



# High-Rate Solid-Liquid Separation Coupled With Nitrogen and Phosphorous Treatment of Swine Manure: Effect on Ammonia Emission

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### Specialty section:

This article was submitted to  
Waste Management in  
Agroecosystems,  
a section of the journal  
Frontiers in Sustainable Food Systems

**Received:** 24 May 2018

**Accepted:** 30 August 2018

**Published:** 28 September 2018

### Citation:

Ro KS, Vanotti MB, Szogi AA,  
Loughrin JH and Millner PD (2018)  
High-Rate Solid-Liquid Separation  
Coupled With Nitrogen and  
Phosphorous Treatment of Swine  
Manure: Effect on Ammonia Emission.  
*Front. Sustain. Food Syst.* 2:62.  
doi: 10.3389/fsufs.2018.00062

A new treatment system was developed to meet multiple environmental performance standards including to substantially reduce ammonia emissions. It was tested full-scale for 2-years in a 5,145-head finishing swine farm with two anaerobic lagoons. The system combined high-rate solid-liquid separation with nitrogen and phosphorus removal processes. Both vertical radial plum mapping (VRPM) and floating static chamber techniques were used to measure NH<sub>3</sub> emission fluxes from anaerobic storage lagoons and the total farm-level NH<sub>3</sub> emission rates. The VRPM used an open-path tunable diode laser absorption spectroscopy (TDL) and the flux chamber used a photoacoustic gas analyzer to accurately measure NH<sub>3</sub> concentration. After the treatment system started, one of the two lagoons became inactive without receiving anymore flushed manure. The ammonia emission flux from the other lagoon with the treated effluent decreased from 43.9 to 6.8 kg-N ha<sup>-1</sup> d<sup>-1</sup> 1.5 years after implementation of the new treatment system. The NH<sub>3</sub> emission flux from the inactive lagoon also decreased similarly because the already stored old manure of the lagoon prior to inactivation was diluted with rainfalls and lost some NH<sub>3</sub> via volatilization. The total farm-level NH<sub>3</sub> emission rates decreased from 1.72 g s<sup>-1</sup> to below detection level of the VRPM technique. Using the minimum detection level of the TDL with R<sup>2</sup> > 90% (i.e., 8.1 8.1 μL L<sup>-1</sup>-m), the total farm-level NH<sub>3</sub> emission rates in the second year were less than 0.04–0.15 g s<sup>-1</sup>. These results suggested that the impact of the new treatment system on NH<sub>3</sub> emission reduction was equivalent to closing conventional swine lagoons while actively growing 5,145 pigs with minimal ammonia emissions from the farm.

**Keywords:** total farm ammonia emission rate, swine lagoon, manure treatment, vertical radial plume mapping method, lagoon emission flux

## INTRODUCTION

Ammonia (NH<sub>3</sub>) is an important fugitive gas mostly emitted from livestock operations in the United States (Doorn et al., 2002; Ro et al., 2017). Ammonia, a precursor of nitrate due to microbial nitrification/denitrification, causes acidification of both soil and surface water, and eutrophication in water bodies. It is also a principal source of atmospheric aerosols. Anaerobic

lagoons are being widely utilized in the southeastern U.S. for storage and treatment of manure from confined swine production operations. The anaerobic treatment reduces the organic load of liquid manures but releases inorganic nitrogen as ammonia. Thus, ammonia emission from the lagoons is of environmental and health concerns in geographic areas with very intense confined swine production (Barker, 1996; Aneja et al., 2000; McCubbin et al., 2002; Szogi et al., 2006; Blunden and Aneja, 2008; Westerman et al., 2010). Addressing the environmental and health issues caused by ammonia emissions and potential contamination of water bodies with swine manure effluents Vanotti et al. (2010), developed an on-farm wastewater treatment system and demonstrated its high efficacy to meet multiple environmental performance standards (Vanotti et al., 2009) on a 5,145-head swine finishing farm. The multi-stage treatment system used solid separation, nitrification-denitrification, and phosphorous removal/disinfection processes. The new treatment system replaced the conventional anaerobic treatment lagoons of a swine farm and improved lagoon water quality dramatically. The treatment system removed 97% of total suspended solids (TSS), 99% of biochemical oxygen demand (BOD), 93% of total phosphorous (TP), 96% of total Kjeldahl nitrogen (TKN), and ammoniacal nitrogen (NH<sub>4</sub>-N) from the manure (Vanotti et al., 2018).

Although the new treatment system significantly improved the lagoon water quality (Vanotti et al., 2018) and reduced odors (Loughrin et al., 2009), its impact on ammonia (NH<sub>3</sub>) emission had not been reported. The improved lagoon water quality would directly impact the NH<sub>3</sub> emissions from the lagoon and the animal houses using the cleaner plant-treated water for flushing manure (Szogi et al., 2006; Ro et al., 2008). Therefore, it is of great interest to assess the NH<sub>3</sub> emission reduction from the whole swine farm utilizing the new second-generation manure treatment system.

Micrometeorological techniques such as the integrated horizontal flux (IHF) and the backward Lagrangian stochastic (bLS) dispersion techniques can be used to measure the total ammonia emission from a swine farm. Although the bLS technique has shown its high accuracy in measuring gas emissions from point and distributed emission sources (Ro et al., 2009, 2011, 2013, 2014), one of the concerns for the use of the bLS technique in measuring emissions from a real farm with a variety of structures (buildings, stand pipes, etc.) is its underlying assumption of idealized wind flow over flat and homogenous terrain. The wind disturbance caused by farm building structures can be minimized by measuring downwind concentrations further downwind distance from the farm such as 10 times the height of the buildings (Flesch et al., 2005). However, measuring downwind concentration at longer distances from an emission source may not be feasible for certain conditions due to limited open space or dilution of emitted gas concentration below the detection limit of an analytical technique.

In contrast, the IHF technique, a mass-balance based method, is not very sensitive to changes in wind turbulence, which can be used to measure an average gas emission rate of a large area (Wilson et al., 1983). The U.S. Environmental Protection Agency published the vertical radial plum mapping (VRPM) technique

based on the IHF principles as Other Test Method 10 (OTM–10) in measuring fugitive gas emission rates from closed landfills (EPA, 2005). The VRPM technique estimates the horizontal flux of gas passing downwind of the emission source based on measured wind speed profiles and path integrated concentrations (PICs) (Ro et al., 2009, 2011; Viguria et al., 2015). The VRPM utilizes a bivariate Gaussian smooth basis function minimization (SBFM) to reconstruct a crosswind-smoothed mass-equivalent concentration map in a vertical plane from the downwind PIC data. Once all parameters for the bivariate Gaussian function are measured for a specific run, the VRPM procedure calculates the mass-equivalent concentration values for every square elementary unit (4 × 4 m) in a vertical plane. Then, the VRPM procedure computes and integrates the elementary unit flux over the entire vertical plane with corresponding wind speed data. Arcadis Inc. (Research Triangle Park, NC) developed the computer-based VRPM software which automatically calculates the emission rates based on the downwind PIC data, wind speed and direction information using the VRPM algorithm.

The objective of this study was to measure the ammonia emissions from the 5,145-head swine finishing farm with the new on-farm manure treatment system during a 2-year evaluation using the VRPM technique.

## MATERIALS AND METHODS

### Farm Description

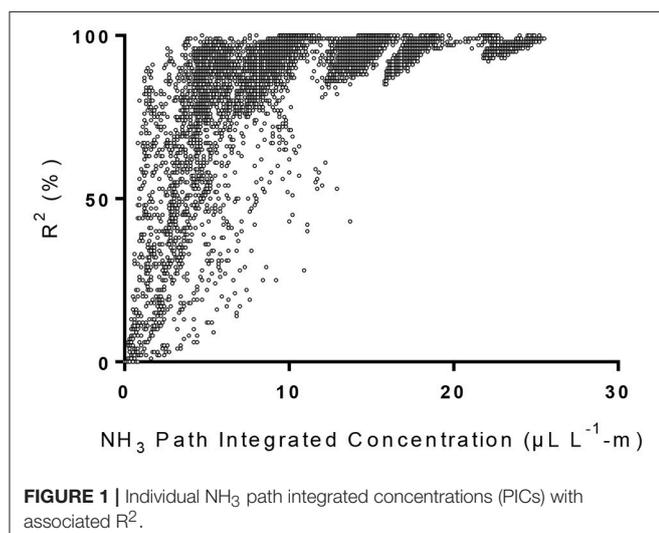
The total NH<sub>3</sub> emissions from a finishing swine farm in North Carolina with a full-scale manure treatment system were measured from December 2006 to September 2008. The farm had seven swine houses with a permitted capacity of 5,145 head feeder to finish (735 head/barn). Two traditional anaerobic lagoons were used for about 11 years before the new manure treatment plant started operation in December 2006. With the new treatment system, the flushing of raw wastewater into the lagoons was discontinued. The treatment system consisted of three process units in series: polymer-enhanced solid-liquid separation, biological N removal, and alkaline phosphorous extraction and disinfection. More detailed description of the new manure treatment system and the farm operation can be found elsewhere (Vanotti et al., 2018).

### Open-Path Tunable Diode Laser Absorption Spectroscopy

An open-path tunable diode laser absorption spectrometer (TDL; GasFinder2.0 for NH<sub>3</sub>, Boreal Laser Inc., Edmonton, AB, Canada) was used to measure path-integrated concentrations (PICs) of NH<sub>3</sub>. The TDL mounted on an automatic positioning device (APD; Model 20 Servo, Sagebrush Technology, Inc., Albuquerque, NM) emits a collimated beam (1,512 nm) aimed at distant three mirrors (retroreflectors) from which it is reflected to the TDL's detector. The TDL was designed for a sampling rate of about 1 Hz and had continuous internal calibration updates every 40 samples using an internal reference cell. The signal from the measurement path is compared with the signal from the internal reference cell and calculate the average gas concentration in the path as  $\mu\text{L L}^{-1}\text{-m}$  (i.e.,  $\mu\text{L L}^{-1}$  multiplied by path length

in m). The TDL also calculates the coefficient of determination ( $R^2$ ) for each measurement to indicate the similarity between the waveform of the sample gas to that of the reference cell gas. A perfect match of the two waveforms would give  $R^2$  of 1.0, and total mismatch would give  $R^2$  of 0.0. Although the company recommends  $5 \mu\text{L L}^{-1}\text{-m}$  as the minimum detection limit (MDL) for NH<sub>3</sub>, we decided to determine the MDL for our TDL that would yield  $R^2 > 90\%$ . Determining the reliable value of MDL was important because the new manure treatment system dramatically improved the lagoon water quality and the NH<sub>3</sub> emission was so low that the path-integrated NH<sub>3</sub> concentrations measured with our TDL became at or below the MDL during the second year of the manure treatment operation in 2008.

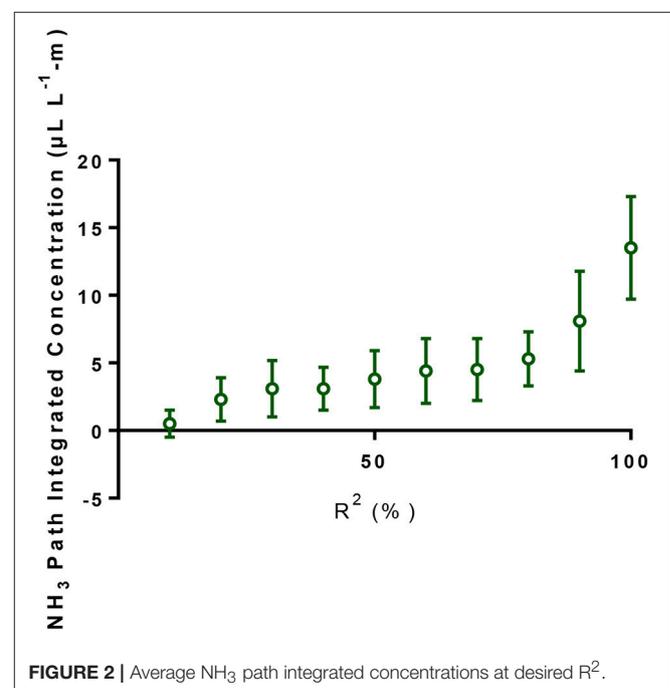
The MDL of our TDL was determined by measuring PICs through a 4.5-m PVC pipe (5.1 cm diameter) in which  $3 \text{ L min}^{-1}$  of a mixture of pure N<sub>2</sub> and calibrated NH<sub>3</sub> gas (5.0 ppm, National Welders Supply Co., Inc., NC) flew through the PVC pipe. The two ends of the PVC pipe were sealed with transparent plastic film. Initially the PVC pipe was filled with ultra-pure nitrogen gas (National Welders Supply Co., Inc.). Using a gas divider (SGD-710C, Horiba STEC, Sunnyvale, CA), gas mixtures of 10% NH<sub>3</sub> + 90% N<sub>2</sub> ( $0.5 \mu\text{L L}^{-1}\text{-m}$  NH<sub>3</sub>), 30% NH<sub>3</sub> + 70% N<sub>2</sub> ( $1.5 \mu\text{L L}^{-1}\text{-m}$  NH<sub>3</sub>), 50% NH<sub>3</sub> + 50% N<sub>2</sub> ( $2.5 \mu\text{L L}^{-1}\text{-m}$  NH<sub>3</sub>), 70% NH<sub>3</sub> + 30% N<sub>2</sub> ( $3.5 \mu\text{L L}^{-1}\text{-m}$ ), and 100% NH<sub>3</sub> ( $5.0 \mu\text{L L}^{-1}\text{-m}$ ) were introduced into the PVC pipe. The measured PICs and the corresponding  $R^2$ -values were plotted as shown in **Figure 1**. We also plotted the average NH<sub>3</sub> PICs at different  $R^2$ -values (**Figure 2**). The average PIC was  $5.3 \mu\text{L L}^{-1}\text{-m}$  at  $R^2$  of 80% (**Figure 2**), which was similar to the NH<sub>3</sub> MDL ( $5.32 \mu\text{L L}^{-1}\text{-m}$ ) reported by the U.S. Environmental Protection Agency's (EPA's) Environmental Technology Verification (ETV) statement (Myers et al., 2000). The MDL with  $R^2$  of 90% was  $8.1 \mu\text{L L}^{-1}\text{-m}$ . We used the MDL of  $8.1 \mu\text{L L}^{-1}\text{-m}$ , when we observed the NH<sub>3</sub> PICs were below MDL during the second year of the new manure treatment system in 2008, to calculate the MDL for the VRPM NH<sub>3</sub> emission rate determination.



## Total NH<sub>3</sub> Emission Rate Measurements Using the VRPM Technique

Total NH<sub>3</sub> emission rates from the swine farm (animal houses, lagoons, and the wastewater treatment system) were measured using the VRPM technique. The VRPM technique utilized the TDL mounted on the APD to measure downwind NH<sub>3</sub> PICs with 3 distant retroreflectors, one positioned at ground-level and the other two mounted on a weather station mast (10 or 20 m height). The upwind NH<sub>3</sub> concentrations were measured with a photoacoustic gas analyzer (INOVA, California Analytical, Orange, CA). The ranges of path lengths and the heights of the three retroreflectors are shown in **Table 1**. The path length between the TDL and the retroreflectors ranged from 129 to 266 m. The VRPM system was positioned downwind from the farm on a vertical plane, approximately perpendicular to the mean wind direction. The wind directions were mostly NNW or NNE. **Figure 3** shows the VRPM setup with the vertical plane approximately perpendicular to the NNE wind. The APD sequentially directed the infrared collimated beam of the TDL to each retroreflector. At each retroreflector, the TDL collected about 12–15 downwind PIC datasets before moving to the next position. Two cup anemometers (CS800-L Climatronics Wind Speed and Direction Sensor, Campbell Scientific, Logan, UT) mounted on the weather station mast at 2 and 10 m heights continuously measured wind speed and direction information during the emission monitoring campaigns.

The post-data filtering criteria recommended by the USEPA OTM-10 were used to remove error-prone data: concordance factor (CCF)  $> 0.8$  (except when estimating the below minimum detection level emission rates with all PICs assuming to have the MDL of  $8.1 \mu\text{L L}^{-1}\text{-m}$ ) and the mean wind direction between  $-10^\circ$  and  $+25^\circ$  from perpendicular to the vertical



optical plane. After filtering data with the above criteria, the relative accuracies (calculated emission rate/actual emission rate) of the VRPM technique were  $1.23 \pm 0.17$  (i.e., 23% over the actual emission rate) and  $0.97 \pm 0.44$  (i.e., 3% less than the actual emission rate) for multi land emission sources and lagoon emission, respectively (Ro et al., 2011; Viguria et al., 2015).

### Lagoon Emission

In addition to the VRPM technique for measuring whole farm NH<sub>3</sub> emission rates, the lagoon emissions were further verified using floating chamber techniques to compare the emission fluxes before and after the new treatment system reaching its steady state condition. The lagoon NH<sub>3</sub> emission fluxes were measured on June 18, 2007 while the treatment system was still under a startup period and on July 24, 2008 when the new treatment system was operating steady state.

### Floating Static Chamber System

The static flux chamber was made of polyvinyl chloride (PVC) pipe (15.2 cm diameter and 29.8 cm length) one end sealed with

an endcap. It was placed at the center of a 50.8 cm square foam sheet (thickness of 5.1 cm) to float on the lagoon water surface. The system was designed to submerge 11 cm of the PVC pipe under water to achieve a complete seal of the chamber headspace. The headspace gas was pulled from the chamber through Teflon tubing to the photoacoustic gas analyzer positioned at the bank of the lagoon and the analyzed gas was recirculated back to the chamber, thereby achieving well mixed condition inside the chamber. The floating flux chamber was launched into the lagoon at about 10 m away from the bank. The lagoon NH<sub>3</sub> emission was measured from 6 (3 points in each lagoon in 2007) to 10 (4 points in Lagoon 1 and 6 points in Lagoon 2 in 2008) different locations of the lagoons. After the treatment system started, Lagoon 2 became inactive without receiving anymore flushed manure from the pig houses. Instead, all manure flushed from the houses was treated first by the new treatment system and the treated effluent was stored in Lagoon 1 before use in crop irrigation. The increase in headspace NH<sub>3</sub> concentration was measured every 0.5–1 min with the photoacoustic gas analyzer for 10 min. The time-series headspace NH<sub>3</sub> concentration data were then used to calculate emission fluxes.

The NH<sub>3</sub> emission flux was calculated by fitting the time-series headspace NH<sub>3</sub> concentration data to a theoretical equation derived from performing a mass balance around the chamber. Assuming that the chamber is completely mixed and sealed, NH<sub>3</sub> mass balance around the chamber gives

$$\frac{dC}{dt} = k(C_s - C) d \tag{1}$$

TABLE 1 | Retroreflector positions.

Retroreflectors	Height above ground (m)	Pathlength (m)
Retroreflector 1 (M1)	1.0	199.2–266.2
Retroreflector 2 (M2)	5.0 or 10.0	128.6–228.5
Retroreflector 3 (M3)	10.0 or 18.4	128.6–228.5

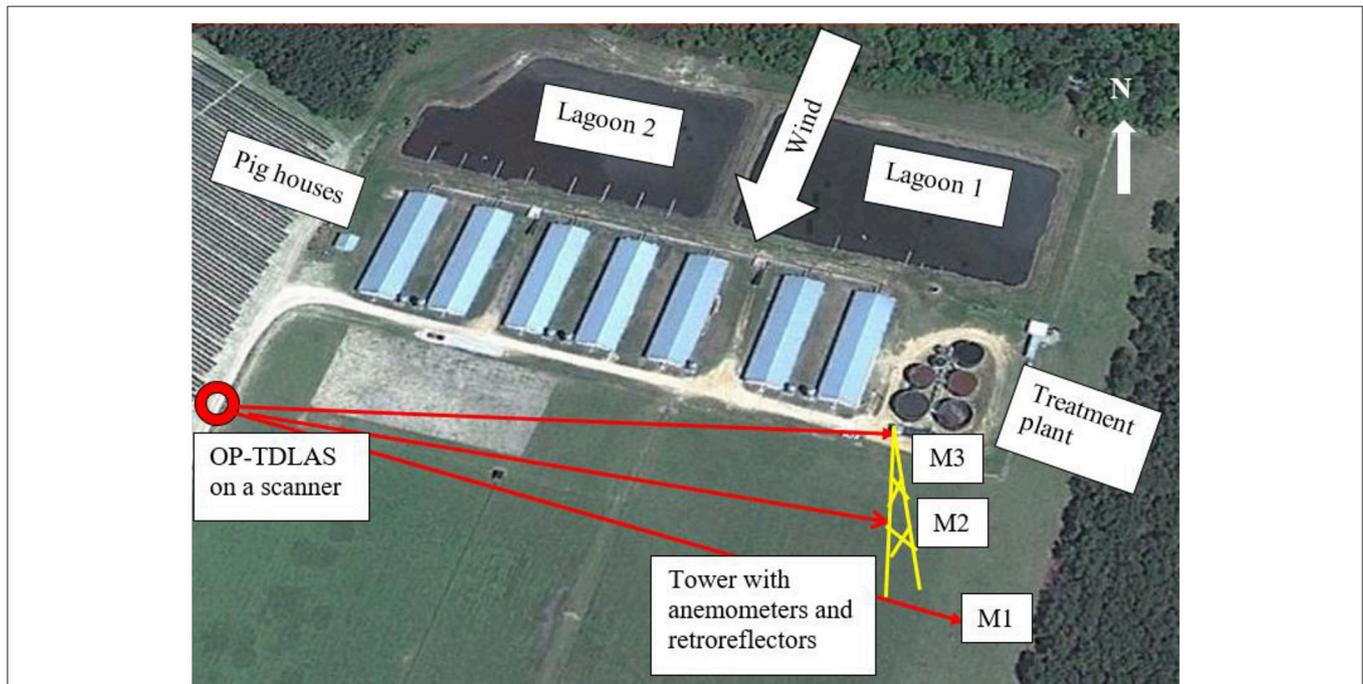


FIGURE 3 | VRPM beam geometry for NNE wind (M1, retroreflector 1 m above ground; M2, retroreflector at 5–10 m above ground; M3, retroreflector at 10–18.4 m above ground).

Where

- $C$  = bulk headspace NH<sub>3</sub> concentration (mg m<sup>-3</sup>),  
 $C_S$  = NH<sub>3</sub> concentration at the water surface (mg m<sup>-3</sup>),  
 $d$  = mixing height of the flux chamber (m<sup>2</sup>)  
 =  $A_d/V$   
 $A_d$  = water surface area (m<sup>2</sup>),  
 $V$  = headspace volume (m<sup>3</sup>),  
 $k$  = mass transfer coefficient (m min<sup>-1</sup>),  
 $t$  = time (min),

Integrating Equation (1) gives

$$C = C_S - (C_S - C_0) \exp\left(\frac{-kd}{t}\right) \quad (2)$$

Where  $C_0$  = initial headspace concentration (mg m<sup>-3</sup>).

Instead of assuming initial concentration of ambient concentration, all three parameters (i.e.,  $C_S$ ,  $C_0$ , and  $k$ ) were estimated simultaneously via non-linear regression analysis of the time-series headspace NH<sub>3</sub> concentration data using GraphPad Prism 7.03 (GraphPad Software, Inc., La Jolla, CA). This simultaneous regression of multi-parameters were recommended by the American Society of Civil Engineers (ASCE) in estimating oxygen transfer efficiency with the similar equation (ASCE, 1992). These three parameters estimated from fitting the time-series NH<sub>3</sub> concentration data to Equation (2), were then used to calculate the instantaneous flux ( $J$ ) as time approached zero:

$$\left. \frac{dC}{dt} \right|_{t \rightarrow 0} \left( \frac{V}{A_d} \right) = J = k(C_S - C_0) \quad (3)$$

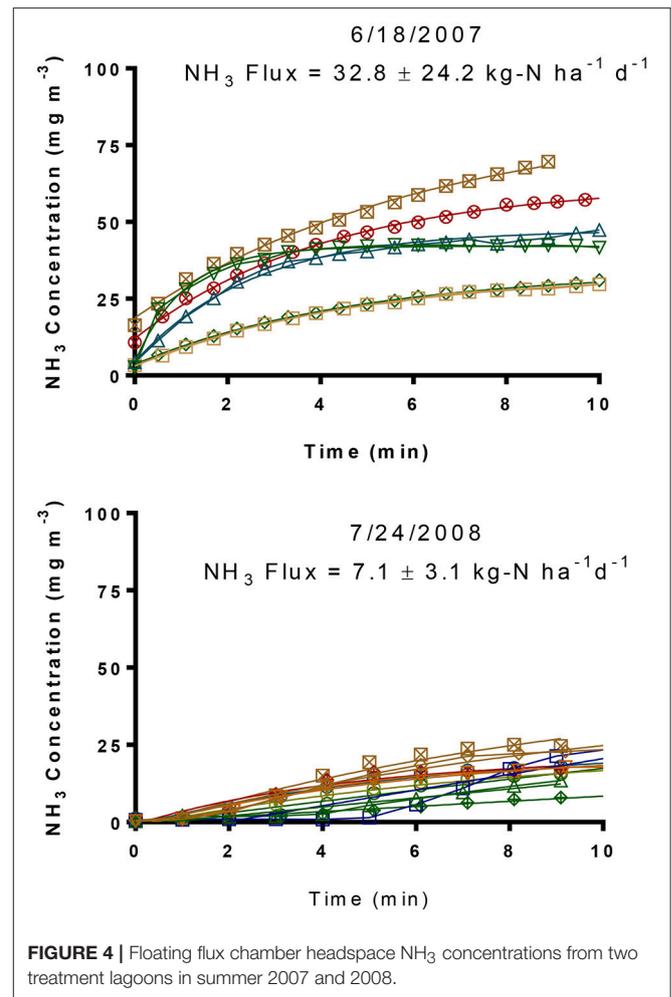
## Statistical Analysis

The central tendency and precision of measurements were presented with arithmetic averages and standard deviations (given as  $\pm$  values). All statistical parameters, analyses of variance (ANOVA) tests, and multi-regression analyses were obtained/performed using GraphPad Prism 7.03.

## RESULTS AND DISCUSSION

### Ammonia Emission Flux From Lagoons Using Floating Static Flux Chamber Technique

The increases in static flux chamber headspace NH<sub>3</sub> concentration with time at 6 (6/18/2007) and 10 (7/24/2008) different locations of the two lagoons and average NH<sub>3</sub> fluxes from each lagoon are shown in **Figure 4** and **Table 2**. Ammonia fluxes from the two lagoons ranged from 14.4 to 78.8 kg-N ha<sup>-1</sup> d<sup>-1</sup> with an average flux of 32.8  $\pm$  24.2 kg-N ha<sup>-1</sup> d<sup>-1</sup> in 2007 (**Table 2**). These NH<sub>3</sub> emission fluxes were comparable to that from conventional swine lagoons without any manure treatment during summer months as reported in the literature (Arogo et al., 2003). It also indicated that the new treatment system had not yet been effective in reducing NH<sub>3</sub> emission from the lagoon 1 receiving treated effluent. Therefore, we decided to discontinue the VRPM monitoring of whole farm NH<sub>3</sub> emission rates until



**FIGURE 4** | Floating flux chamber headspace NH<sub>3</sub> concentrations from two treatment lagoons in summer 2007 and 2008.

**TABLE 2** | NH<sub>3</sub> emission fluxes from the two lagoons.

	Emission Flux in June 2007 (kg-N ha <sup>-1</sup> d <sup>-1</sup> )	Emission Flux in July 2008 (kg-N ha <sup>-1</sup> d <sup>-1</sup> )
Lagoon 1	43.9 $\pm$ 32.4 <sup>a†</sup>	6.8 $\pm$ 2.8 <sup>b</sup>
Lagoon 2	21.7 $\pm$ 6.5 <sup>a</sup>	7.3 $\pm$ 3.6 <sup>b</sup>
Average for both lagoons	32.8 $\pm$ 24.2	7.1 $\pm$ 3.1

<sup>†</sup>Emission flux values followed by the same superscript letter (a or b) were not significantly different at  $P < 0.05$  (ANOVA).

the new treatment system reached steady state and impacted NH<sub>3</sub> emission from the farm.

**Figure 4** (bottom) shows that the flux-chamber time-series headspace ammonia concentrations increased to less than 25 mg L<sup>-1</sup> after the chamber was deployed. In contrast, the NH<sub>3</sub> concentrations increased to 75 mg L<sup>-1</sup> 10 min after deployment, indicating much higher emission fluxes in 2007 than in 2008. The NH<sub>3</sub> emission fluxes from the two lagoons ranged from 1.9 to 11.0 kg-N ha<sup>-1</sup> d<sup>-1</sup> with an average flux of 7.1 kg-N  $\pm$  3.1 kg-N ha<sup>-1</sup> d<sup>-1</sup>. The average NH<sub>3</sub> emission fluxes were 6.8  $\pm$  2.8 kg-N ha<sup>-1</sup> d<sup>-1</sup> from Lagoon 1 and 7.3  $\pm$  3.6 kg-N ha<sup>-1</sup> d<sup>-1</sup> from

the inactive Lagoon 2. The significant decrease in NH<sub>3</sub> emission fluxes resulted from improving lagoon water quality by the new treatment system for Lagoon 1. The NH<sub>3</sub> emission flux from Lagoon 2 also decreased because the already stored old manure of the Lagoon 2 prior to inactivation was diluted with rainfalls and lost some NH<sub>3</sub> via volatilization. The decrease in NH<sub>3</sub> emission flux was further validated by the fact that the total ammoniacal N (TAN) of the lagoon liquid in June 2007 was 197 mg L<sup>-1</sup> [or 20.0 mg L<sup>-1</sup> NH<sub>3</sub> (aq)-N] while that in July 2008 was only 32.7 mg L<sup>-1</sup> {32.5 and 33.0 mg L<sup>-1</sup> TAN [or 5.1 and 2.8 mg L<sup>-1</sup> NH<sub>3</sub> (aq)-N] for Lagoons 1 and 2, respectively} (Vanotti et al., 2018). These results suggested that the impact of the new treatment system on NH<sub>3</sub> emission reduction was equivalent to closing conventional swine lagoons while actively growing 5,145 pigs.

### Whole Farm Ammonia Emission Reduction With the VRPM Technique

The NH<sub>3</sub> emission rates, measured with the VRPM technique, were the whole-farm emission rate that included three main NH<sub>3</sub> sources: (1) the NH<sub>3</sub> emissions from seven animal houses, (2) the new wastewater treatment system, and (3) the two lagoons (Figure 3). These NH<sub>3</sub> emissions rates were measured from 12/7/2006 to 9/17/2008 (Table 3 and Figure 5). The start date (12/7/2006) was a day before the start date of the new wastewater treatment system. The NH<sub>3</sub> emission rate on 12/7/2006 was 0.80 g/s. However, 3 months after starting the new treatment system, the NH<sub>3</sub> emission rate increased to 2.64 g/s, because the air temperature along with the wind speed were much higher. In addition, it was too short period of time to observe the impact of the new treatment system on lagoon water quality (the lagoon renovation capacity with treated effluent was 1.2 lagoon volumes per year or hydraulic residence time, HRT = 0.8 years). After observing the NH<sub>3</sub> emission flux from the lagoons was comparable to that from conventional swine lagoons without any treatment (Figure 4 top), NH<sub>3</sub> emission rate was not measured for the rest of 2007 to give more time for the new manure treatment system fully impacting the total farm emission. In 2008, NH<sub>3</sub> emission rates were monitored in relatively cold (4/4/2008), mild (9/16–9/17/2008), and hot days (7/24/2008 and

8/20/2008). Regardless the wide variation of air temperatures and wind speeds, in the second year, downwind NH<sub>3</sub> PICs were all below the MDL (i.e., 8.1 μL L<sup>-1</sup>-m) of TDL. Below-detection-limit emission rates of these days were estimated by assuming all PICs had the MDL concentration of 8.1 μL L<sup>-1</sup>-m (Table 3). These below-detection emission rate ranges from 0.04 to 0.15 g/s, more than an order of magnitude lower the initial emission rates. These data clearly demonstrated that the new treatment system substantially reduced the NH<sub>3</sub> emission from the swine farm.

The NH<sub>3</sub> emissions rates obtained prior and during initial operation of the new wastewater treatment in this full-scale study were compared to emissions rates from other full-scale studies with conventional and converted lagoons in North Carolina. Initially with lower air and lagoon water temperatures (December 2006), the estimated live weight (LW) based emission rate of 0.80 g s<sup>-1</sup> [1.19 kg N wk<sup>-1</sup> (1,000 kg LW)<sup>-1</sup>] was similar to the winter combined house-lagoon NH<sub>3</sub> emission rate of 1.06 kg N wk<sup>-1</sup> (1,000 kg LW)<sup>-1</sup> from a conventional swine farm with similar number of pigs for a 5,784-head finisher farm using anaerobic lagoon technology (Aneja et al., 2008a). The emission rate obtained immediately after beginning the new treatment system in February 2007 was 2.64 g s<sup>-1</sup> [3.92 kg N wk<sup>-1</sup> (1,000 kg LW)<sup>-1</sup>], due to very high wind speed at that day (8.33 m/s compared to 2.67 m/s in 12/7/2006) while the water temperatures were similar. The emission rate was almost linearly increased

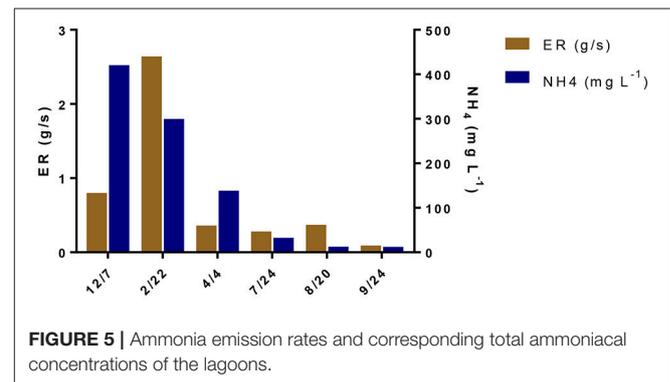


FIGURE 5 | Ammonia emission rates and corresponding total ammoniacal concentrations of the lagoons.

TABLE 3 | Summary of temperatures, wind speed, and NH<sub>3</sub> emission rates from the swine farm.

Sampling period <sup>†</sup>	Mean air temperature <sup>‡</sup> (°C)	Wind speed (m s <sup>-1</sup> )	Average NH <sub>3</sub> concentration <sup>§</sup> (μL L <sup>-1</sup> )	NH <sub>3</sub> emission rate (g s <sup>-1</sup> ) <sup>#</sup>
12/7/2006 12:15–14:55	15.3 ± 0.6	2.67 ± 0.92	0.29 ± 0.05	0.80 ± 0.16
2/22/2007 15:45–16:30	22.4 ± 0.05	8.33 ± 2.20	0.27 ± 0.03	2.64 ± 0.32
4/4/2008 10:15–12:30	16.9 ± 2.7	3.46 ± 1.03	<MDL <sup>¶</sup>	< 0.15
7/24/2008 11:50–18:20	29.3 ± 1.1	1.59 ± 0.75	<MDL	< 0.12
8/20/2008 11:10–15:30	30.9 ± 1.0	2.38 ± 1.06	<MDL	< 0.13
9/16/2008 14:10–16:15	22.5 ± 0.6	3.52 ± 1.23	<MDL	< 0.05
9/17/2008 9:30–10:45	19.2 ± 0.6	3.01 ± 1.12	<MDL	< 0.04

<sup>†</sup> New wastewater treatment system started operation December 9, 2006.

<sup>‡</sup> Mean air temperatures measured at 2 m above ground on site during measurement period.

<sup>§</sup> NH<sub>3</sub> concentration.

<sup>¶</sup> <MDL, below minimum detection limit (<8.1 μL L<sup>-1</sup>-m or about 0.08 μL L<sup>-1</sup> for a 100-m path length).

<sup>#</sup> Calculated assuming 8.1 μL L<sup>-1</sup>-m for all PICs.

with wind speed. Note that during this initial startup period, the effects of the new treatment system on lagoon water quality were minimal.

After 1.5 years of operation the total emissions (combining animal houses, treatment plant, and lagoons) of the treatment plant were  $<0.15 \text{ g s}^{-1}$  [ $0.22 \text{ kg N wk}^{-1}$  ( $1,000 \text{ kg LW})^{-1}$ ] for April 2008 (Table 3). Astonishingly, even for hot days in July and August 2008, the downwind NH<sub>3</sub> concentrations were below its detection limit. Comparing to swine lagoon NH<sub>3</sub> emission rates with similar water temperature of  $30.2^\circ\text{C}$  [ $2.4 \text{ kg N wk}^{-1}$  ( $1,000 \text{ kg LW})^{-1}$ , (Szogi et al., 2006)], this reduction in total NH<sub>3</sub> emission was indeed remarkable.

Compared to the average of the first two emissions for the periods of December 2006 and February 2007 ( $1.72 \text{ g s}^{-1}$ ), total NH<sub>3</sub> emissions from the April 2008 to September 2008 periods were reduced by 94%. In comparison, the new treatment plant removed an average of 96.5% of the soluble NH<sub>4</sub>-N contained in the raw flushed manure with most of the removal (84%) occurring at the biological N treatment step (Vanotti et al., 2018). Concentrations of NH<sub>4</sub>-N in the lagoons were also reduced significantly during the emission evaluation period from 371 to  $485 \text{ mg L}^{-1}$  in 2006 to lower than  $65 \text{ mg L}^{-1}$  in 2008 (Vanotti et al., 2018).

Low NH<sub>3</sub> emission rates similar to those recorded in 2008 were also found in earlier studies (Aneja et al., 2008b) of a first generation version of the same wastewater treatment system (Vanotti et al., 2007) that was retrofitted in a 4,360-finishers production unit and removed 98.7% of the soluble NH<sub>4</sub> from liquid waste. According to Aneja et al. (2008b), the NH<sub>3</sub> emissions for this first-generation wastewater treatment plant were  $0.02 \text{ kg N wk}^{-1}$  ( $1,000 \text{ kg LW})^{-1}$  in the warm season and  $0.0004 \text{ kg N wk}^{-1}$  ( $1,000 \text{ kg LW})^{-1}$  in the cold season. These low NH<sub>3</sub> emissions represented reductions of 94.4% for the warm season and 99.0% for the cool season with respected to a conventional lagoon system (Aneja et al., 2008a). On a separate study of the same first-generation wastewater treatment system, Szogi et al. (2006) found that total annual NH<sub>3</sub> emission from the converted lagoon was  $1,210 \text{ kg N y}^{-1}$  and equivalent to  $0.10 \text{ kg N wk}^{-1}$  ( $1,000 \text{ kg LW})^{-1}$ . In contrast the NH<sub>3</sub> emissions from the conventional lagoon totaled  $12,540 \text{ kg N y}^{-1}$  [ $1.22 \text{ kg N wk}^{-1}$  ( $1,000 \text{ kg LW})^{-1}$ ]. Compared with the conventional lagoon, annual NH<sub>3</sub> emissions from the converted lagoon were reduced 90% (Szogi et al., 2006).

The NH<sub>3</sub> concentration in the air inside the houses was also reduced as a result of recycling cleaner water for pit recharge under the animal houses (Szogi and Vanotti, 2008). Compared with the previous conventional lagoon management, the new treatment system lowered NH<sub>3</sub> concentrations in the house

exhaust air by an average of 75.1%. Even though the wastewater treatment had instant effect on reducing NH<sub>3</sub> in the manure, and the NH<sub>3</sub> in the recycled water used for flushing the barns, the beneficial effects on emissions at the farm level were not seen immediately; the dirty liquid in the former lagoons needed time to be cleaned up. Actual lagoon 1 volume was  $9,565 \pm 750 \text{ m}^3$  and received  $11,552 \text{ m}^3$  per year of the clean plant effluent (Vanotti et al., 2018). In this study, one year of continuous operation of the wastewater treatment plant was necessary to observe marked differences in NH<sub>3</sub> emissions at the farm level.

## SUMMARY

The NH<sub>3</sub> emissions from a 5,145-head finishing swine farm before and after the new manure treatment system implementation were measured using both micrometeorological VRPM and static chamber techniques. The NH<sub>3</sub> emission flux from the lagoons decreased from  $32.8$  to  $7.1 \text{ kg-N ha}^{-1} \text{ d}^{-1}$ . The reduction in the total farm NH<sub>3</sub> emission was even more dramatic: All downwind NH<sub>3</sub> concentrations 1.5 year after starting up of the new treatment system were all below MDL. The dramatic decrease in total ammoniacal nitrogen in the lagoon validated this exceedingly low NH<sub>3</sub> emission from the farm.

## AUTHOR CONTRIBUTIONS

KR designed and conducted the emission experiments, collected and post-processed data, and wrote the draft. MV, AS, JL, and PM conducted water quality work, data summarization and processing. All authors participated in writing of the manuscript.

## ACKNOWLEDGMENTS

This research was part of USDA-ARS National Program 212: Soil and Air; ARS Project 6082-12630-001-00D Improvement of Soil Management Practices and Manure Treatment/Handling Systems of the Southern Coastal Plain. It was partially funded by the North Carolina Department of Justice, Office of the Attorney General through the Smithfield Foods Environmental Enhancement Fund Grant Agreement, USDA-ARS Project 6657-13630-003-04/NCSU Subcontract #2005-0978-03. The authors acknowledge Mel Johnson and William Brigman, USDA-ARS Florence, SC, for assistance with field monitoring and ammonia emission measurements. Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

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**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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