

Article

# Enhanced Dispersion and Removal of Ammonia Emitted from a Poultry House with a Vegetative Environmental Buffer

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**Abstract:** Vegetative environmental buffers (VEBs), which are composed of tolerant trees, shrubs, and tall grasses, can be used to control and reduce the transport of ammonia (NH<sub>3</sub>) emissions from animal feeding operations (AFOs). However, the effectiveness of VEBs has not been quantitated. In this study, we measure the dispersion and removal of NH<sub>3</sub> in simulated emissions from a small broiler house that was equipped with a VEB. The dispersion enhancement due to the VEB was estimated by comparing the measured downwind concentration of the co-released tracer gas, methane (CH<sub>4</sub>), to the theoretical CH<sub>4</sub> concentrations at the same distance downwind without the VEB. The accuracy of the theoretical downwind concentrations calculated using the forward Lagrangian stochastic (fLS) technique was 95%, which was validated by comparing the measured and calculated CH<sub>4</sub> concentrations in a separate experiment without the VEB. The VEB enhanced the dispersion of CH<sub>4</sub> and reduced the downwind concentration to 63% of the theoretical concentration. In addition to dispersion, the VEB removed another 22% of the NH<sub>3</sub>, resulting in a net 51% decrease of the theoretical downwind concentration. These results clearly demonstrated that the VEB was effective both in dispersing and removing NH<sub>3</sub> emitted from the broiler house.

**Keywords:** vegetative environmental buffer; broiler house emission; ammonia removal; dispersion enhancement; Lagrangian dispersion analysis

## 1. Introduction

Animal Feeding Operations (AFOs) generate and emit a variety of airborne pollutants. These include the fugitive gases, such as ammonia (NH<sub>3</sub>), hydrogen sulfide (H<sub>2</sub>S), and particulate matter (PM), which can create chronic health concerns for workers and animals [1–5]. Furthermore, volatile organic carbon (VOC) emissions from livestock can be a public odor nuisance and have been identified as one of the most significant animal emissions at the local level [6]. Regulations in California have also been promulgated to reduce volatile organic compound (VOC) emissions from agriculture to decrease ozone concentrations [7,8]. The development of cost-effective air emission mitigation technologies for

AFOs and an assessment of the effectiveness of these technologies are urgently needed to improve our environmental performance and to help producers address Federal and state regulatory pressures.

A current management strategy that is used to control and reduce transport of AFO emissions is vegetative environmental buffers (VEBs). Vegetative environmental buffers consist of trees, shrubs, and/or tall grasses around the exhaust fans of poultry houses to reduce PM, VOC, and NH<sub>3</sub> emissions. Recently, Natural Resources Conservation Service (NRCS) National Plant Materials Center (PMC) determined which plant species are most viable under the harsh atmospheric conditions [9,10] of high pollutant concentrations that are emitted from the AFOs. Because AFO facilities are behind trees and shrubs, VEBs also enhance the aesthetics of the facilities and the landscape. Consequently, VEBs have led to increased public positive perception of AFOs and demonstrated producer environmental stewardship.

Tyndall and Colletti [11] reviewed various mechanisms how VEBs can be effective in mitigating livestock odor: (1) physical interception and capture of dust, aerosols, and gases by trees and shrubs; (2) dilution and dispersion of downwind odor compounds; (3) land deposition, dust, and other aerosols due to reduced wind speeds; and, (4) a biological sink for intercepted odorous chemicals. Parker et al. [12] reported that a VEB reduced odor concentrations 15 m from the VEB; however, they also pointed out that gas concentrations at 150 and 300 m downwind of swine barns were not significantly different from control barns without a VEB. Therefore, it appears that the effectiveness of a VEB in reducing odor concentration depends on the location of the sensors downwind of the VEB.

Reduction in NH<sub>3</sub> concentrations across VEBs have been reported in the literature [4,11,13–15]. Malone [14] and Malone et al. [13] reported that emitted NH<sub>3</sub> concentrations were reduced by 30–67% by a VEB consisting of three rows of trees. However, it was not clear as to what extent the reduction in concentrations were due to simple dispersion (i.e., dilution) or to actual removal by plant biomass (i.e., absorption, synthesis, adsorption, plant uptake, deposition, etc.). Similarly, Adrizal et al. [4] measured NH<sub>3</sub> concentrations at five poultry farms that were equipped with VEBs where they observed that NH<sub>3</sub> concentrations decreased by an average of 78% across the VEBs. They also reported evidence for foliar N entrapment and NH<sub>3</sub> incorporation by the VEB. However, meteorological data were not collected, so the influence of change in wind direction and turbulence on NH<sub>3</sub> removal efficiency by the VEB itself could not be evaluated.

The objective of this study was to evaluate quantitatively the effectiveness of a VEB in removing and dispersing NH<sub>3</sub> emissions from a broiler house by comparing the released NH<sub>3</sub> downwind concentrations to a co-released inert tracer gas, methane (CH<sub>4</sub>). The assumption was that CH<sub>4</sub> is effectively inert relative to the reactive and much more readily sorbed NH<sub>3</sub>. The tracer gas also served as a reference to evaluate the effects of dispersion as a function of distance from the emission source. We examined the relationship between the broiler house gas emission rates ( $Q$ ) and the corresponding concentrations ( $C$ ) of these gases downwind of the broiler house with or without VEBs.

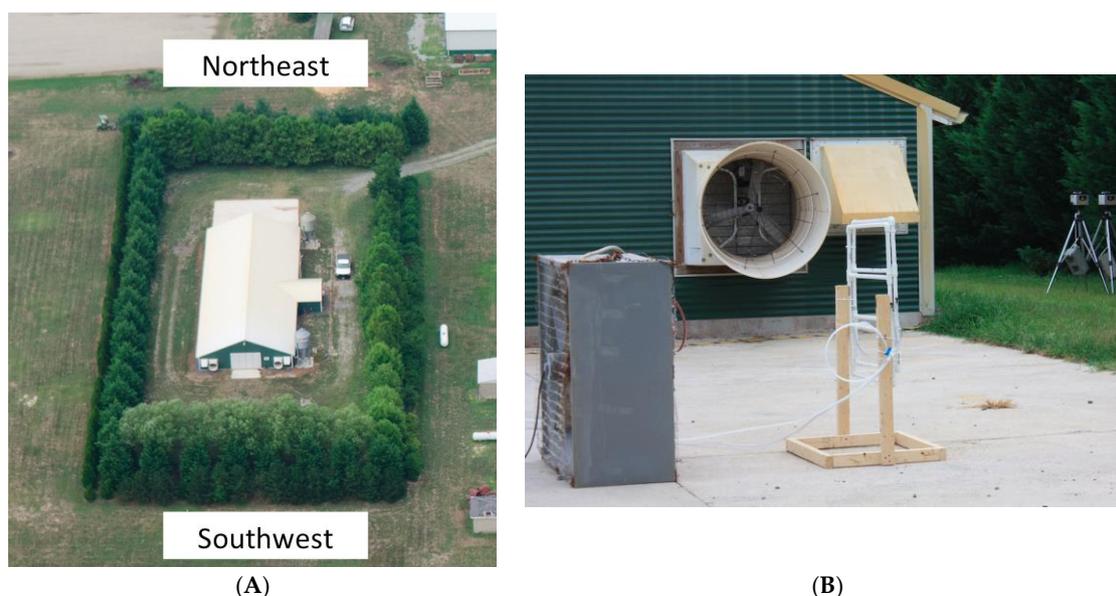
The hypothesis was that a VEB would alter the ratios of  $C/Q$  when compared to not having a VEB and that the reduction in  $C/Q$  would result in a mitigation effect of the VEB. Because no two broiler house emission systems are the same, evaluating houses without (control) versus with (variable) a VEB is difficult as well as isolating the effect of VEB type, barn configuration, local topography, surrounding vegetation, and meteorological conditions on  $C/Q$ . Thus, the first approach employed in this study uses a well-developed atmospheric dispersion model to calculate the theoretical  $C/Q$  values that would exist if there was no VEB. The second approach compares the  $C/Q$  of NH<sub>3</sub> and CH<sub>4</sub> at a broiler house with a VEB.

## 2. Materials and Methods

### 2.1. Experimental Site

The experimental site was located in Georgetown, DE, and consisted of a research broiler house with a surrounding multi-layer VEB (Figure 1A). The environmentally-controlled experimental house

(34.7 m length  $\times$  12.1 m width), was oriented southwest to northeast and was divided into two partitions, (17.3 m  $\times$  12.1 m each). The two partitions (capacity = 2400 birds/partition) were identical and shared the same center wall and control room. There were four endwall fans (two 0.6-m and two 0.9-m diameter fans) for each partition. The VEB (43 m  $\times$  98 m) consisted primarily of green giant arborvitae (*Thuja standishii*  $\times$  *plicata*), Leyland cypress (*Cupressus*  $\times$  *leylandii*), and Austree willow (*Salix matsudana*  $\times$  *alba*) was installed in the spring of 2003. The spacing between the layers and between the trees in each layer was 3 m. No bird production was on-going during the experimental periods, and the house fans were not operating.



**Figure 1.** The experimental site and setup (A): broiler house with vegetative environmental buffers (VEB) and (B): Polyvinyl chloride (PVC) gas release apparatus in front of a 0.9-m freestanding, box fan.

## 2.2. Simulated Emissions

Pure CH<sub>4</sub> and NH<sub>3</sub> gases (Air Products and Chemicals, Allentown, PA, USA) in compressed gas cylinders were simultaneously released using mass flow controllers (GFC57S-VDL4, Aalborg, Orangeburg, New York, NY, USA) at a measured rate of 30 g/min through a 0.9  $\times$  0.9 m PVC apparatus (Figure 1B) that was placed in front of a 0.9-m box fan outside of the northeast end of the house. Data were collected during three experimental periods from 30 July 2013 to 3 August 2013, however, only two experimental periods were considered here (see below). Gases were released for 60 min with a 30-min downtime between releases. The release point was 9 and 21 m in front of the VEB for Experiment 1 and 2, respectively. Because CH<sub>4</sub> is essentially inert and has about the same density, the concentration ratio of these two gases will not change with distance unless NH<sub>3</sub> is removed. If NH<sub>3</sub> is removed, the ratio will be less than one. Thus, simultaneous measurements of downwind CH<sub>4</sub> and NH<sub>3</sub> concentrations allowed for the calculation of the extent of NH<sub>3</sub> sorption by the VEB biomass and other processes. Furthermore, the ratio of the measured downwind CH<sub>4</sub> concentration to the theoretical downwind CH<sub>4</sub> concentration without a VEB with the same emission rate allowed for the calculation of the extent of gas dispersion due to the VEB.

## 2.3. Sensors

An open-path tunable diode laser absorption spectrometers (TDLs, GasFinder2.0 for CH<sub>4</sub>, Boreal Laser Inc., Edmonton, AB, Canada) with retroreflectors were used to measure path-integrated concentrations (PICs). The TDLs were designed for a sampling rate of about 1 Hz and had continuous internal calibration updates every 40 samples using an internal reference cell. Each of the TDLs

were calibrated on-site for the determination of a correction factor for each gas. Two CH<sub>4</sub> TDLs were factory-calibrated just before the experiments, while the third TDL was calibrated by comparing measured ambient CH<sub>4</sub> concentrations (115.3 m path length) to that measured by the other TDLs. Three NH<sub>3</sub> TDLs were calibrated through 1.5-m calibration tubes containing 52.5 ppm of NH<sub>3</sub>. The TDLs were further adjusted for temperature and pressure corrections for the field study site.

The PIC data and the three-dimensional wind speeds were averaged for 15-min intervals. The resolutions of the TDLs were estimated by determining the root mean squares of differences in consecutive 15-min average PICs (13 to 16 datasets for each TDLs), while measuring gases with the same concentrations. The average PIC resolutions of the CH<sub>4</sub> and NH<sub>3</sub> TDLs were 5.15 and 4.62 ppm·m, respectively. The concentration measurements were started before the gas release and persisted afterwards to estimate the time-varying ambient background concentrations. This background measurement was used to calculate the change in concentration, i.e.,  $\Delta C = C_{\text{observed}} - C_{\text{background}}$ . A three-dimensional sonic anemometer (CSAT3, Campbell Scientific, Inc., Logan, UT, USA) was used to measure wind speeds at 20 Hz. The three-dimensional (3-D) sonic anemometer provided the wind information needed for calculations of friction velocity ( $u^*$ ), Obukhov stability length ( $L$ ), surface roughness length ( $z_0$ ), and wind direction. To avoid error-prone periods, the following post data-filtering criteria were used [16]:

- Obukhov stability length scale,  $|L| \geq 5$  m (i.e., avoid highly stable/unstable atmospheric stratification);
- friction velocity  $u^* \geq 0.1$  m/s; and,
- net changes in PICs due to release of tracer gases > resolutions of each TDLs.

Three experimental runs were conducted with the TDLs strategically located to measure downwind PICs from the emission source with anticipated dominant wind directions. During the period of 30 July 2013 to 31 July 2013, the dominant wind direction was not favorable for obtaining reliable downwind PICs. Furthermore, low wind speeds with  $u^*$  less than 0.1 m/s were observed. Therefore, the datasets obtained during this period were excluded from further analysis. The subsequent experimental setups and wind conditions during Experiment 1 (31 July 2013 to 1 August 2013) and Experiment 2 (2 August 2013 to 3 August 2013) are shown in Figure 2.

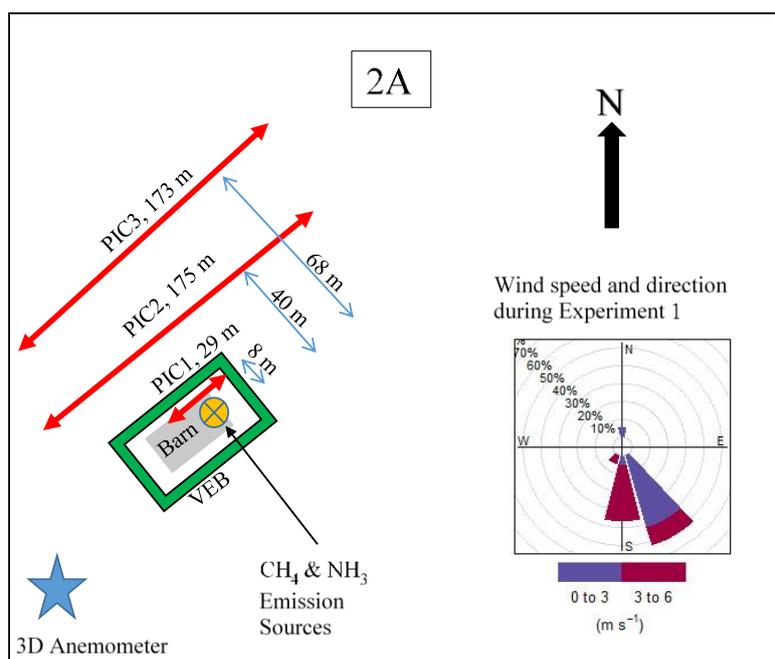
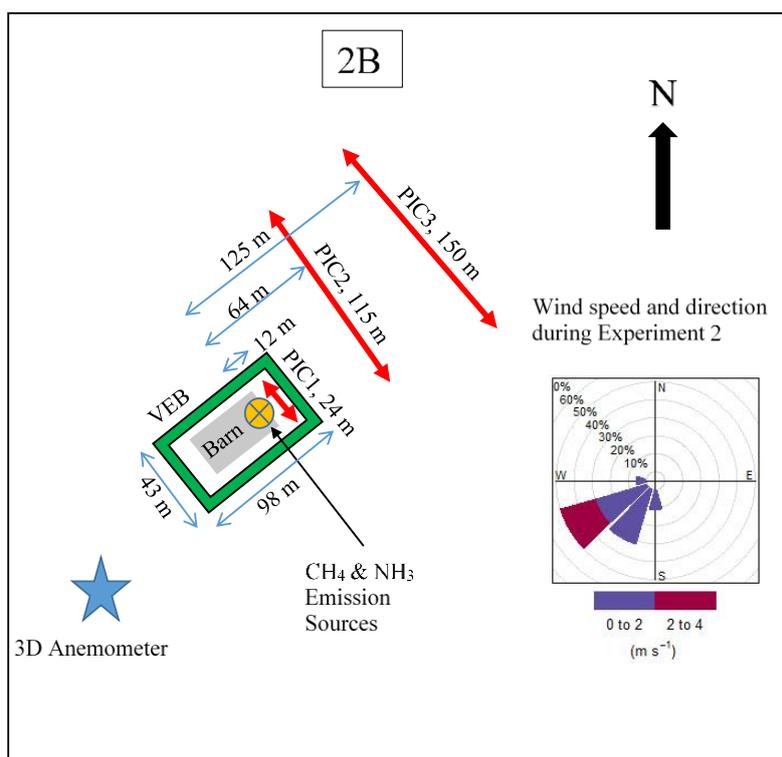


Figure 2. Cont.



**Figure 2.** Field experimental seups and wind conditions during (A) Experiment 1 and (B) Experiment 2.

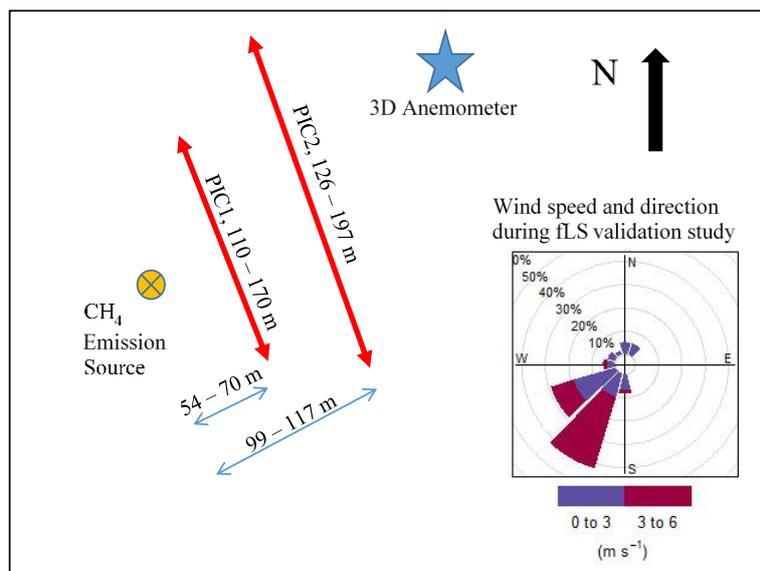
#### 2.4. Forward Lagrangian Stochastic (fLS) Technique Validation Study

The theoretical downwind CH<sub>4</sub> and NH<sub>3</sub> concentrations without a VEB were calculated using a Lagrangian stochastic (LS) dispersion model (WindTrax, <http://www.thunderbeachscientific.com/>) with known emission rates. Accuracies of the LS model for estimating the emission rates from concentration measurements made downwind of emission sources (hereafter called backward Lagrangian stochastic (bLS) technique) has been documented in the literature [17–25]. Relative errors that are associated with the bLS are suggested to be 10% to 15% for short-range cases (where concentration is taken within 1 to 2 km of the source). WindTrax can also be used to estimate the downwind concentration accurately from an emission source without a VEB if the emission rate is known (hereafter called forward Lagrangian stochastic (fLS) technique). It logically follows that the downwind concentration can be calculated using the fLS technique with a similar level of accuracy with a known emission rate.

To confirm the accuracy of the fLS technique, independent trace gas release experiments were conducted on a grass field at the USDA-ARS Coastal Plains Soil, Water and Plant Research Center in Florence, SC, USA, during March and April 2014. Methane was used as a tracer. The positions of point emission source and PICs were similar to that of the Delaware field Experiment 2 (Figure 3). During the study period, the site was covered with short Bermuda grass less than 0.1 m tall. The accuracy of the fLS technique was calculated as:

$$\text{Accuracy} = C_{\text{measured}} / C_{\text{fLS}} \quad (1)$$

where  $C_{\text{measured}}$  = measured CH<sub>4</sub> concentration (ppm) and  $C_{\text{fLS}}$  = calculated CH<sub>4</sub> concentration using the fLS technique (ppm).



**Figure 3.** Forward Lagrangian stochastic method (fLS) validation experiment setup and wind conditions during experiments.

The central tendency and precision of measurements were presented with arithmetic averages and standard deviations (given as  $\pm$  values). All of the statistical parameters and tests (i.e., mean, standard deviation, *t*-tests, and analyses of variance (ANOVA)) were obtained/performed using GraphPad Prism 7.03 (GraphPad Software, Inc., La Jolla, CA, USA).

### 3. Results and Discussion

#### 3.1. Accuracy of the fLS Technique

The accuracy of the fLS technique ( $C_{\text{measured}}/C_{\text{fLS}}$ ) was determined by comparing the theoretical  $\text{CH}_4$  downwind concentrations that were calculated using the fLS technique to the measured  $\text{CH}_4$  downwind concentrations (Table 1 and Figure 4). However, many of the 15-min datasets collected on 20 March 2014 and several on 1 April 2014 were excluded because the dominant wind paths were outside the two PICs; therefore, fewer datasets were analyzed during these periods. The average percent accuracy of the fLS technique for PIC1 and PIC2 for each day ranged from 89% to 105% and 90% to 99%, respectively. The average accuracy ratios of all the runs for PIC1 ( $94\% \pm 7\%$ ) and PIC2 ( $96\% \pm 4\%$ ) were not statistically different ( $p < 0.05$ , unpaired *t*-test with Welch's correction). The combined overall average percent accuracy of both PICs was  $95\% \pm 6\%$ . The results of this experiment provide strong evidence that the fLS is a reliable technique to predict the theoretical downwind concentration without any barriers, such as a VEB.

**Table 1.** Average percent accuracy of methane ( $\text{CH}_4$ ) using the fLS technique with wind speed and friction velocity ( $u^*$ ) (values  $\pm$  standard deviation).

Date	Wind Speed (m/s)	Friction Velocity $u^*$ (m/s)	Percent Accuracy for PIC1 (%) $C_{\text{measured}}/C_{\text{fLS}}$	Percent Accuracy for PIC2 (%) $C_{\text{measured}}/C_{\text{fLS}}$	Number of Runs per Day
14 March 2014	$3.4 \pm 0.5$	$0.33 \pm 0.07$	$105 \pm 3$	$90 \pm 1$	21
20 March 2014	$1.7 \pm 0.7$	$0.22 \pm 0.06$	$96 \pm 4$	$96 \pm 2$	7
1 April 2014	$2.8 \pm 0.4$	$0.25 \pm 0.04$	$92 \pm 4$	$99 \pm 3$	16
10 April 2014	$3.2 \pm 0.4$	$0.33 \pm 0.06$	$89 \pm 4$	$98 \pm 1$	37
All Runs	$2.8 \pm 0.8$	$0.29 \pm 0.07$	$94 \pm 7$	$96 \pm 4$	86

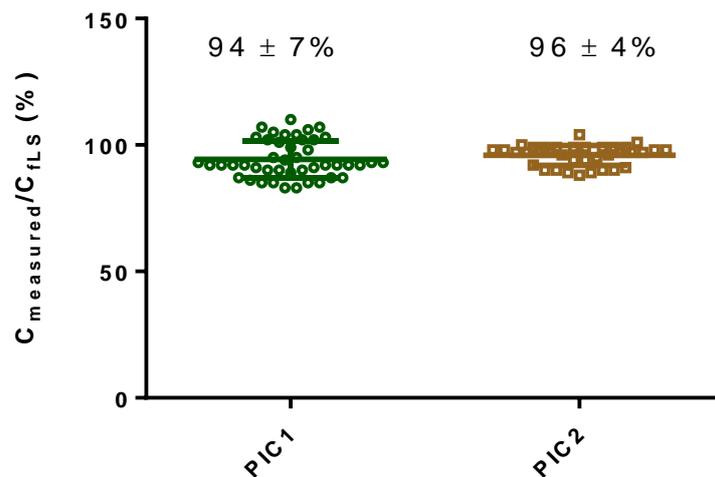


Figure 4. Percent accuracy of the fLS technique.

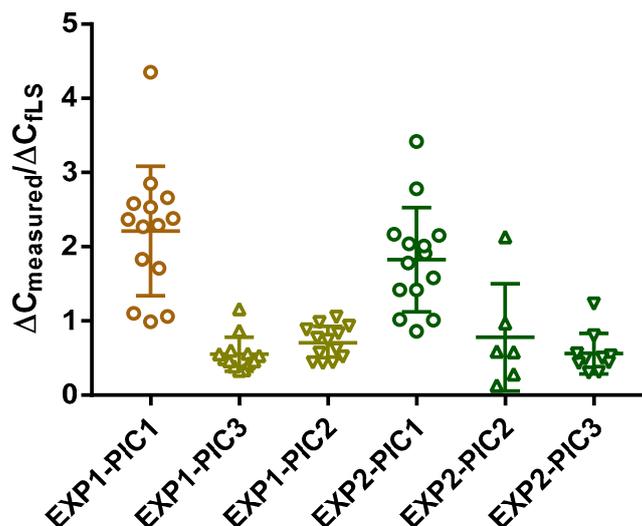
### 3.2. Enhanced Dispersion by a VEB

The effectiveness of a VEB in dispersing emitted gases was evaluated by comparing the measured downwind  $\text{CH}_4$  concentrations to theoretical concentrations that would exist if there was no VEB. The theoretical downwind concentrations were calculated using the fLS technique. If the VEB did not affect the dispersion, the ratio of the two measured downwind concentrations ( $C_{\text{measured,PIC2}}$  and  $C_{\text{measured,PIC3}}$ ) outside the VEB to the two theoretical concentrations ( $C_{\text{fLS,PIC2}}$  and  $C_{\text{fLS,PIC3}}$ ) would be unity because  $\text{CH}_4$  is essentially inert. The average ratios of  $\text{CH}_4$  concentration ( $C_{\text{measured}}/C_{\text{fLS}}$ ) in Experiment 1 were  $0.94 \pm 0.06$  and  $0.93 \pm 0.07$  for PIC2 and PIC3, respectively (Table 2 and Figure 5). For Experiment 2, the average ratios were slightly lower than that of Experiment 1, with  $0.91 \pm 0.12$  and  $0.93 \pm 0.06$  for PIC2 and PIC3, respectively. For each experiment, the  $\text{CH}_4$  ratio,  $C_{\text{measured}}/C_{\text{fLS}}$ , for PIC2 and PIC3 were not significantly different ( $p < 0.05$ , ANOVA, Table 2), so a combined average for each experiment was calculated,  $0.93 \pm 0.06$  and  $0.92 \pm 0.10$  for Experiments 1 and 2, respectively. This initial assessment suggests that little dispersion was caused by the VEB, however, these calculations did not exclude the background concentration. To quantify the extent to which the VEB decreased downwind concentrations by dispersion (also considering background gas concentrations), the changes in the measured  $\text{CH}_4$  concentration ( $\Delta C_{\text{measured}}$ ) were compared to that of theoretical changes in concentration based on the released concentration without the VEB ( $\Delta C_{\text{fLS}}$ ). Again, in the absence of dispersion, this ratio,  $\Delta C_{\text{measured}}/\Delta C_{\text{fLS}}$ , should be unity for PIC2 and PIC3. Values for  $\Delta C_{\text{measured}}/\Delta C_{\text{fLS}}$  were 0.71 and 0.55 were observed compared to the theoretical changes without the VEB for PIC2 and PIC3, respectively, in Experiment 1. In Experiment 2, the values were 0.78 and 0.56 for PIC2 and PIC3, respectively (Table 2). However, these reductions that were observed at PIC2 and PIC3 locations within each experiment were not statistically different from each other either within the experiment or between experiments. The overall average of downwind concentration ratios for PIC2 and PIC3 in both Experiments 1 and 2 was  $0.63 \pm 0.34$ , i.e., dispersion by the VEB decreased the concentration to 63%.

**Table 2.** Comparisons of measured and theoretical downwind concentration ratios of CH<sub>4</sub>.

PICs	Experiment 1		Experiment 2	
	$C_{\text{measured}}/C_{\text{fLS}}^{\dagger}$	$\Delta C_{\text{measured}}/\Delta C_{\text{fLS}}^{\ddagger}$	$C_{\text{measured}}/C_{\text{fLS}}^{\dagger}$	$\Delta C_{\text{measured}}/\Delta C_{\text{fLS}}^{\ddagger}$
Average of PIC1	1.67 ± 0.54 <sup>a</sup> (14)	2.21 ± 0.87 <sup>c</sup> (14)	1.49 ± 0.36 <sup>a</sup> (14)	1.83 ± 0.70 <sup>c</sup> (14)
Average of PIC2	0.94 ± 0.06 <sup>b</sup> (13)	0.71 ± 0.22 <sup>d</sup> (13)	0.91 ± 0.15 <sup>b</sup> (5)	0.78 ± 0.72 <sup>d</sup> (6)
Average of PIC3	0.93 ± 0.07 <sup>b</sup> (13)	0.55 ± 0.23 <sup>d</sup> (13)	0.93 ± 0.06 <sup>b</sup> (10)	0.56 ± 0.27 <sup>d</sup> (10)
Average of PIC2 and PIC3	0.93 ± 0.06	0.63 ± 0.23	0.92 ± 0.10	0.63 ± 0.34

<sup>†</sup> Values followed by the same letter within the  $C_{\text{measured}}/C_{\text{fLS}}$  category were not significantly different ( $p < 0.05$ , ANOVA). <sup>‡</sup>  $\Delta C_{\text{measured}}/\Delta C_{\text{fLS}} = (\Delta C_{\text{measured}} - \Delta C_{\text{background}})/(\Delta C_{\text{fLS}} - \Delta C_{\text{background}})$ . Values followed by the same letter within the  $\Delta C_{\text{measured}}/\Delta C_{\text{fLS}}$  category were not significantly different ( $p < 0.05$ , ANOVA).



**Figure 5.** The CH<sub>4</sub> ratios of the change in measured CH<sub>4</sub> concentration with a VEB to that for theoretical CH<sub>4</sub> concentration without a VEB during Experiments 1 and 2.

### 3.3. Removal of NH<sub>3</sub> by the VEB

Because the molecular weights of CH<sub>4</sub> and NH<sub>3</sub> are similar, these gases should disperse similarly. However, the CH<sub>4</sub> background concentrations (ca. 1.9 ppm) were larger than the NH<sub>3</sub> background (ca. 0.4 ppm), so a simple comparison of the observed apparent concentrations resulting from the co-release of these gases would not yield accurate values of the percent NH<sub>3</sub> removal. Instead, the net changes in gas concentration beyond the background concentration ( $\Delta C$ ) were used to compare the  $C/Q$  of the two gases (Table 3). If NH<sub>3</sub> behaves like a near-inert gas, CH<sub>4</sub>, the values of  $(\Delta C_{\text{measured}}/Q)_{\text{NH}_3}/(\Delta C_{\text{measured}}/Q)_{\text{CH}_4}$  will be unity. However, if other processes beyond dispersion remove NH<sub>3</sub>, then the measured values of  $(\Delta C/Q)_{\text{NH}_3}/(\Delta C/Q)_{\text{CH}_4}$  will be less than unity.

**Table 3.** Net changes in measured gas concentration per emission rate  $\{(\Delta C/Q)_{\text{NH}_3}/(\Delta C/Q)_{\text{CH}_4}\}$ .

Location of PICs	Experiment 1	Experiment 2
PIC1	0.97 ± 0.13 <sup>a,†</sup> (14)	1.00 ± 0.08 <sup>a</sup> (14)
Overall average for PIC1 in Experiments 1 and 2	0.99 ± 0.11	
PIC2	0.64 ± 0.39 <sup>a</sup> (8)	0.94 ± 0.60 <sup>a</sup> (5)
PIC3	0.68 ± 0.30 <sup>a</sup> (6)	0.90 ± 0.68 <sup>a</sup> (8)
Average of PIC2 and PIC3	0.66 ± 0.34	0.92 ± 0.62
Overall average of PIC2 and PIC3 in Experiments 1 and 2	0.78 ± 0.50	

<sup>†</sup> Values followed by the same letter were not significantly different ( $p < 0.05$ , ANOVA).

Greater reductions in  $\text{NH}_3$  concentration were observed in Experiment 1 (0.64 and 0.68 for PIC2 and PIC3, respectively) than in Experiment 2 (0.94 and 0.90 for PIC2 and PIC3, respectively; Table 3). However, these differences in  $\text{NH}_3$  reduction between the two experiments were not statistically significant ( $p < 0.05$ ). The overall average change in  $\text{NH}_3$  concentration was  $0.78 \pm 0.50$  for both PIC2 and PIC3 for all of the runs in Experiments 1 and 2. This represents an additional 22% ( $100\% - 78\% = 22\%$ ) reduction of  $\text{NH}_3$  that was removed by the VEB beyond dispersion. From the previous calculations, the downwind concentrations were reduced to 63% due to dispersion. Thus, the additional 22% removal would result in a total decrease in  $\text{NH}_3$  concentration to 49% (i.e.,  $78\% \times 63\% = 49\%$ ) of the theoretical downwind  $\text{NH}_3$  concentration observed at PIC2 and PIC3 if a VEB was not present.

The percent decrease in  $\text{NH}_3$  downwind concentration can also be estimated by directly comparing the change in measured  $\text{NH}_3$  concentration to that of the theoretical concentration that would exist without the VEB. Table 4 shows the ratios of  $\Delta C_{\text{measured}}/\Delta C_{\text{fLS}}$  for  $\text{NH}_3$ , i.e., the changes in measured and theoretical concentrations as was done for the dispersion study with  $\text{CH}_4$ . The overall average change in  $\text{NH}_3$  downwind concentration from this method was 0.51 of the theoretical  $\text{NH}_3$  concentration without the VEB. This translates to a 49% reduction in the emitted concentration that is similar to the result that was determined by comparing the measured concentrations of  $\text{CH}_4$  and  $\text{NH}_3$ . It also further validates our approach in assessing the impact of VEB on dispersion and removal of  $\text{NH}_3$ .

**Table 4.** Comparisons of the changes in measured and theoretical downwind  $\text{NH}_3$  concentrations ( $\Delta C_{\text{measured}}/\Delta C_{\text{fLS}}$ )<sup>†</sup>.

Location of PICs	Experiment 1	Experiment 2
PIC1	$2.31 \pm 1.00^a$ (14)	$1.90 \pm 0.61^a$ (14)
Average of PIC1 for Experiments 1 and 2	$2.10 \pm 0.84$	
PIC2	$0.55 \pm 0.35^b$ (8)	$0.38 \pm 0.17^b$ (13)
PIC3	$0.46 \pm 0.13^b$ (6)	$0.65 \pm 0.27^b$ (10)
Average of PIC2 and PIC3	$0.51 \pm 0.27$	$0.50 \pm 0.27$
Overall average of PIC2 & PIC3 for Experiments 1 and 2	$0.51 \pm 0.26$	

<sup>†</sup> Values followed by the same letter were not significantly different ( $p < 0.05$ , ANOVA).

### 3.4. Increase in Gas Concentrations within the VEB

The ratios of the change in measured concentration to the theoretical concentration without the VEB for  $\text{CH}_4$  in front of the VEB (i.e., PIC1) during Experiment 1 and 2 were  $2.21 \pm 0.87$  and  $1.83 \pm 0.70$ , respectively (Table 2). Similarly, higher ratios were observed for  $\text{NH}_3$ ;  $2.31 \pm 1.00$  and  $1.90 \pm 0.61$  for Experiment 1 and 2, respectively (Table 4). These higher-than-unity ratios suggested that the concentrations inside the VEB were higher than those without the VEB. These higher concentrations indicated that the emitted gases accumulated within the VEB, which may be due to restriction in wind flow and eddy formation within the VEB. Interestingly, almost no  $\text{NH}_3$  removal was observed within the VEB at PIC1, as suggested by the measured values of the ratio  $(\Delta C/Q)_{\text{NH}_3}/(\Delta C/Q)_{\text{CH}_4}$ , which were near unity (overall average of  $0.99 \pm 0.11$  for all of the runs in both Experiments 1 and 2). Both  $\text{CH}_4$  and  $\text{NH}_3$  increased within the VEB, but no significant  $\text{NH}_3$  removal was observed because little vegetative biomass was available onto which  $\text{NH}_3$  could be removed via adsorption/absorption inside the VEB area (Figure 1). The higher concentrations of emitted gas inside the VEB area calls for careful monitoring of the health-affecting gases, such as  $\text{H}_2\text{S}$  and  $\text{NH}_3$ , to ensure the safety of farm workers.

## 4. Conclusions

The effectiveness of VEBs in removing and dispersing  $\text{NH}_3$  emission from poultry houses was investigated by conducting a series of simulated gas-release experiments from a poultry house equipped with a well-established VEB. Known rates of  $\text{CH}_4$  and  $\text{NH}_3$  were released just outside

of the house. The measured downwind concentrations were compared with the theoretical downwind concentrations that would exist without the VEB. The theoretical concentrations without the VEB were calculated using the fLS technique. From independent tracer gas release experiments, we found that the overall percent accuracy of the fLS technique was  $95\% \pm 6\%$ , indicating that the fLS technique is a reliable way of predicting theoretical downwind concentrations without a VEB.

Using  $\text{CH}_4$  as an inert gas, we found that a VEB-enhanced dispersion resulted in concentrations that were 63% of the emitted gas when compared with the theoretical concentrations for a system without the VEB. Emitted gas concentrations inside the VEB area were about twice as large as the theoretical concentrations that would exist without the VEB. The ratios of the measured concentrations of  $\text{NH}_3$  and  $\text{CH}_4$  showed that an additional 22% of the  $\text{NH}_3$  was removed beyond the reduction in downwind from dispersion. The resulting downwind  $\text{NH}_3$  concentration after the dispersion and removal by the VEB was 49% of the theoretical concentration that would exist without the VEB.

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