximately 2 $m^3 s^{-1}$ at full speed and 37 Pa static pressure. Fans 3, 4, 5, and 6 were single-speed wall fans that moved 2.5 $m^3 s^{-1}$ at 37 Pa static pressure and were programmed to come on in three stages: stage 1 was fan 3, stage 2 was fan 4, and stage 3 turned fans 5 and 6 on together.

Table 1 summarizes the biofilter airflow rates, dimensions, and empty bed contact times (EBCT) calculated using procedures in the University of Minnesota biofilter design guide (Schmidt et al., 2004). For design purposes, the fan airflow rates for fans 1 through 6 were assumed to be 75% of the reported rates due to increased static pressure and other flow-reducing factors (e.g., corrosion and dirt).

The initial depth of the new media was approximately 45 cm with a target settled depth of 35 cm. The media was purchased from a logging supply company that produced the two media by grinding birch logs and branches with a grinder with either a 5 cm or a 10 cm screen. The southeast (SE) biofilter was covered with ground birch mulch that passed through a 10 cm screen on the grinder, and the northeast (NE) biofilter was covered with ground birch mulch that passed through a 5 cm screen on the grinder. No compost or other amendments were added to the media.

Water was added to both flat-bed biofilters using sprinklers connected to garden hoses. The sprinklers were located adjacent to the ducts between filters 1 and 5 (fig. 2) and wet a semicircle approximately 8 m in radius. A valve on a timer wet each biofilter for approximately 30 min per day to wet the media without noticeable leaching.

MEDIA CHARACTERISTICS

In 2010, the old flat-bed and A-frame biofilters were part of another project assessing biofilter performance in the field, reported by Akdeniz and Janni (2012). Media was taken from each biofilter to measure porosity, density, particle size, and pressure drop across the media as received.

Media porosity (as-received media) was measured using

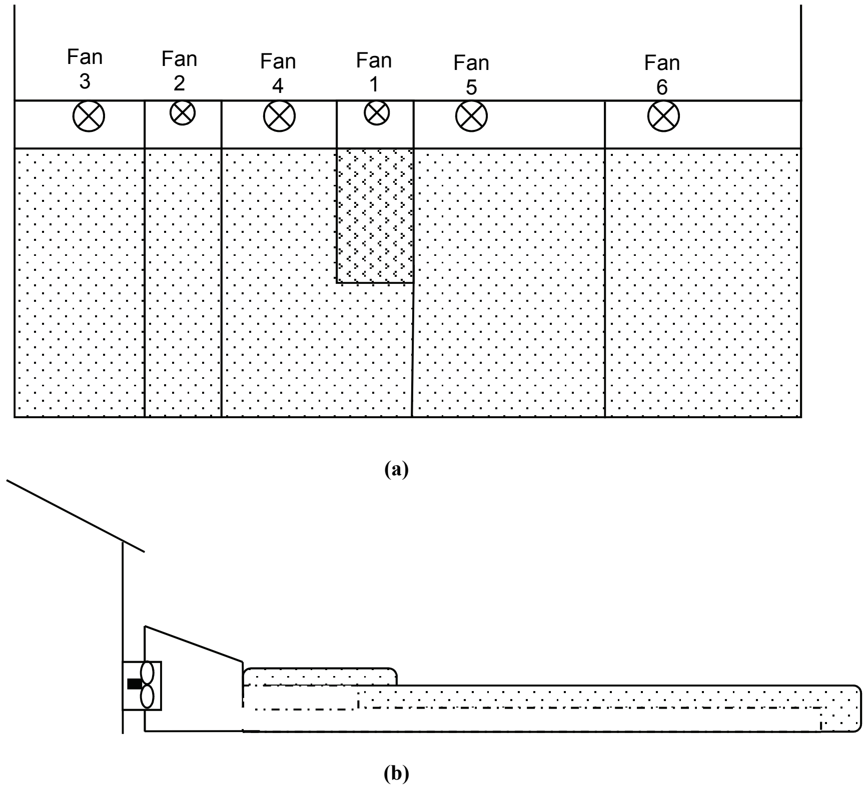

Figure 2. Schematics of the layout of the rejuvenated flat-bed biofilters: (a) horizontal and (b) vertical (not drawn to scale).

Table 1. Flat-bed fan airflow rates, dimensions, and empty bed contact times (EBCT).

Fan[a]	75% of Reported Fan Airflow Rate (m^3 s^{-1})	Length (m)	Width (m)	Target Depth (m)	Target EBCT (s)
1	0.2	3.7	1.2	0.3	6
2	1.5	7.9	1.2	0.3	2
4	1.7	7.9	2.5 to 3.7	0.3	4
3, 5, and 6	1.7	7.9	3.7	0.3	5

[a] Fans 1, 3, 4, 5, and 6 were single-speed fans. Fan 2 was a variable-speed fan.

two buckets and a simple method for packing one bucket with media and measuring the amount of water added to fill the voids (Nicolai and Janni, 2001; Akdeniz et al., 2011). Percent porosity was calculated by multiplying the ratio of the water volume to the media volume by 100.

Media weight (as-received media) for calculating media density (kg m^{-3}) was measured by subtracting the tare weight of a 1 L glass container from the weight of the glass container filled with media. Density was calculated as the ratio of the net media weight divided by the container volume (Akdeniz et al., 2011).

In 2010, media particle size distributions (as-received media) were measured using seven Tyler brass sieves with 38.1, 25.4, 19.1, 15.9, 12.7, 9.4, and 4.7 mm openings and a solid tray at the bottom. Media particle size distribution (%) was calculated by multiplying the ratio of the weight of the media on each sieve to the total media weight by 100 (Akdeniz et al., 2011).

In 2011, media particle size distributions (as-received media) were measured using nine Tyler brass sieves with 50.8, 38.1, 25.4, 19.1, 15.9, 12.7, 11.1, 9.4, and 4.7 mm openings and a solid tray at the bottom. Between 210 and 240 g of media was placed on the top sieve, and the entire stack was shaken and tapped for 5 min (Ro-Tap Testing Sieve Shaker Model B, Tyler Industrial Products, Mentor, Ohio). The media mass on each sieve was weighed. Media particle size distribution (%) was calculated using the same procedure as in 2010.

In 2010, media unit pressure drop (Pa m^{-1}) versus unit airflow rate (m^3 s^{-1} m^{-2}) was measured using a media column described by Nicolai and Janni (2001) and Akdeniz et al. (2011). After filling the column and settling the media, the static pressure was measured with a pressure sensor (model 267, Setra Systems, Inc., Boxborough, Mass.) at six fan (AXC150A, Continental Fan, Buffalo, N.Y.) settings (20%, 30%, 40%, 60%, 80%, and 100% power), and inlet airflow rate was measured with a vane anemometer (RVA801, Alnor, Shoreview, Minn.).

In 2011, the same procedure as in 2010 was used to measure unit pressure drop (Pa m^{-1}) versus unit airflow rate (m^3 s^{-1} m^{-2}). Different target media depths (0.1, 0.2, 0.3, and 0.4 m) were used in 2011. The measurements were replicated four times.

AIR SAMPLING

Air entering and leaving the biofilters was sampled similarly in both years using six Teflon lines. Table 2 lists the sample line numbers and sampling locations. In both years, the end of the line sampling air entering each biofilter was placed in the duct near the outlet of the continuously running pit fans (fan 1 in fig. 2).

A technique used by Hoff et al. (2009) was used to sam-

Table 2. Sample line numbers and locations.

Sample Line	2010 Location	2011 Location
1	Entering flat-bed (old media)	Entering SE flat-bed
2	Leaving flat-bed (old media)	Leaving SE flat-bed
3	Leaving flat-bed (old media)	Leaving SE flat-bed
4	Entering A-frame	Entering NE flat-bed
5	Leaving A-frame	Leaving NE flat-bed
6	Leaving A-frame	Leaving NE flat-bed

ple the air leaving a biofilter. The ends of the sample tubes sampling the air leaving the biofilters (i.e., 2, 3, 5, and 6) were placed approximately 4 cm below the biofilter surface with the air inlet pointing downward and a short screened section to keep dirt out of the sampling line. This method eliminated the effects of sample hoods and precipitation on airflow from the biofilter.

Two hydrophobic polytetrafluoroethylene (PTFE) filters (1 μm openings, 47 mm diameter; Advantec MFS, Inc., Dublin, Cal.) were added to each sample line in series to protect the sampling pump and gas analyzers from moisture and particulate matter in the air samples (Akdeniz and Janni, 2012). The first filter, which served as a moisture trap, had small holes made with a needle so that air could pass through easily. The second filter had no added holes in the filter and served as a dust filter.

Semi-Continuous Sampling

The semi-continuous gas sampling system (GSS) sequentially drew sample air from the seven sample locations (two inlet and four outlet samples of the biofilters and a GSS exhaust line) and delivered the sample air to analyzers in an environmentally controlled equipment trailer. The trailer contained the GSS with Teflon tube sample lines connected to a computer-controlled sampling manifold, gas analyzers, environmental instrumentation, computer, data acquisition system, calibration gas cylinders, and other supplies. The computer-controlled GSS used a 15 min sample sequence for semi-continuous sampling, with 5 min for analyzer stabilization and 10 min for data collection. Readings were averaged over the 10 min collection period. The semi-continuous GSS measured gas concentrations in the six sample lines approximately 14 times per 24 h (1,440 min per day / [7 sample lines × 15 min per sample line] = 13.7 samples per 24 h). This sampling schedule avoided sampling each line at exactly the same time each day. The semi-continuous data were collected and processed on-site in the instrument trailer computer using LabView components and software (National Instruments, Austin, Tex.). Data were transferred daily to campus computer servers via a wireless connection.

24 h Sampling

The 24 h sampling units used for this project were adapted from those described by Janni et al. (2010). For this project, the 24 h sampling was connected downstream (positive pressure side) of the GSS system pumps using stainless steel tees in the six sample lines. This allowed simultaneous sampling using both the semi-continuous sampling system and the 24 h bag sampling units. Each 24 h sampling unit had a timer (H3CR-F8-300 AC 100240, Omron Corp., Schaumburg, Ill.), three-way solenoid valve (648T033, Neptune Research, Inc., West Caldwell, N.J.), needle valve, and 50 L FlexFoil bag (SKC, Inc., Eighty Four, Pa.). FlexFoil bags were selected based on previous tests of their capabilities to store NH_3, H_2S, and greenhouse gases during 24 h sampling (Akdeniz et al., 2011). The sample bags were reused until replacement was necessary because of damage or a detected leak. The sample bags were flushed three times with nitrogen and left empty between uses. The solenoid valve was controlled by the timer to either exhaust the air or fill the 50 L FlexFoil sampling bag. The GSS pump ran continuously to maintain fresh sample air in the system. Teflon tubing and stainless steel connections were used throughout the system. The airflow rate through the needle valve was about 450 mL min^{-1}. Sample air was added to the FlexFoil bags 4 min every hour during each 24 h sample period (43 L total). This sampling time was chosen based on previous experiments reported by Janni et al. (2010). Because analyzer response times differed, the 24 h bag sample readings were taken 10 min (for NH_3 and H_2S), 2 min (for CH_4), and 5 min (for N_2O) after the bags were connected to the analyzers.

Gas Analyzers

Hydrogen sulfide (H_2S) concentrations were measured with a pulsed fluorescence analyzer (model 450i, Thermo Electron Corp., Franklin, Mass.), ammonia (NH_3) concentrations were measured with a chemiluminescence analyzer (model 17C, Thermo Electron Corp.), methane (CH_4) concentrations were measured with a gas chromatograph analyzer (model 55C, Thermo Electron Corp.), nitrous oxide (N_2O) concentrations were measured with a photo-acoustic infrared analyzer (320EU, Teledyne Technologies, Inc., San Diego, Cal.), and carbon dioxide (CO_2) concentrations were measured using two photo-acoustic infrared units (MSA 3600, Mine Safety Appliances Co., Cranberry Township, Pa.) with separate ranges (i.e., 0 to 2000 ppm and 0 to 10,000 ppm). The analyzers were calibrated weekly.

Sampling Comparison

The 24 h bag sampling units were used nine times each year to measure gas concentrations in the six sample lines used for the semi-continuous measurements. The average concentration of the 14 semi-continuous measurements obtained during the same 24 h of sampling was compared to the 24 h bag sample gas concentrations. Pigs were in the barn each time 24 h samples were collected. Semi-continuous sampling continued between pig groups.

ANALYSIS

Concentration ratios (i.e., the 24 h bag concentration over the semi-continuous concentration) were calculated for each concentration measurement and used for statistical analysis of the concentration data. These ratios were used for statistical analysis because they were steadier over the range of gas concentrations measured than were differences in gas concentrations and differences in percent reduction. The ratios were used to estimate the mean ratio, ratio confidence intervals, and prediction intervals for each gas. Calculations were done on the natural log scale to correct for unequal variances in percent reductions and transformed back to the original scale for presentation.

Percent reductions for each biofilter outlet measurement were calculated using:

$$\text{Percent reduction} = 100\frac{(inlet - outlet)}{inlet} \quad (1)$$

where *inlet* is the inlet gas concentration, and *outlet* is the average outlet gas concentration using both lines. The average of the two outlet sample lines was used to avoid correlation between percent reduction values using the same inlet concentration.

The difference in percent reduction was also used for statistical analysis because percent reduction is an important characteristic when comparing mitigation practices. The difference in percent reduction was the percent reduction found using 24 h bag measurements minus the percent reduction found using the average concentration of the 14 semi-continuous measurements obtained during the same 24 h period. The average outlet concentration was used to avoid a correlation between two percent reduction values calculated with the single inlet concentration.

Differences between biofilters were tested separately for each gas using a generalized ANOVA, allowing for both different means and variances for each biofilter. If no differences were found at the $p < 0.05$ significance level, the data were combined. This analysis was performed on the natural log of the concentration ratios (24 h bag over semi-continuous) for all paired observations. The results were transformed back to the original scale for presentation and discussion.

RESULTS AND DISCUSSION

MEDIA CHARACTERISTICS

The biofilter media used in the four biofilters represented a range of media characteristics. In 2010, the 3.5-year-old flat-bed biofilter media was 0.4 m deep and had the highest density, low porosity, and the highest unit pressure drop values among the four media (table 3, fig. 4). The

Table 3. Biofilter media characteristics (Akdeniz and Janni, 2012).

Year and Biofilter	Media Type	Media Age	Porosity (%)[a]	Density (kg m^{-3})[a]
2010 Flat-bed	Wood chips and compost	3.5 years	53.5 ±3.8 n = 3	408 ±5 n = 3
2010 A-frame	Wood chips	1.5 years	58.7 ±2.2 n = 3	211 ±8 n = 3
2011 SE	Birch mulch, 10 cm screen	New	60.0 ±2.0 n = 4	195 ±11 n = 8
2011 NE	Birch mulch, 5 cm screen	New	52.9 ±1.6 n = 4	187 ±6 n = 8

[a] n = number of samples.

2010 A-frame biofilter media ranged from 0.3 to 0.5 m deep and was more porous and less dense compared to the old flat-bed biofilter media (table 3). In 2011, the 10 cm screen media in the rejuvenated SE flat-bed biofilter had a higher porosity than the 5 cm screen media in the rejuvenated NE flat-bed biofilter (table 3). The 10 cm and 5 cm screen birch mulch media had similar densities (table 3).

The mean media porosity and density values of the two 2010 biofilters were statistically different ($p < 0.05$) (Akdeniz and Janni, 2012). The two 2011 media had statistically different porosities and densities ($p < 0.05$).

The old flat-bed media and the 5 cm screen birch mulch media in 2011 had the most small particles of all four biofilter media (fig. 3). The 5 cm screen media had more than 61% of the media pass through the 4.7 mm sieve and collect in the tray, while the old flat-bed media had the next highest percentage that collected in the tray (45%). The 5 cm screen media had over 80% of the media pass through both the 9.8 and 4.7 mm sieves, while the old flat-bed media had almost 70% pass through both the 9.8 and 4.7 mm sieves.

The A-frame biofilter media had fewer small particles than the old flat-bed biofilter and the 5 cm screen birch mulch media (fig. 3). Only 31% of the media passed through the 4.7 mm sieve. Almost 53% of the media passed through both the 9.4 and 4.8 mm sieves. The 10 cm screen birch mulch media had the fewest small particles. Only

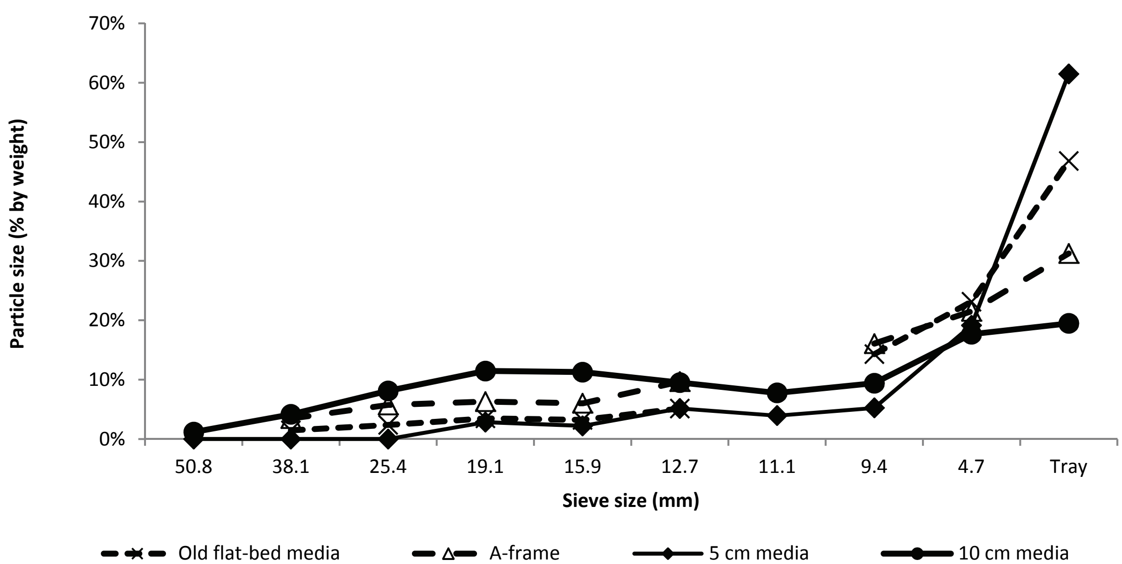

Figure 3. Media particle size at each sieve size.

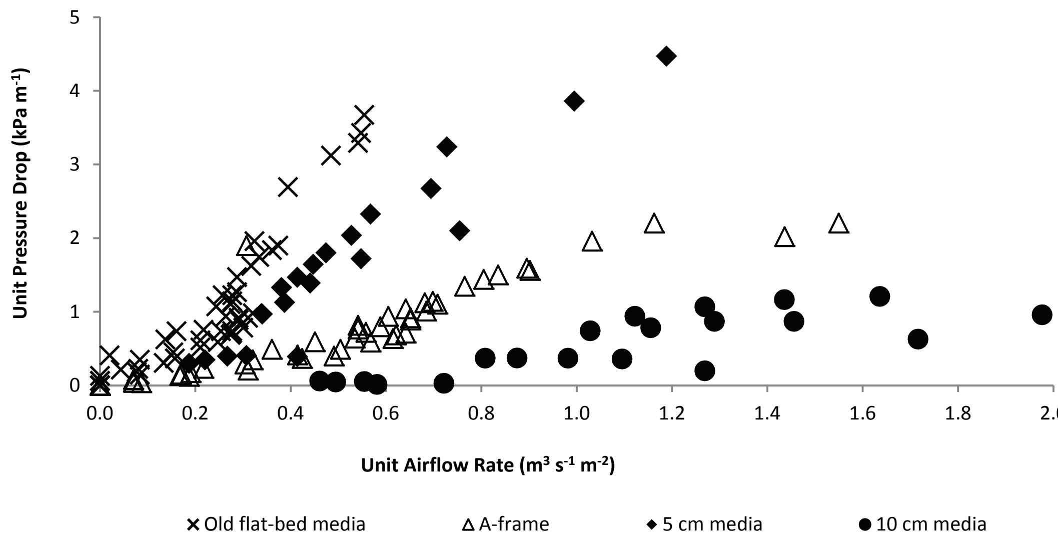

Figure 4. Biofilter media unit pressure drop versus unit airflow rate of flat-bed and A-frame biofilters (Akdeniz and Janni, 2012).

19% of the media passed through the 4.7 mm sieve, and slightly over 47% of the media passed through both the 9.4 and 4.7 mm sieves.

As expected, the media with higher percentages of small particles (old flat-bed and 5 cm screen) had higher pressure drops per meter of media depth than the media with fewer small particles (A-frame and 10 cm screen) (fig. 4). These results support the observation by Yang et al. (2011) that small media particles have a large impact on airflow resistance. The pressure drop relationship for the flat-bed biofilter media was similar to that reported by Maia et al. (2012a) for compost media.

The media sampled in 2010 were more than a year old and well settled. In 2011, the media were new and expected to settle. The depth at the end of sampling across the entire SE biofilter with 10 cm screen media ranged from 28 to 45 cm, while the depth over the entire NE biofilter with 5 cm screen media ranged from 20 to 48 cm. Media depth over the biofilter treating air from the continuously running exhaust fan (fan 1, where all of the gas sampling was conducted) ranged from 35 to 38 cm on the SE biofilter and from 30 to 36 cm on the NE biofilter. Assuming that the initial media depths were similar, the 5 cm screen media on the NE biofilter settled slightly more than the 10 cm screen media on the SE biofilter.

GAS CONCENTRATIONS

Tables 4 and 5 summarize the mean, standard deviation, maximum, minimum, and number of 24 h samples of NH_3, H_2S, CO_2, CH_4, and N_2O concentrations measured using 24 h bag samples and semi-continuous sampling for six locations on different biofilters for 2010 and 2011, respectively. Sample year, location, and line number are listed in the leftmost column. Occasionally, samples were not collected because either the hydrophobic PTFE filters in the sample lines were plugged with moisture or sample lines had leaks or kinks. Sample line 5, which was an outlet concentration for the A-frame biofilter sampled in 2010, had only four samples. The appropriate number of samples was used in calculations and statistical analysis.

The 2010 data summarized in table 4 were collected over a four-month period. Sample dates were June 24, July 7 and 20, August 5 and 17, September 8 and 21, and October 6 and 13. Air samples were collected from four groups of nursery pigs in the nursery barn during this period. The 2011 data summarized in table 5 were collected on June 29, July 13 and 26, August 10 and 23, September 9, 14, and 29, and October 12. Air samples were collected from three groups of nursery pigs in the two nursery rooms in 2011. The complete semi-continuous data set (not shown) indicated that gas concentrations vary with nursery pig age, pig size, and ventilating rate. This explains the range between the maximum and minimum concentrations and the standard deviations observed.

In general, the data in tables 4 and 5 suggest that the 24 h bag concentrations related well to the semi-continuous concentrations for NH_3, CO_2, CH_4, and N_2O. Means, standard deviations, maximums, and minimums were similar. Differences in mean NH_3 concentrations across both years were 1.5 ppm or less. Differences in mean H_2S concentrations across both years varied more widely, from 15 to 157 ppb. Differences in mean CH_4 concentrations were 6 ppm or less. Differences in mean N_2O concentrations were 37 ppb or less.

In 2010, the mean inlet gas concentrations of the flat-bed biofilter with a common duct (table 4, sample line 1) were higher than the mean concentrations of NH_3, H_2S, CO_2, CH_4, and N_2O for the inlet to the A-frame biofilter in 2010 (table 4, sample line 4). The mean concentrations of NH_3, H_2S, CO_2, and CH_4 of the 2010 flat-bed biofilter (table 4, sample line 1) were also higher than those of the inlet to the 2011 rejuvenated SE biofilter (table 5, sample line 1) and NE biofilter (table 5, sample line 4). The higher gas concentrations for line 1 in 2010 were presumed to be due to backdrafting of air into the nursery room through the closed but leaky shutters on the fans that were not running.

Table 4. Mean, standard deviation (SD), and range of NH_3, H_2S, CO_2, CH_4, and N_2O concentrations measured using 24 h bag samples (24 h) and semi-continuous sampling (Semi) for six locations during 2010 on two biofilters and ambient conditions (*n* = number of samples).

2010		NH_3 (ppm)		H_2S (ppb)		CO_2 (ppm)		CH_4 (ppm)		N_2O (ppb)	
Location	Statistic	24 h	Semi	24 h	Semi	24 h	Semi	24 h	Semi	24 h	Semi
Flat-bed inlet 1	Mean	10.9	12.4	840	899	1,079	1,099	100	97	420	435
	SD	8.9	9.7	845	811	359	388	61	56	72	65
	Max.	32.1	34.9	2,360	2,310	1,800	1,860	200	170	573	583
	Min.	3.5	3.7	102	131	630	613	24	24	360	357
	n	9	9	9	9	9	9	9	9	9	9
Flat-bed outlet 2	Mean	2.0	1.9	80	109	1,010	999	79	73	813	836
	SD	1.4	1.6	59	77	285	299	50	35	594	27
	Max.	4.7	5.0	187	243	1,500	1,530	164	114	2,000	2,090
	Min.	1.2	0.8	27	28	640	627	21	22	430	473
	n	6	6	6	6	6	6	6	6	6	6
Flat-bed outlet 3	Mean	1.7	1.9	132	192	984	979	67	70	551	569
	SD	0.8	1.8	129	196	369	453	44	44	261	197
	Max.	3.4	6.5	420	681	1,700	1,890	140	144	1,200	997
	Min.	0.9	0.5	22	23	660	604	21	29	365	343
	n	9	9	9	9	9	9	9	9	9	9
A-frame inlet 4	Mean	4.1	4.4	358	476	889	890	8.1	8.3	374	384
	SD	2.4	3.1	305	289	187	185	2.6	2.4	68	59
	Max.	9.4	11.5	985	998	1,100	1,128	21	29	468	463
	Min.	0.9	0.5	22	23	590	585	4.6	4.9	260	290
	n	8	8	8	8	8	8	8	8	8	8
A-frame outlet 5	Mean	1.3	0.8	101	157	863	804	5.5	4.8	458	443
	SD	0.6	0.2	38	88	163	84	0.9	0.8	134	59
	Max.	2.2	0.98	143	289	1,100	899	6.9	5.8	640	500
	Min.	0.65	0.50	22	23	590	585	4.6	3.9	260	290
	n	4	4	4	4	4	4	4	4	4	4
A-frame outlet 6	Mean	1.7	1.6	190	230	909	926	7.6	7.7	411	431
	SD	0.8	0.9	180	140	204	229	2.6	2.4	121	112
	Max.	2.6	3.0	610	563	1,160	1,216	11.7	11.9	640	640
	Min.	0.55	0.50	22	23	570	585	4.4	3.9	260	285
	n	8	8	8	8	8	8	8	8	8	8

Table 5. Mean, standard deviation (SD), and range of NH_3, H_2S, CO_2, CH_4, and N_2O concentrations measured using 24 h bag samples (24 h) and semi-continuous (Semi) sampling for six locations during 2011 sampling on two rejuvenated flat-bed biofilters (*n* = number of samples).

2011		NH_3 (ppm)		H_2S (ppb)		CO_2 (ppm)		CH_4 (ppm)		N_2O (ppb)	
Location	Statistic	24 h	Semi	24 h	Semi	24 h	Semi	24 h	Semi	24 h	Semi
SE inlet 1	Mean	3.5	4.0	344	269	851	843	67	65	686	699
	SD	2.4	2.9	360	302	244	244	40	31	214	252
	Max.	8.7	10.4	800	770	1220	1200	130	112	997	990
	Min.	1.6	2.0	6.1	19	550	540	25	29	460	390
	n	8	7	8	8	8	8	8	7	8	8
SE outlet 2	Mean	1.0	0.8	218	94	837	894	26	26	550	513
	SD	0.4	0.3	250	97	323	338	14	13	135	133
	Max.	1.5	1.3	680	250	1340	1400	50	43	760	790
	Min.	0.4	0.5	1	6	430	420	3	8	430	390
	n	7	6	7	7	7	7	7	6	7	7
SE outlet 3	Mean	1.12	1.05	196	95	687	634	25	30	529	504
	SD	0.45	0.95	245	89	192	204	12	27	113	99
	Max.	1.73	2.6	730	250	1080	1080	48	88	700	640
	Min.	0.54	0.2	2	6	390	365	4	5	425	390
	n	9	8	9	9	9	9	9	7	9	9
NE inlet 4	Mean	7.0	7.3	374	359	844	789	49	49	552	555
	SD	4.1	4.5	392	417	200	207	23	21	62	74
	Max.	12.3	13.4	940	1110	1130	1110	85	86	640	690
	Min.	1.4	2.6	44	47	590	590	18	26	450	440
	n	8	7	8	8	8	8	8	7	8	8
NE outlet 5	Mean	4.9	5.8	235	78	849	873	50	49	563	580
	SD	4.2	3.8	294	72	224	245	21	22	84	87
	Max.	11.1	12.0	844	180	1160	1160	85	86	700	730
	Min.	0.4	2.4	8	12	600	600	23	25	462	460
	n	7	6	7	7	7	7	7	6	7	7
NE outlet 6	Mean	4.8	5.9	180	47	876	892	50	52	592	604
	SD	3.4	3.4	253	33	206	181	23	18	96	137
	Max.	10.7	11.2	790	120	1210	1140	93	81	750	860
	Min.	1.8	2.1	12	6.8	600	640	24	35	450	400
	n	9	8	9	9	9	9	9	7	9	9

This backdrafting allowed the gas concentrations to increase because less fresh outdoor ventilation air was brought into the nursery. The fans on the A-frame biofilter had individual ducts that conducted pit and wall fan exhaust air to the A-frame plenum. While it was possible to backdraft air from the A-frame biofilter plenum, it required a longer path for the air to flow back from the A-frame biofilter plenum through the fan duct and the closed leaky shutters. In 2011, the biofilter was rejuvenated and the duct was divided (fig. 2) so that each fan supplied a separate biofilter, so there was little opportunity for backdrafting and the exhaust concentrations to increase.

In 2010, the similar CO_2 concentrations measured in the biofilter outlets (table 4, sample lines 2, 3, 5, and 6) and inlets (table 4, sample lines 1 and 4) indicated that the sample lines were sampling air passing through the biofilters and not being diluted with ambient air. In 2011, the mean CO_2 concentrations for sample line 3 were approximately 160 to 210 ppm lower than the mean CO_2 concentrations of the air entering the SE biofilter, which indicated that this line may have been diluted with ambient air (table 5). The CO_2 concentrations measured in the biofilter outlets (table 5, sample lines 2, 5, and 6) and inlets (table 5, sample lines 1 and 4) indicated that the sample lines were sampling air passing through the biofilters and not being diluted with ambient air.

The mean CH_4 concentrations in table 4 associated with the flat-bed biofilter (sample lines 1, 2, and 3) were an order of magnitude higher than those associated with the A-frame biofilter (sample lines 4, 5, and 6) in 2010 and the rejuvenated biofilters in 2011 (table 5). It is not clear why the 2010 SE nursery room had higher CH_4 concentrations than the other rooms.

Nitrous oxide concentrations of the outlet sample lines of the 2010 flat-bed biofilter with the old media (table 4, sample lines 2 and 3) and the 2011 biofilter with 5 cm screen media were often higher than the corresponding inlet sample line (table 3, sample line 1, and table 4, sample line 4), which indicated nitrous oxide generation in these biofilters. Researchers have reported N_2O generation when the biofilter is fed NH_3 and the media becomes wet enough to generate anaerobic zones (Martinec et al., 2001; Ro et al., 2008). The 2010 flat-bed biofilter compost and wood chip media was approximately 3.5 years old. The wood chips were highly degraded, and an earthworm was observed in the media when air sample lines 2 and 3 were installed. In addition, the region experienced a wet spring in 2010, which thoroughly saturated the media, making it prone to anaerobic conditions. The 2011 NE flat-bed biofilter media had more small particles (fig. 3), which may have led to anaerobic zones where N_2O may have been generated.

In general, the data in tables 4 and 5 suggest that the 24 h bag concentrations related well to the semi-continuous concentrations for NH_3, CO_2, CH_4, and N_2O. Means, standard deviations, maximums, and minimums were generally similar across methods. In 2010, the mean H_2S concentrations measured using the 24 h bag method were consistently lower than the H_2S concentrations measured using the semi-continuous sampling system. In 2011, the semi-continuous concentrations were consistently lower than those measured using 24 h sampling. There was no obvious reason for this difference.

Gas Concentration Differences

Figure 5 is a graph of concentration differences (24 h bag sample minus semi-continuous sampling) for NH_3, H_2S, CO_2, CH_4, and N_2O for 2010 and 2011. Negative values were generated when the 24 h bag sample concentration was less than the semi-continuous concentration.

Most NH_3 concentration differences (68 out of 87) were within ±2 ppm of the semi-continuous concentrations, ranging from 0.5 to 35 ppm over the two years of sampling. NH_3 concentration differences ranged from -5.1 to 4.6 ppm.

Most H_2S concentration differences (79 out of 93) were within ±200 ppb of the semi-continuous concentrations, ranging from 23 to 2,310 ppb over the two years of sampling. H_2S concentration differences ranged from -344 to 744 ppb. It is noteworthy that all six readings collected on one date (2 September 2011) had differences between 515 and 744 ppb because all of the bag samples had high H_2S concentrations, between 625 and 844 ppb. No information was collected to explain these H_2S readings from the 24 h bag samples.

Most CO_2, CH_4, and N_2O concentration differences were within ±100 ppm, ±10 ppm, and ±75 ppb, respectively, of the semi-continuous concentrations. A total of 87 out of 93 CO_2 concentration differences were within ±100 ppm, 76 out of 88 CH_4 concentration differences were within ±10 ppm, and 82 out of 93 N_2O concentrations were within ±175 ppb of the semi-continuous concentrations. The concentration difference results indicate that the 24 h sampling system concentrations were comparable to the semi-continuous sampling concentrations.

Gas Concentration Ratios

Ideally, if the two sampling methods were equivalent, then the concentration ratios (24 h bag concentration over the semi-continuous concentration) would be one and not different with respect to gas, biofilter, or year. A generalized ANOVA analysis found that the concentration ratios were not statistically different ($p > 0.05$) between filters for all gases (NH_3, H_2S, CO_2, CH_4, and N_2O) in 2010, when the flat-bed biofilter with old media and the A-frame biofilter were used. In 2011, the concentration ratios for NH_3, H_2S, and CO_2 were not statistically different ($p > 0.05$), but the ratios for CH_4 and N_2O were statistically different ($p < 0.05$). All concentration ratios were statistically different ($p < 0.05$) between years for all gases (NH_3, H_2S, CO_2, CH_4, and N_2O).

Table 6 lists the ratio medians for all five gases and both the predicted and confidence intervals. A ratio of one indicates that both methods had the same gas concentration. A ratio less than one indicates that the 24 h bag concentration was less than the semi-continuous concentration and a ratio greater than one indicates that the 24 h bag concentration was greater than the semi-continuous concentration.

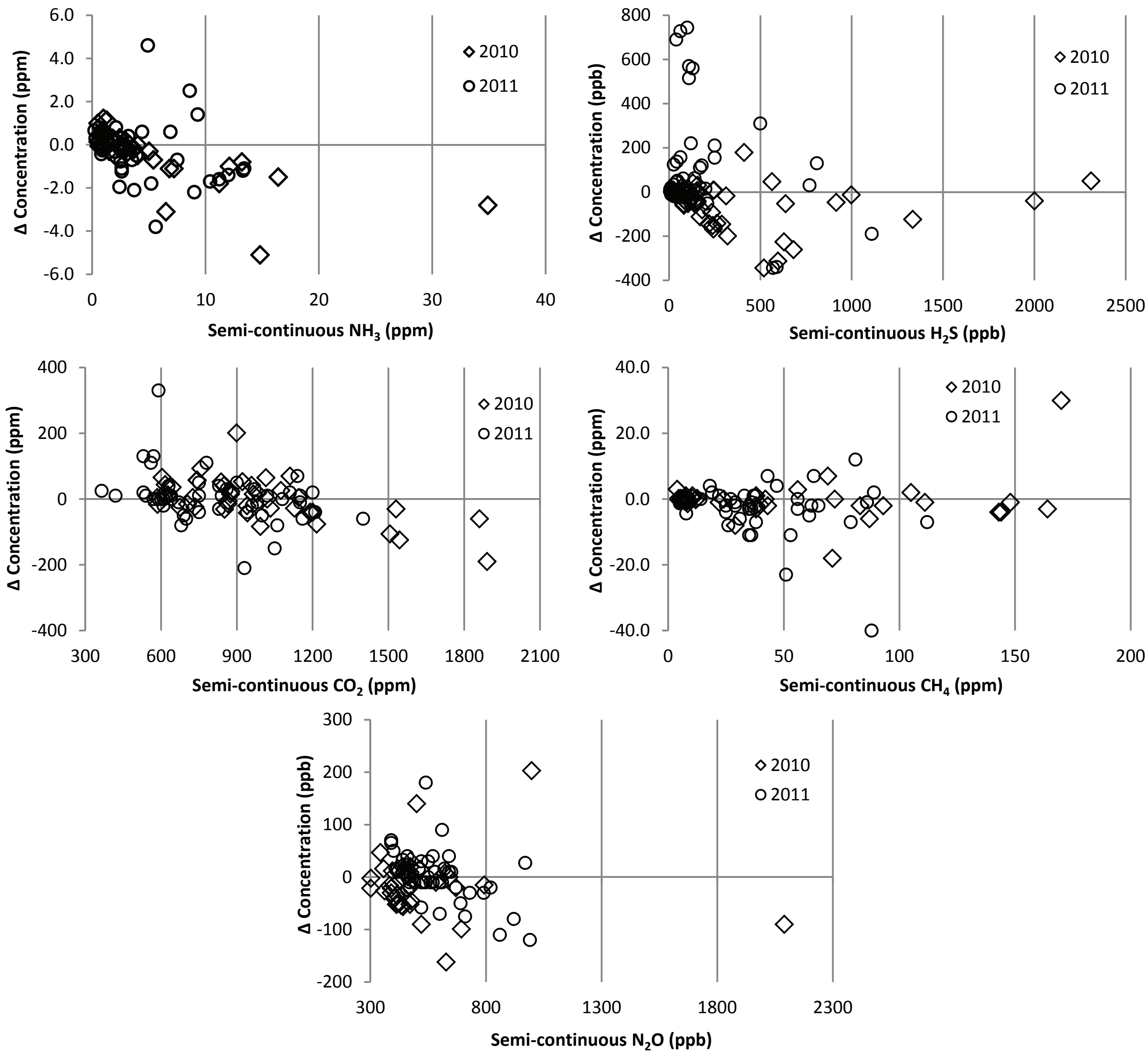

Figure 5. Concentration differences (24 h bag sample minus semi-continuous) for NH_3, H_2S, CO_2, CH_4, and N_2O in 2010 and 2011 (number of samples n = 44 for all gases in 2010, and n = 43, 49, 49, 44, and 49 for NH_3, H_2S, CO_2, CH_4, and N_2O, respectively, in 2011).

Table 6. Ratio medians (24 h bag sampling concentration divided by semi-continuous concentration) and confidence and predicted intervals.

Gas	Year	Biofilters[a]	Ratio Median	Confidence Interval Low	Confidence Interval High	Predicted Interval Low	Predicted Interval High
NH_3	2010	Flat-bed and A-frame	1.087	0.979	1.146	0.63	1.79
	2011	SE and NE	0.956	0.843	1.115	0.39	2.41
H_2S	2010	Flat-bed and A-frame	0.607	0.629	0.796	0.33	1.54
	2011	SE and NE	1.685	1.115	1.848	0.25	8.26
CO_2	2010	Flat-bed and A-frame	1.012	0.993	1.023	0.91	1.11
	2011	SE and NE	1.018	0.988	1.038	0.85	1.20
CH_4	2010	Flat-bed and A-frame	0.994	0.962	1.031	0.79	1.25
	2011	SE	0.805	0.776	0.955	0.54	1.37
	2011	NE	0.919	0.894	0.995	0.74	1.20
N_2O	2010	Flat-bed and A-frame	0.948	0.940	0.988	0.82	1.13
	2011	SE	1.055	1.004	1.072	0.88	1.22
	2011	NE	0.980	0.964	1.009	0.88	1.10

[a] Flat-bed = flat-bed biofilter with old media, SE = southeast flat-bed biofilter with 10 cm screen birch mulch media, and NE = northeast flat-bed biofilter with 5 cm screen birch mulch media.

Most ratio medians for NH_3, CO_2, and N_2O were near one, indicating good agreement between the two methods both years. For NH_3 and N_2O, the ratios were greater than one in 2010 and less than one in 2011. The 2010 H_2S ratio median was 0.607, which indicates that the 24 h bag sampling method underestimated the H_2S concentration compared to the semi-continuous method by approximately 40%. The 2011 H_2S ratio median was 1.685, which indicates that the H_2S concentrations for the 24 h bag method were higher than the semi-continuous concentrations by more than 68%.

The CH_4 ratio medians were all less than one: 0.994 in 2010, and 0.805 for the SE biofilter and 0.919 for the NE biofilter in 2011. The 2011 results indicate that 24 h bag concentrations were nearly 20% and 8% less than semi-continuous concentrations, respectively.

The confidence and predicted intervals are fairly large. Confidence intervals, which are based on standard errors, contain the true average with 95% confidence. Predicted intervals are based on standard deviations and estimate the range within which 95% of the data points will fall.

Gas Percent Reductions

Gas concentrations measured using the 24 h and semi-continuous sampling methods were used to compare the percent reductions found using equation 1. Table 7 summarizes the means, standard deviations, maximums, minimums, and number of samples for the NH_3, H_2S, CO_2, CH_4, and N_2O percent reductions calculated using equation 1 for 24 h bag concentrations and semi-continuous concentrations from two outlet locations on each biofilter in 2010. Table 8 summarizes the data for the two rejuvenated biofilters in 2011. It is noted that a single inlet biofilter concentration was used to calculate both percent reductions for each biofilter.

In 2010, the mean NH_3 percent reductions for the flat-bed biofilter (outlets 2 and 3) were higher than the mean NH_3 percent reductions for the A-frame biofilter, ranging from 79% (outlet 3 using 24 h concentrations) to 86% (outlet 2 using semi-continuous concentrations). The mean A-frame biofilter NH_3 percent reductions were lower, ranging from 51% (outlet 6 using 24 h concentrations) to 78% (out-

Table 7. Mean, standard deviation (SD), and range of NH_3, H_2S, CO_2, CH_4, and N_2O percent reductions calculated using either 24 h bag (24 h) or semi-continuous (Semi) concentrations for four outlets on two biofilters during 2010 sampling (*n* = number of samples, and negative values indicated gas generation).

2010		NH_3 (%)		H_2S (%)		CO_2 (%)		CH_4 (%)		N_2O (%)	
Location	Statistic	24 h	Semi	24 h	Semi	24 h	Semi	24 h	Semi	24 h	Semi
Flat-bed outlet 2	Mean	81	86	71	70	4	5	23	23	-77	-81
	SD	11	4	14	16	7	8	14	16	118	129
	Max.	88	90	83	83	17	18	50	49	-15	-15
	Min.	63	78	50	47	-2	-2	13	8	-317	-344
	n	6	6	6	6	6	6	6	6	6	6
Flat-bed outlet 3	Mean	79	82	79	74	8	12	23	19	-31	-31
	SD	13	11	12	15	18	17	31	30	55	42
	Max.	92	93	89	90	40	38	74	66	19	4
	Min.	57	63	57	46	-13	-3	-11	-21	-164	-124
	n	9	9	9	9	9	9	9	9	9	9
A-frame outlet 5	Mean	68	78	50	63	1	5	22	35	-23	-15
	SD	13	14	28	17	18	21	26	27	29	8
	Max.	81	91	88	88	18	23	55	56	-4	-5
	Min.	55	63	21	52	-24	-24	-9	-2	-66	-25
	n	4	4	4	4	4	4	4	4	4	4
A-frame outlet 6	Mean	51	53	33	41	-2	-3	6	8	-9	-12
	SD	28	33	44	30	3	6	8	8	12	21
	Max.	82	89	80	75	3	5	19	22	7	2
	Min.	14	9	-61	-7	-5	-12	-8	-1	-66	-60
	n	8	8	8	8	8	8	8	8	8	8

Table 8. Mean, standard deviation (SD), and range of NH_3, H_2S, CO_2, CH_4, and N_2O percent reductions calculated using either 24 h bag (24 h) or semi-continuous (Semi) concentrations for four outlets on two rejuvenated flat-bed biofilters during 2011 sampling (*n* = number of samples, and negative values indicate gas generation).

2011		NH_3 (%)		H_2S (%)		CO_2 (%)		CH_4 (%)		N_2O (%)	
Location	Statistic	24 h	Semi	24 h	Semi	24 h	Semi	24 h	Semi	24 h	Semi
SE outlet 2	Mean	64	73	25	42	0	-10	40	39	11	17
	SD	17	12	36	22	22	28	39	43	17	19
	Max.	84	88	84	69	46	49	97	93	48	53
	Min.	35	58	-29	14	-18	-39	0	-16	-1	0
	n	7	6	7	7	7	7	7	6	7	7
SE outlet 3	Mean	61	70	31	54	17	22	45	38	18	22
	SD	25	37	31	22	22	19	45	55	16	18
	Max.	85	93	80	76	51	56	96	95	50	54
	Min.	12	-8	-6	14	-8	-6	-32	-44	1	0
	n	8	7	8	8	8	8	8	7	8	8
NE outlet 5	Mean	9	6	27	57	0	-3	-2	5	-8	-12
	SD	89	22	52	29	7	3	14	6	13	17
	Max.	84	36	92	79	13	1	14	16	12	-2
	Min.	-163	-23	-35	9	-6	-8	-28	0	-25	-46
	n	6	5	6	6	6	6	6	6	6	6
NE outlet 6	Mean	10	-1	39	68	-2	-14	-11	-10	-7	-8
	SD	70	43	53	27	5	21	36	20	10	13
	Max.	81	72	89	96	5	-2	23	8	13	9
	Min.	-148	-50	-50	32	-8	-66	-94	-39	-18	-25
	n	8	7	8	8	8	8	8	7	8	8

let 5 using semi-continuous concentrations). The mean H_2S percent reductions for the flat-bed biofilters, which ranged from 70% (outlet 2 using semi-continuous concentrations) to 79% (outlet 3 using 24 h concentrations), were higher than those for the A-frame biofilter, which ranged from 33% (outlet 6 using 24 h concentrations) to 63% (outlet 5 using semi-continuous concentrations). The mean CH_4 percent reductions for the flat-bed biofilter with old media ranged from 19% (outlet 3 using semi-continuous concentrations) to 23% (outlet 2 using either concentrations and outlet 3 using 24 h concentrations). The mean CH_4 percent reductions for the A-frame biofilter ranged from 6% (outlet 6 using 24 h concentrations) to 35% (outlet 5 using semi-continuous concentrations). The mean N_2O percent reductions were negative for both biofilters, indicating generation rather than reduction. The flat-bed biofilter with its denser media had higher mean NH_3, H_2S, and CH_4 percent reductions than the A-frame biofilter. Outlet 6 on the A-frame biofilter consistently had lower percent reductions than outlet 5 on the A-frame biofilter. The percent reduction results indicate that the flat-bed and A-frame biofilters were able to remove NH_3, H_2S, and CH_4 and generate N_2O. Mean percent reductions of NH_3 and H_2S were higher than the percent reductions of CH_4.

In 2011, the SE biofilter with the 10 cm screen media had higher percent gas reductions for NH_3, CH_4, and N_2O than the NE biofilter, which had 5 cm screen media with more small particles. The mean percent NH_3 gas reductions for the SE biofilter ranged from 61% to 73%, while the mean percent NH_3 reductions for the NE biofilter ranged from -1% to 15%. A negative percent reduction indicates generation in the biofilter media. One sampling date (2 September 2011) had very large negative percent NH_3 reductions (i.e., -23% and -50% by the semi-continuous method and -148% and -168% by the 24 h bag method), but even after removing these data, the NE biofilter had lower percent reductions (data not shown).

The mean percent CH_4 gas reductions for the SE biofilter ranged from 38% to 45%, while the mean percent CH_4 gas reductions for the NE biofilter ranged from -11% to 5%. Negative reduction values indicate gas generation in the biofilter. N_2O had a similar pattern, where the SE biofilter N_2O percent reduction values were 11% to 22%, while the NE biofilter had mean negative percent reductions ranging from -7% to -12%, indicating N_2O generation.

The mean H_2S percent reduction values obtained using the 24 h bag sampling method were lower than the values obtained using semi-continuous sampling. Based on the semi-continuous data, the mean H_2S percent reduction values were similar, ranging from 42% to 68%. The mean H_2S percent reduction values obtained using the 24 h bag sampling method ranged from 25% to 39%.

The semi-continuous percent reduction results indicate that all four biofilters were able to reduce NH_3, H_2S, and CH_4 emissions. The semi-continuous data were used in this discussion. In general, the flat-bed biofilter with old media monitored in 2010 had the greatest percent reduction of NH_3 (82% and 86%) and H_2S (70% and 74%). The 2011 flat-bed biofilter with 10 cm screen birch mulch media had the next best reductions in NH_3 (70% and 73%), followed by the 2010 A-frame biofilter (53% and 78%). The 2011 flat-bed biofilter with 5 cm screen birch mulch media had the next best reduction in H_2S (57% to 68%) followed by the 2010 A-frame biofilter (41% and 63%) and the 2011 flat-bed biofilter with 10 cm screen birch mulch media (42% and 54%).

The percent CH_4 reductions were greatest with the 2011 flat-bed biofilter with the 10 cm screen birch mulch media (38% to 39%). The 2010 flat-bed biofilter with old media and the 2010 A-frame biofilter had overlapping percent CH_4 reductions ranging from 8% to 35% reduction.

Nitrous oxide (N_2O), a greenhouse gas, was reduced by the 2011 flat-bed biofilter with 10 cm screen birch mulch media (17% and 22%). The N_2O reduction values were negative for the other biofilters, indicating that N_2O was being generated in the biofilters. Data from the 2010 flat-bed biofilter with old media had the largest negative percent reductions (-31% to -81%) while the 2010 A-frame and the 2011 flat-bed biofilter with 5 cm screen birch mulch media had negative reductions ranging from -8% to 15%. Moisture management and media selection are important factors in N_2O generation in biofilters (Akdeniz and Janni, 2012; Maia et al., 2012b).

Many design and operating factors impact gas reduction or generation in biofilters. The four biofilters used for this study had NH_3, H_2S, CH_4, and N_2O gas reductions similar to many other field studies. Chen and Hoff (2009) concluded that biofilters with a typical 5 s empty bed retention time and 55% media moisture content, with a mixture of compost and wood chips, can achieve average gas reductions of 78% and 81% for H_2S and NH_3, respectively, based on 30 on-site studies reviewed. Nineteen of the reviewed studies reported percent NH_3 reductions ranging from 6% to approximately 100% (Chen and Hoff, 2009). Riis and Lyngbye (2008) reported 14% NH_3 removal in summer and little reduction in winter with a vertical biofilter treating air from a swine finishing facility. Hood et al. (2011) reported 89% to 92% NH_3 removal using a downflow compost-woodchip biofilter treating swine barn ventilation air. Chen and Hoff (2012) reported 41% NH_3 removal using wood chips to treat air from a deep-pit swine finishing barn. Akdeniz and Janni (2012) reported average NH_3 reductions of 61% and 64% for biofilters treating air from two deep-pit swine finishing barns.

Fourteen reviewed studies reported percent H_2S reductions ranging from generation (-4% removal) to approximately 100% removal (Chen and Hoff, 2009). Chen and Hoff (2012) reported 83% H_2S removal using wood chips to treat air from a deep-pit swine finishing barn. Akdeniz and Janni (2012) reported H_2S reductions of 77% and 80% for biofilters treating air from two swine finishing barns.

Two studies reviewed by Chen and Hoff (2009) reported CH_4 reductions that ranged from generation (-2.1% reduction) to up to 85% removal (Martinec et al., 2001; Melse and Werf, 2005). Hood et al. (2011) reported less than 13% CH_4 removal in the summer but up to 51% CH_4 removal in the fall. Akdeniz and Janni (2012) reported CH_4 reductions of 23% and 27% for biofilters treating air from two swine finishing barns.

Martinec et al. (2001) reported N_2O generation ranging from 16% to 29% from biofilters. Hood et al. (2011) reported 14% to 18% N_2O removal using a downflow compost-woodchip biofilter treating swine barn ventilation air. Akdeniz and Janni (2012) reported N_2O generation of 12% and 13% for biofilters treating air from two swine finishing barns.

Gas Percent Reduction Differences

Figure 6 is a graph of gas percent reduction differences (24 h percent reduction minus semi-continuous percent reduction) for NH_3, H_2S, CO_2, CH_4, and N_2O in 2010 and 2011. Ideally, the gas percent reduction differences would be zero. Negative values indicate that the percent reduction calculated using 24 h concentrations were less than the percent reduction calculated using the semi-continuous concentrations.

Most NH_3 gas percent reduction differences (35 out of 52) were less than ±20%. The gas percent reduction differences ranged from -140% to 95% over the two years of sampling.

Most H_2S gas percent reduction differences (35 out of 56) were less than ±20% of the semi-continuous concentrations, ranging from 19 to 2,310 ppb inlet concentrations over the two years of sampling.

Most CO_2, CH_4, and N_2O percent reduction differences were within ±20% of the semi-continuous concentrations. A total of 87 out of 93 CO_2 percent reduction differences, 76 out of 88 CH_4 percent reduction differences, and 82 out of 93 N_2O percent reduction differences were within ±20% of the semi-continuous concentrations. The percent reduction difference results indicate that the 24 h sampling system concentrations were comparable to the semi-continuous sampling concentrations.

The generalized ANOVA analysis using the percent reduction differences found that the NH_3, H_2S, CO_2, CH_4, and N_2O percent reduction differences were not statistically

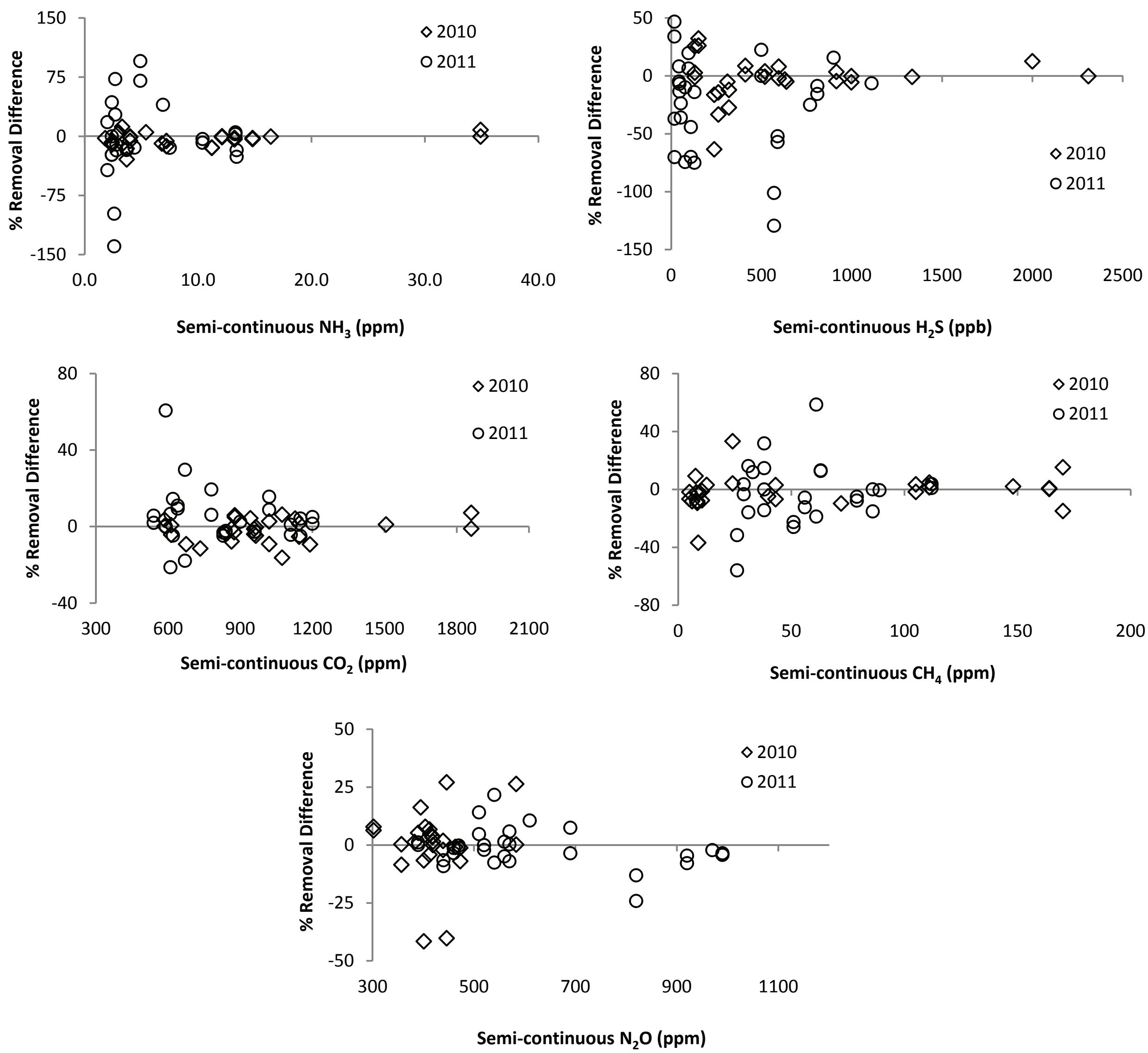

Figure 6. Percent reduction differences (24 h bag sampling percent reduction minus semi-continuous percent reduction) for NH_3, H_2S, CO_2, CH_4, and N_2O in 2010 and 2011 (number of samples n = 27 for all gases in 2010, and n = 25, 29, 29, 26, and 29 for NH_3, H_2S, CO_2, CH_4, and N_2O, respectively, in 2011).

Table 9. Median percent reduction differences and confidence intervals.

Gas	Year	Biofilters[a]	Median Percent Reduction Difference[b]	Confidence Interval		Predicted Interval	
				Low	High	Low	High
NH_3	2010	Flat-bed and A-frame	-3.52	-6.6	-0.4	-16.4	9.3
	2011	SE	-9.40	-16.1	-2.7	-27.1	8.3
	2011	NE	2.99	-45.1	51.1	-124	130
H_2S	2010	Flat-bed and A-frame	-1.33	-8.3	5.6	-29.9	27.2
	2011	SE and NE	-23.05	-6.4	0.0	-89.6	43.5
CO_2	2010	Flat-bed and A-frame	-2.02	-4.1	0.1	-10.7	6.7
	2011	SE	1.40	-2.9	5.7	-10.7	13.5
	2011	NE	10.71	-3.3	24.7	-28.9	50.3
CH_4	2010	Flat-bed and A-frame	-1.50	-5.0	2.0	-16.1	13.1
	2011	SE and NE	-2.02	-9.9	5.8	-31.5	27.4
N_2O	2010 2011	Flat-bed and A-frame SE and NE	0.10	-2.2	2.4	-13.3	13.5

[a] Flat-bed = flat-bed biofilter with old media, SE = southeast flat-bed biofilter with 10 cm screen birch mulch media, and NE = northeast flat-bed biofilter with 5 cm screen birch mulch media.

[b] 24 h bag sampling percent reduction minus semi-continuous percent reduction.

different ($p > 0.05$) between the old flat-bed biofilter and the A-frame biofilter in 2010. In 2011, the H_2S and CH_4 percent reduction differences were not statistically different ($p > 0.05$) between the 10 cm and 5 cm screen media flat-bed biofilters. In 2011, the NH_3, CO_2, and N_2O percent reduction differences were statistically different ($p < 0.05$) between the 10 cm and 5 cm screen media flat-bed biofilters. The percent reduction differences for NH_3, H_2S, CO_2, and CH_4 were statistically different ($p < 0.05$) between 2010 and 2011 but not for N_2O.

Table 9 lists the median percent reduction differences (24 h bag sampling percent reduction minus semi-continuous percent reduction) and the both predicted and confidence intervals. Negative values indicate that the 24 h bag method percent reductions were lower than the percent reductions calculated using semi-continuous method concentrations. These results indicate that the mean H_2S and CH_4 percent reductions calculated using 24 h bag concentrations were lower than those found using semi-continuous concentrations. The median N_2O percent difference was near zero, indicating that the two methods produced similar percent reduction estimates. The median percent reduction differences for NH_3 were negative for the 2010 old media flat-bed biofilter, the 2010 A-frame biofilter, and the 2011 SE biofilter with 10 cm screen birch mulch media. The median percent reduction difference for NH_3 was positive for the NE biofilter with 5 cm screen birch mulch media.

The confidence and predicted intervals were fairly large. Confidence intervals, which are based on standard errors, contain the true average with 95% confidence. Predicted intervals are based on standard deviations and estimate the range within which 95% of the data points will fall.

CONCLUSIONS

Results from NH_3, H_2S, CO_2, CH_4, and N_2O concentration data collected from the ventilation air from a swine nursery barn with deep manure pits and biofilters during summer months in 2010 and 2011 indicate that the 24 h bag sampling concentrations and percent reductions tracked the semi-continuous sampling method concentrations and percent reductions well. Most (77%) NH_3 concentration differences (24 h bag sample minus semi-continuous) were within ±2 ppm of the semi-continuous concentrations. Most (78%) H_2S concentration differences were within ±200 ppb, 87% of CH_4 concentration differences were within ±10 ppm, and 88% of N_2O concentration differences were within ±75 ppb.

Ratio means for NH_3, CO_2, and N_2O were close to one (between 0.95 and 1.09), indicating similar concentrations using the two methods. The H_2S ratio means varied across years, from 0.61 in 2010 to 1.68 in 2011. The CH_4 ratio means for the four biofilters were less than one (between 0.80 and 0.99), indicating that the 24 h bag CH_4 concentrations were less than the semi-continuous concentrations.

The semi-continuous percent reduction results indicate that the four biofilters were able to reduce NH_3, H_2S, and CH_4 emissions. Mean percent NH_3 reductions for three of the four biofilters ranged from 53% to 86%. Mean percent H_2S reductions ranged from 41% to 74%. The percent CH_4 reductions for three of the four biofilters ranged from 8% to 39%. Data from one biofilter indicated that it reduced N_2O concentrations by 17% to 22%, while the other three biofilters generated N_2O in the biofilters by 8% to 81%.

Differences between percent reductions determined using 24 h bag samples and semi-continuous sample data were mostly less than ±20% for all gases.

The 24 h bag sampling system tested was an effective method for measuring gas concentrations and percent reductions of an air treatment system in the field.

ACKNOWLEDGEMENTS

This project was supported by the Agriculture and Food Research Initiative Competitive Grant No. 2010-85112-20520 from the USDA National Institute of Food and Agriculture. We also acknowledge the assistance of Dr. Aaron Rendahl with the statistical analysis.

REFERENCES

Akdeniz, N., & Janni, K. A. (2012). Full-scale biofilter reduction efficiencies assessed using portable 24-hour sampling units. *J. A&WMA, 62*(2), 170-182.

Akdeniz, N., Janni, K. A., & Salnikov, I. A. (2011). Biofilter performance of pine nuggets and lava rock as media. *Biores. Tech., 102*(8), 4974-4980. http://dx.doi.org/10.1016/j.biortech.2011.01.058.

Chen, L., & Hoff, S. J. (2009). Mitigating odors from agricultural facilities: A review of literature concerning biofilters. *Appl. Eng. Agric., 25*(5), 751-766. http://dx.doi.org/10.13031/2013.28854.

Chen, L., & Hoff, S. J. (2012). A two-stage wood chip-based biofilter system to mitigate odors from a deep-pit swine building. *Appl. Eng. Agric., 28*(6), 893-901.

Gay, S. W., Wheeler, E. F., Zajaczkowski, J. L., & Topper, P. A. (2006). Ammonia emissions from U.S. tom turkey growout and brooder houses under cold weather minimum ventilation. *Appl. Eng. Agric., 22*(1), 127-134. http://dx.doi.org/10.13031/2013.20189.

Groen Label. (1996). Beoordelingsrichlijn in het kader van Groen Label stallen, uitgave maart. [Guideline for the assessment of Green Label housing systems, March edition 1996, in Dutch]. The Hague, The Netherlands: Publications of the Ministeries of Environment and Agriculture.

Hayes, M. D., Xin, H., Li, H., Shepherd, T. A., Zhao, Y., & Stinn, J. (2013). Ammonia, greenhouse gas, and particulate matter emissions of aviary layer houses in the Midwestern United States. *Trans. ASABE, 56*(5), 1921-1932.

Heber, A. J., Bogan, W. W., Ni, J.-Q., Lim, T. T., Ramirez-Dorronsoro, J. C., Cortus, E. L., Diehl, C. A., Hanni, S. M., Xiao, C., Casey, K. D., Gooch, C. A., Jacobson, L. D., Koziel, J. A., Mitloehner, F. M., Ndegwa, P. M., Robarge, W. P., Wang, L., & Zhang, R. (2008). The National Air Emissions Monitoring Study: Overview of barn sources. In *Proc. 8th Intl. Livestock Environ. Symp.* (pp. 199-205). St. Joseph, Mich.: ASABE.

Hoff, S. J., Harmon, J. D., Chen, L., Janni, K. A., Schmidt, D. R., Nicolai, R. E., & Jacobson, L. D. (2009). Partial biofiltration of exhaust air from a hybrid ventilated deep-pit swine finisher barn. *Appl. Eng. Agric., 25*(2), 269-280. http://dx.doi.org/10.13031/2013.26330.

Hood, M., Shah, S. B., Kolar, P., & Strikeleather, L. F. (2011). Design and operation of a biofilter for treatment of swine house pit ventilation exhaust. ASABE Paper No. 1111023. St. Joseph, Mich.: ASABE.

Janni, K. A., Akdeniz, N., Schmidt, D. R., Jacobson, L. D., & Hetchler, B. P. (2010). A 24-hour air sample collection system. ASABE Paper No. 1009597. St. Joseph, Mich.: ASABE.

Maia, G. D., Sales, G. T., Day, G. B., Gates, R. S., & Taraba, J. L. (2012a). Characterizing physical properties of gas-phase biofilter media. *Trans ASABE, 55*(5), 1939-1950. http://dx.doi.org/10.13031/2013.42356.

Maia, G. D., Day, G. B., Gates, R. S., Taraba, J. L., & Coyne, M. S. (2012b). Moisture effects on greenhouse gases generation in nitrifying gas-phase compost biofilters. *Water Res., 46*(9), 3023-3031. http://dx.doi.org/10.1016/j.watres.2012.03.007.

Martinec, M., Hartung, E., Jungbluth, T., Schneider, F., & Wieser, P. H. (2001). Reduction of gas, odor, and dust emissions for swine operations with biofilters. ASAE Paper No. 014079. St. Joseph, Mich.: ASABE.

Melse, R. W., & Van der Werf, A. W. (2005). Biofiltration for mitigation of methane emission from animal husbandry. *Environ. Sci. Tech., 39*(14), 5460-8. http://dx.doi.org/10.1021/es048048q.

Mosquera, J., & Ogink, N. W. (2005). Determination of the variation sources associated with ammonia emission measurements of animal housing. Leuven, Belgium: AgEng.

Nicolai, R. E., & Janni, K. A. (2001). Determining pressure drop through compost-woodchip biofilter media. ASAE Paper No. 014080. St. Joseph, Mich.: ASAE.

Ogink, N. W., Mosquera, J., & Melse, R. W. (2008). Standardized testing procedures for assessing ammonia and odor emissions from animal housing systems in the Netherlands. In *Proc. Mitigating Air Emissions from Animal Feeding Operations Conf.* (pp. 291-295). Ames, Iowa: Iowa State University Extension.

Riis, A. L., & Lyngbye, M. (2008). Odor and ammonia reductions in ventilation air from growing-finishing pig units using vertical biofilters. In *Proc. 8th Intl. Livestock Environ. Symp.* (pp. 261-268). St. Joseph, Mich.: ASABE.

Ro, K. S., McConnell, L. L., Johnson, M. H., Hunt, P. G., & Parker, D. (2008). Livestock air treatment using PVA-coated powdered activated carbon biofilter. *Appl. Eng. Agric., 24*(6), 791-798. http://dx.doi.org/10.13031/2013.25367.

Schmidt, D. R., Janni, K. A., & Nicolai, R. E. (2004). Biofilter design information. BAEU-18. St. Paul, Minn.: University of Minnesota, Department of Biosystems and Agricultural Engineering.

Schmidt, D. R., Clanton, C. J., & Jacobson, L. D. (2008). Standardized testing and reporting for mitigation technologies. In *Proc. Mitigating Air Emissions from Animal Feeding Operations Conf.* (pp. 284-290). Ames, Iowa: Iowa State University Extension.

Xin, H., Liang, Y., Tanaka, A., Gates, R. S., Wheeler, E. F., Casey, K. D., Heber, A. J., Ni, J. Q., & Li, H. (2003). Ammonia emissions from U.S. poultry houses: Part I. Measurement system and techniques. In *Proc. 3rd Intl. Conf. on Air Pollution from Agricultural Operations* (pp. 106-115). St. Joseph, Mich.: ASABE.

Yang, L., Wang, W., Funk, T. L., & Gates, R. S. (2011). Biofilter media characterization and airflow resistance test. *Trans. ASABE, 54*(3), 1127-1136. http://dx.doi.org/10.13031/2013.37104.

Zhao, Y., Xin, H., Shepherd, T., Hayes, M., Stinn, J., & Li, H. (2013). Thermal environment, ammonia concentrations, and emissions of aviary houses with white laying hens. *Trans. ASABE, 56*(3), 1145-1156. http://dx.doi.org/10.13031/trans.56.10097.